Keele UNIVERSITY

Validating models of injury risk prediction in football players

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ABBREVIATIONS LIST

2D	- Two Dimensional
3D	- Three Dimensional
ACL	- Anterior Cruciate Ligament
AJC	- Ankle Joint Centre
ANK	- Marker placed on lateral malleolus; may be preceded by L or R e.g. LANK or RANK indicating left or right side respectively
ASI	- Marker placed on the anterior superior iliac spine; may be preceded by L or R e.g. LASI or RASI indicating left or right side respectively
ASIS	- Anterior Superior Iliac Spine
BEX	- Marker placed on back of thorax; may be preceded by L or R e.g. LBEX or RBEX indicating left or right side respectively
BHD	- Marker placed on back of head; may be preceded by L or R e.g. LBHD or RBHD indicating left or right side respectively
BRANN	- Bayesian Regularised Artificial Neural Network
C7	- Marker placed on 7th Cervical vertebrae
CLAV	- Marker placed on Clavicle
CMJ	- Counter movement jump
EJC	- Elbow Joint Centre
ELB	- Marker placed on lateral epicondyle of humerus; may be preceded by L or R e.g. LELB or RELB indicating left or right side respectively
F-MARC	FIFA Medical and Research Centre
FA	- Football Association; governing body for the United Kingdom
FHD	- Marker placed on front of head; may be preceded by L or R e.g. LFHD or RFHD indicating left or right side respectively
FIFA	- Fédération Internationale de Football Association
FIN	- Marker placed proximal to second metacarpophalangeal joint; may be preceded by L or R e.g. LFIN or RFIN indicating left or right side respectively

FMS - Functional Movement Screen; a screening test

FRA - Marker placed on the forearm; may be preceded by L or R e.g. LFRA or RFRA indicating left or right side respectively

HEE - Marker placed on the calcaneus; may be preceded by L or R e.g. LHEE or RHEE indicating left or right side respectively

HJC - Hip Joint Centre; may be preceded by L or R e.g. LHJC or RHJC indicating left or right side

HR - Heart rate

HUP - Proximal humerus (shoulder joint centre)

IR1 - Intermittent Recovery one (1st subtest of the Yo-Yo shuttle run test)

IR2 - Intermittent Recovery two (2nd subtest of the Yo-Yo shuttle run test)

KAD - Knee Alignment Device

KAX - Knee Axis Marker

KD1 - Knee Alignment Device marker 1

KD2 - Knee Alignment Device marker 2

KJC - Knee Joint Centre

KME - Marker placed on the knee medial epicondyle; may be preceded by L or R e.g. LKME or RKME indicating left or right side respectively

KNE - Marker placed on the knee lateral epicondyle; may be preceded by L or R e.g. LKME or RKME indicating left or right side respectively

MID_THI - Virtual marker recreated to represent the middle of the thigh segment

ORLAU - Orthotic Research and Locomotor Assessment Unit

PEX - Marker placed on the iliac crest; may be preceded by L or R e.g. LPEX or RPEX indicating left or right side respectively

PSI - Marker placed on the Posterior Superior Iliac Spine; may be preceded by L or R e.g. LPSI or RPSI indicating left or right side respectively

PSIS - Posterior Superior Iliac Spine

RBAK - Marker placed on back of thorax right scapula;

RJAH - Robert Jones and Agnes Hunt Orthopaedic Hospital National Health Service Foundation Trust

ROM - Range of Movement

RPE - Rate of Perceived Exertion

SHO - Marker placed over the acromio-clavicular joint ; may be preceded by L or R e.g. LSHO or RSHO indicating left or right side respectively

SJ - Squat jump

SJC - Shoulder Joint Centre

STRN - Marker placed on the Sternum

T10 - Marker placed on the 10th Thoracic vertebrae

TEX - Marker placed on the front of thorax; may be preceded by L or R e.g. LTEX or RTEX indicating left or right side respectively

THI - Marker placed on the thigh segment; may be preceded by L or R e.g. LTHI or RTHI indicating left or right side respectively

TIB - Marker placed on the lower leg segment; may be preceded by L or R e.g. LTIB or RTIB indicating left or right side respectively

TOE - Marker placed proximal to the first metatarsophalangeal joint; may be preceded by L or R e.g. LTOE or RTOE indicating left or right side respectively

UEFA - Union of European Football

UPA - Marker placed on the humeral segment; may be preceded by L or R e.g. LUPA or RUPA indicating left or right side respectively

VICON - a 3D motion analysis photogrammetric system (©Vicon Motion Systems Ltd); for this thesis the term VICON will be used to refer to the photogrammetric system used

VO2 max - A measure of the maximum volume of oxygen used by an individual. It is measured in millilitres per kilogramme of body weight per minute (ml/kg/min).

WJC - Wrist Joint Centre

WRA - Marker placed on medial aspect of the wrist distal to radial styloid; may be preceded by L or R e.g. LWRA or RWRA indicating left or right side respectively

WRB - Marker placed on lateral aspect of the wrist distal to ulna styloid; may be preceded by L or R e.g. LWRB or WRB indicating left or right side respectively

ABSTRACT

Association football (soccer) is a popular sport and there is a high risk of injury for participants. Within the context of professional clubs, the risk of injury is also associated with the risk of financial costs. Therefore, injury reduction processes are considered important, and previous studies have sought to identify and model injury risk factors. Although formal screening tests e.g. The Functional Movement Screen (FMS) and monitoring procedures e.g. Union of European Football Associations (UEFA) have been developed for modelling and predicting injuries, the processes in current use, lack precision or clinical usefulness. The aims of this thesis were therefore to explore why existing methods of screening, measuring and modelling are not effective in predicting injuries. In order achieve this the following things were done;

- Literature review to evaluate the UEFA screening process and advocated variables,
- Validation of the FMS, the most commonly used exercise screening test, against a 3D photogrammetric system (Vicon (©Vicon Motion Systems Ltd))
- Injury modelling on a pre-established database designed in accordance with the UEFA guidelines

The literature review confirmed that the established database was compliant with the UEFA screening guidelines. The most commonly used screening measure (FMS) for injury risk was found to be an invalid measure and therefore removed from the modelling process. The models developed were unable to prospectively model injuries accurately ($R = 0.23$), and the primary problem was a large number of false positives i.e. those predicted as having risk of injury not sustaining injury. Reasons for poor model performance could be attributed to inappropriate screening methods, inadequate datasets or inadequate modelling methods for rare events.

Future work should focus on addressing the limitations in the existing UEFA screening framework and simultaneously develop better methods of rare event modelling from small datasets.

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ETHICAL APPROVAL

For this thesis, ethical approval from the Keele University Ethical Review Panel was gained prior to data collection and evaluation of the existing Keele University Men's Football Club database (Appendix I).

For data collection conducted at the Royal Jones and Agnes Hunt Orthopaedic Hospital NHS Trust, ethical approval was gained prior to data collection from the National Research Ethics Service, research ethics committee reference 13/WM/0045 (Appendix II).

1 INTRODUCTION

Association football or soccer is a popular sport, with approximately 200,000 professionals and a further 240 million amateur male and female participants worldwide (Junge and Dvorak 2004). Fédération Internationale de Football Association (FIFA) is the world governing body for football and the Football Association (FA) is the governing body for England. Football is England's largest national team sport, with men's and women's football being the first and third largest team sports respectively (The Football Association 2013). Each governing body actively promotes the uptake of football, and over the last 5 years, The FA has invested over £ 100 million pounds a year back into the game across all levels to encourage participation in the sport (The Football Association 2013). The term "football' is inclusive of rugby, futsal, American football, Australian rules football, beach soccer and many others, but these will not be included in this review. The term football used in this review will refer to FIFA 11 a side football and associated youth development programmes which have been modified to accommodate the progression of youth footballers into to the 11 a side game.

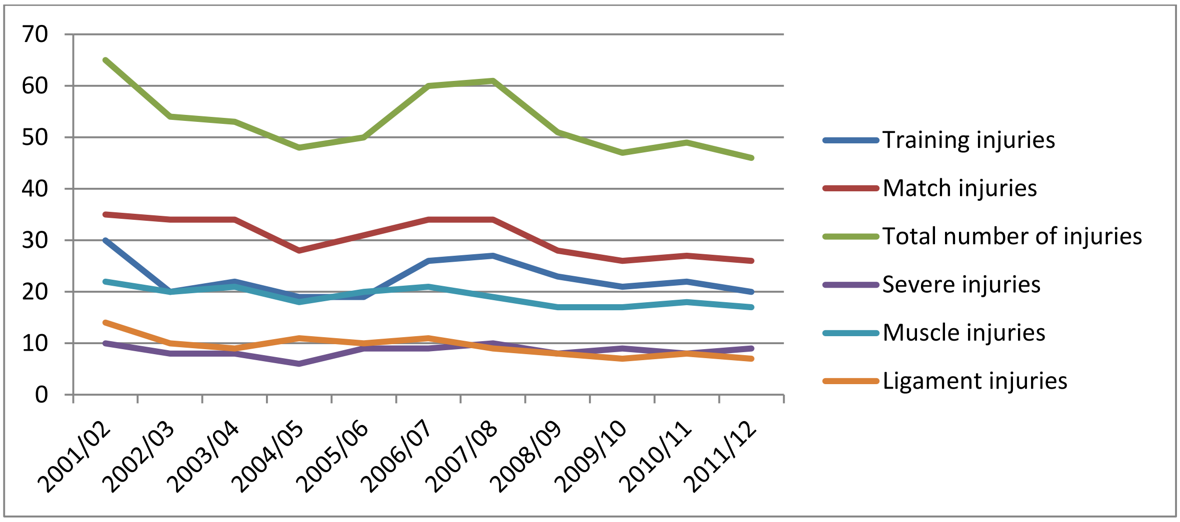
Football is played both professionally and recreationally with a wide variation of skill levels and ages. At the age of nine, players may be involved in football academies or local football events aimed at developing and identifying talented players. Associated with the high levels of participation is a high level of injury risk (Drawer and Fuller 2002). The risk of injury associated with participation in professional football as being "unacceptably" high, 1000 times higher when compared to other professions in manufacturing, construction and service (Drawer and Fuller (2002). Professionally, an injury sustained during participation in professional football may consequently result in abstention from training, matches or retirement from the sport. As many as 79 out of 185 surveyed English professional footballers (43% (95% CI 36% – 50%) reported being forced to retire from the game due to either acute or chronic injuries (Drawer and Fuller 2001). High rates of injury can negatively impact on the performance of an individual. Similarly an increased number of individuals sustaining injury within a team can negatively affect team performance within a competitive league (Haggland et al 2013). Poor performance of teams within a competitive league can result in relegation to lower leagues which do not have the same potential for revenue generation. There are therefore additional psychosocial effects associated with the performance of a football team which can affect job security for individual players, coaching, medical and backroom staff.

Due to the high levels of injury observed within football, several studies have attempted to identify risk factors or predictors of injury within football. The initial injury screening often occurs before the start of the official season in a period known as pre-season. The role of preseason screening is not clearly defined with in the literature with ambiguity around whether it is a process for predicting future injury, or a process for identifying existing injuries. Numerous types of injuries occur within football, ranging from traumatic head injuries to sudden cardiac death and soft tissue injuries (F-MARC 2009). The management of head injuries and screening of cardiac conditions is well documented and has become a mandatory screening process within professional football clubs. This is largely due to events within the media and standards set out by the FIFA Medical and Research Centre (F-MARC) (McCrory et al 2013).

Within the literature it is recognised that differences exist between genders for injury type and incidence. Proposed reasons for the between gender differences exist as a result of anatomical, biomechanical, hormonal and neuromuscular differences (Hewett et al 2005; Prodromos et al 2007; Walden et al 2011). Arguably risk factors within any gender are poorly understood; therefore making it hard to predict which players will sustain injury in either gender. Although female footballers are reportedly two to eight times more likely to sustain severe injuries, such as anterior cruciate ligament (ACL) injuries when compared to males (Prodromos et al 2007; Walden et al 2011), it would appear that current methods for reducing injuries have been successful (Gilchrist et al 2008). In comparison, the occurrence of severe injuries in males has remained unchanged over the last decade (Ekstrand et al 2013, figure 1.1). As trends for injuries within male football have remained unchanged, despite the implementation of screening tests and exercise interventions, there is therefore a need to investigate why current models are not working. Male footballers have therefore been selected for this review in order to minimise any confounding variables that would exist between genders.

Following the consensus statement by Fuller et al (2006) it is standard practice to report the incidence of injuries per 1000h of match or training exposure. Within male football, Ekstrand et al (2013) is the only study that attempted to longitudinally investigate injury patterns for 27 professional football teams, consisting of 1743 players, over an 11 year period in the UEFA Champions League injury study. A decreasing trend in the occurrence of ligamentous sprain injuries between the 2001/02 and 20011/12 seasons was reported, with a reduction of 14.6/1000h (±6) to 9/1000h (±6) respectively. Over the same period, the incidence of muscular strains (2001/02 = 22/1000h (±8), 2011/12 = 19/1000h (±8)) and severe injuries (2001/02 = 10/1000h (±4), 2011/12 = 9/1000h (±4)) has, however, remained similar (figure 1.1.) (Ekstrand et al 2013). It would therefore be possible to infer that existing methods aimed at reducing and identifying risk factors for these injuries have not been effective. The injury trends reported by Ekstrand et al (2013) are not a true longitudinal cohort as the data set had comprised of only four consistent teams throughout the 11 year study period. This results in less than 15% of the sample population being consistent. Additionally, whilst the four teams remained consistent throughout the study it is unlikely that the same players within those four teams would have been followed up over the 11 year period. Inference of injury trends from within this study should therefore be interpreted with this understanding. Despite Ekstrand et al (2013) reporting a decreasing trend in ankle injuries as statistically significant, the mean reduction in injuries from 14/1000h (±6) to 9/1000h (±6) is not clinically significant and should be interpreted in view of the sample. On review of the results by Ekstrand et al (2013) it can be argued that injury trends within male football have remained fairly consistent in terms of injury risk, type of injury and location of injury for all injuries reported (figure 1.1)

Figure 1.1 Team mean number of injuries according to type from the 2001/2002 to 2011/2012 season (produced with data from Ekstrand et al 2013)



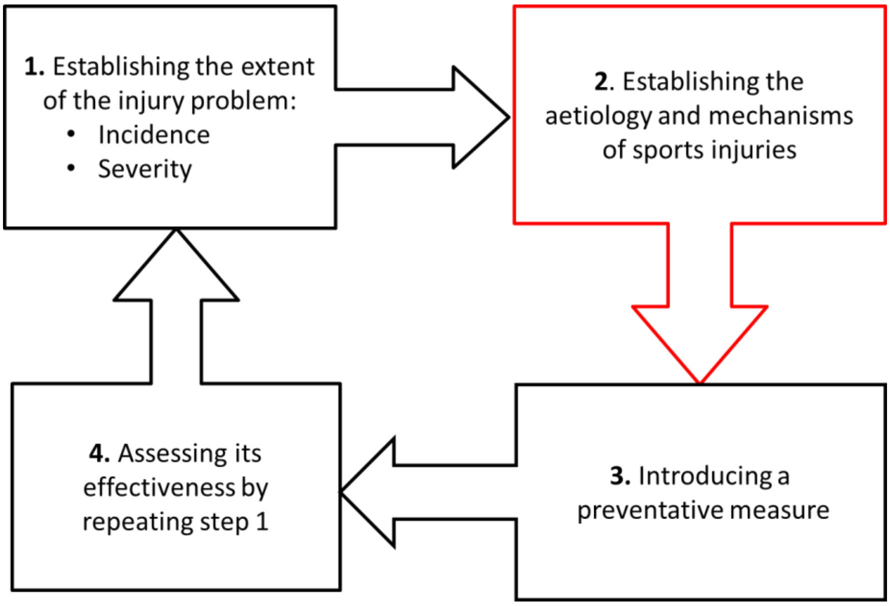
Each team's season data were adjusted to a squad size of 25 players and 11 months of activity

The incidence of injuries in training and match play has been well documented in European football (Ekstrand et al 2013) and injury rates seem to remain consistent both within and between studies (Ekstrand et al 2011, Hawkins et al 2001). Throughout a season, an average professional outfield player within the English or European leagues is expected to sustain at least 1-2 injuries resulting in them being unavailable for 1 competitive game (Hawkins et al 2001; Ekstrand et al 2013). Injury rate is almost seven times higher in matches when compared to training 26.7/1000h compared to 4.0/1000 (relative risk 6.7, 95% CI 6.4 - 7.0) (Ekstrand et al 2013). The incidence of injuries shows an increased tendency over time in the first and second halves of matches with less than 10% of injuries occurring in the first 15 minutes of each half and more than 20% of injuries occurring within the final 15 minutes of each half. This was observed for contusions, sprains and strains (Ekstrand et al 2011). A majority (87.2%, 95% CI 86.2% to 88.1%) of injuries sustained in football affect the lower limbs, with muscular strains, ligament sprains and contusions being the most common injury types (Ekstrand et al 2011). The thigh is the most common injury subtype site (16.5%, 95% CI 15.4% - 17.6%) with hamstring strains accounting for 11.7% (95% CI 10.7% - 12.6%) of the injuries and quadriceps 4.8% (95% CI 4.2% - 5.4%). Other common subtypes of injures included adductor strains (8.9%, 95% CI 8.0% - 9.7%), ankle sprains (7.0%, 95% CI 6.3% - 7.8%) and medial collateral ligament (MCL) strains (4.8%, 95% CI 4.2% - 5.4%). Trauma reportedly accounts for 81% and 59% of injuries sustained in matches and training respectively, whilst overuse injuries account for 28% of all injuries. Foul play by opposition teams during matches can account for up to 20.4% (95% CI 18.9% - 22.0%) of injuries sustained. More than half the injuries sustained during football are minor (< 7 days absence) although up to 16% can be severe injuries (>28 day absence) (Ekstrand et al 2011). Common subtypes of severe injuries were hamstring strains 12.0% (95% CI 9.5% - 14.3%), medial collateral ligament (MCL) injuries 9.0% (95% CI 6.9% - 11.2%), quadriceps strain 6.9% (95% CI 5.0% - 8.7%) and adductor strain 6.0% (95% CI 4.3 - 7.8%). Repeat injuries can account for between 12% to 30% of the total injuries and result in significantly longer absences than first time injuries, 24 versus 18 days respectively (Ekstrand et al 2011; Hagglund et al 2004). It is thought that soft tissue injuries are preventable by monitoring of training and match load, as well as the implementation of screening tools used to inform preventative exercise based strategies. Despite the existence of a standardised FIFA pre-competition medical assessment (PCMA) a wide variety of screening tests still exists within in football (F-MARC 2009). The ability of screening procedures to identify players at risk of future injury or with current injury has not been well established. Despite a lack of supporting evidence, McCall et al (2015) recognised that the use of screening tests is widespread with the three most common tests being the Functional Movement Screen, questionnaires on psychological evaluation and isokinetic muscle testing within professional football.

Prior to the implementation of a standardised framework for injury reporting by Fuller et al (2006), injury reporting within football was not systematic. This resulted in variations of injury incidence and severity between studies, mainly as a result of differences in the use of terms and definitions surrounding injury severity and classification of injuries. Despite a method of standardised reporting, methods of recording injury remain inadequate in capturing the complexity of variables leading to injury, and as a result existing models for injury prediction do not work. The categories for recording and classifying injury mechanisms are fairly broad and as a result may miss any detail that is relevant to injury causation. Additionally, factors and circumstances that are concurrently present at the time of injury may become falsely associated with injury causation. Current practice in injury documentation requires the practitioner to record information related to the injury mechanism in terms of a traumatic circumstance, which can be attributed to a single event, or an overuse circumstance, which cannot be attributed to a single event. The injury is then further classified as being caused by contact (with a player or ball in which the presence of foul play is questioned), or non-contact. Ekstrand and Gillquist (1983a) report contact injuries being caused by tackling or kicking and non-contact during running or cutting. Around this framework the consensus statement allows studies to investigate other proposed factors for injury, such as the training surface on which the injury occurred or time spent on the surface. Several important factors are neglected in this approach of injury recording such as preceding circumstances as well as body and limb positioning at the time of injury. Additionally, whilst Fuller et al (2006) have produced a standardised framework for injury recording and reporting, the way in which injury subcategories are clustered varies between studies. This results in a lack of coherence between studies for injury reporting which complicates the identification of injury risk factors for prospective modelling and makes interpretation of results between studies difficult.

Ekstrand and Gillquist (1983b) acknowledged that injuries are multi factorial. Given the complexity of factors associated with injury causation, it is hard to separate and specify which factors will lead to injury. Risk factors or mechanisms for injury may vary between anatomical location and structures, as well as the type of injury sustained. In order to identify risk factors or predictors of injury, a detailed understanding of the mechanisms is imperative. Van Mechelen et al (1992) developed a four step model for injury prevention in sports (figure 1.2). Step one requires identification of the extent of the problem. This is described in relation to the injury severity and type of injuries affecting the sport. In Step two, mechanisms and risk factors for injury must be identified. Following this, an intervention is introduced with the desired outcome of reducing injury occurrence in step three. Step four follows the same process as step one in order to evaluate if any changes in injury patterns have occurred. Step two, involving identification of mechanisms for injury, is arguably the most important and most poorly executed step of the model.

Figure 1.2 Four step model for injury prevention research (van Mechelen et al 1992)



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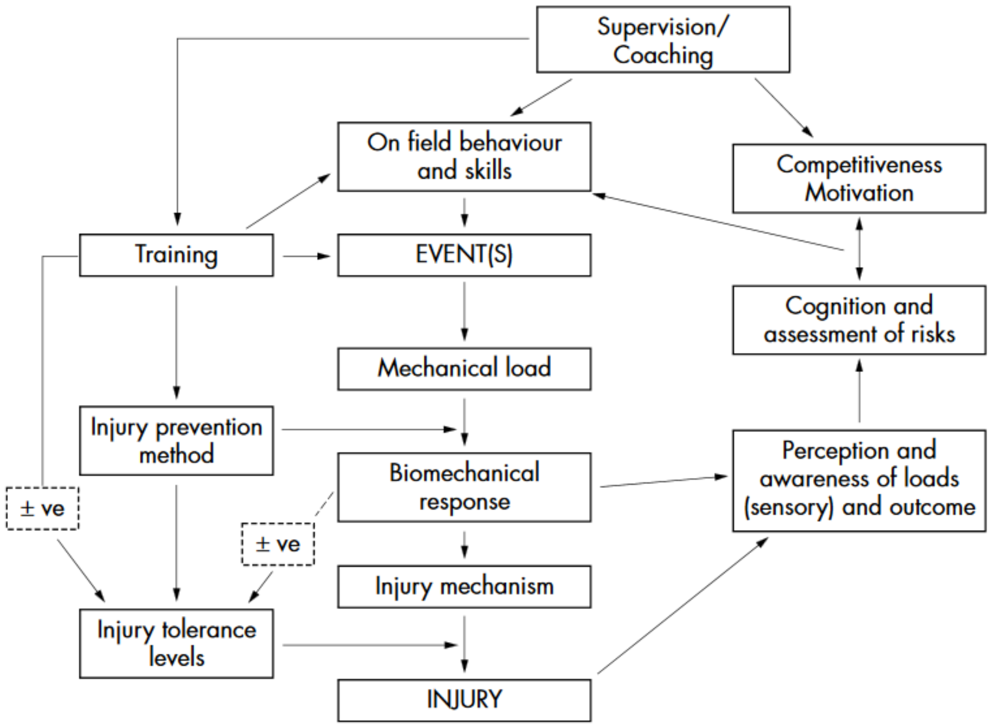
Some models not specific to football but related to injury in sport, have also been identified for describing proposed factors for injury. The models such as those by McIntosh (2005) (figure 1.3) and Bahr and Krosshaug (2005) (figure 1.4), show the interaction of varying proposed factors in injury occurrence.

Figure 1.3 Schematic of injury model (McIntosh 2005)



The ± symbol indicates that training or a biomechanical response during an event may increase or decrease the injury tolerance level.

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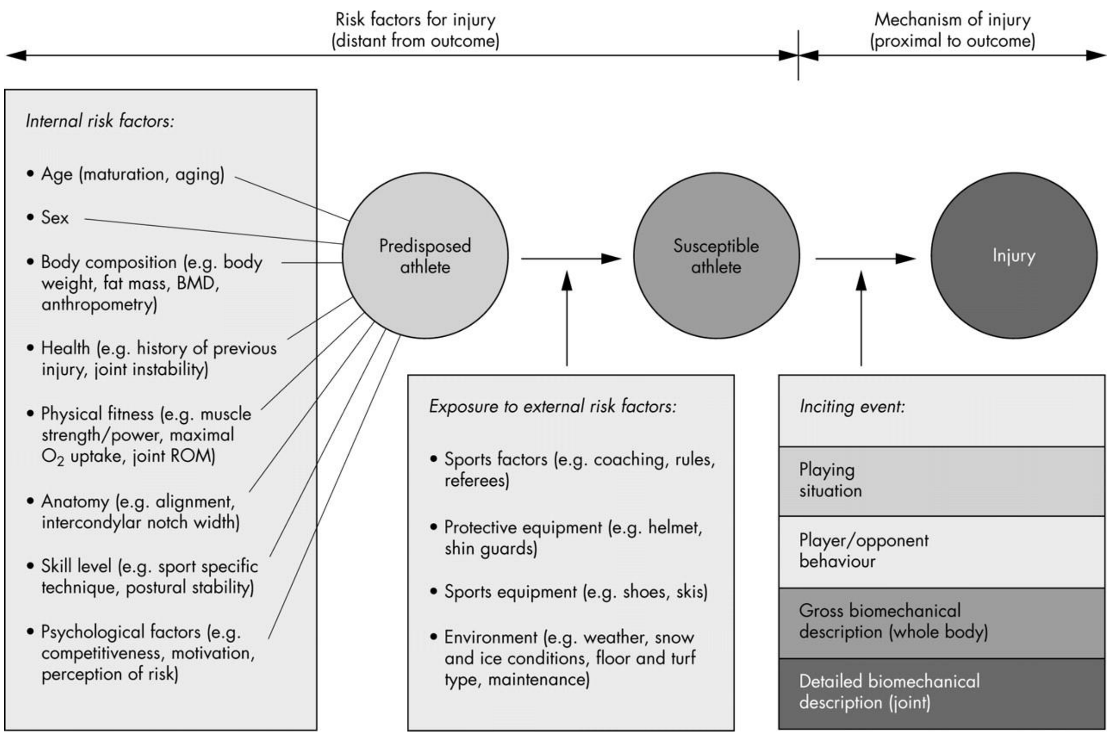
Figure 1.4 Comprehensive model for injury causation (Bahr and Krosshaug 2005)



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However, the individual risk factors identified within each model are postulated to be causative of injury and are yet to be consistently associated with injury occurrence. Methods of injury recording are insufficient in identifying accurate risk factors for injury causation. As a result of this several risk factors in injury causation and injury prediction have been omitted, whilst some factors have being erroneously associated with injury causation and prediction. A failure to accurately identify appropriate risk factors is evident as the occurrence of severe and muscular strain injuries has remained consistent over the last decade. There is therefore need for a search aimed at identifying and evaluating risk factors for injury within football.

1.1 Literature Search

A literature review was conducted within the databases AMED, CINHALPlus, MEDLINE, PSYCHinfo and SPORTDiscus. The literature review was aimed at identifying studies that investigated predicting, identifying or modelling risk factors for injury in male footballers. Search terms were created from headings and keywords within the relevant databases, namely; risk, predict, recurrence, prevent, model, functional movement screen (FMS), performance, injury, and sport. These can be seen within the relevant appendices for each database AMED (Appendix III), CINHALPlus (Appendix IV), MEDLINE (Appendix V), PSYCHinfo (Appendix VI), and SPORTDiscus (Appendix VII). The terms performance and functional movement screen were selected to investigate if injury was associated with measures of performance or screening tests of functional movement. Within each title, a search was conducted using "OR" with the associated headings and synonymous keywords. Between titles, a further search was conducted using "AND" as per the search strategy below.

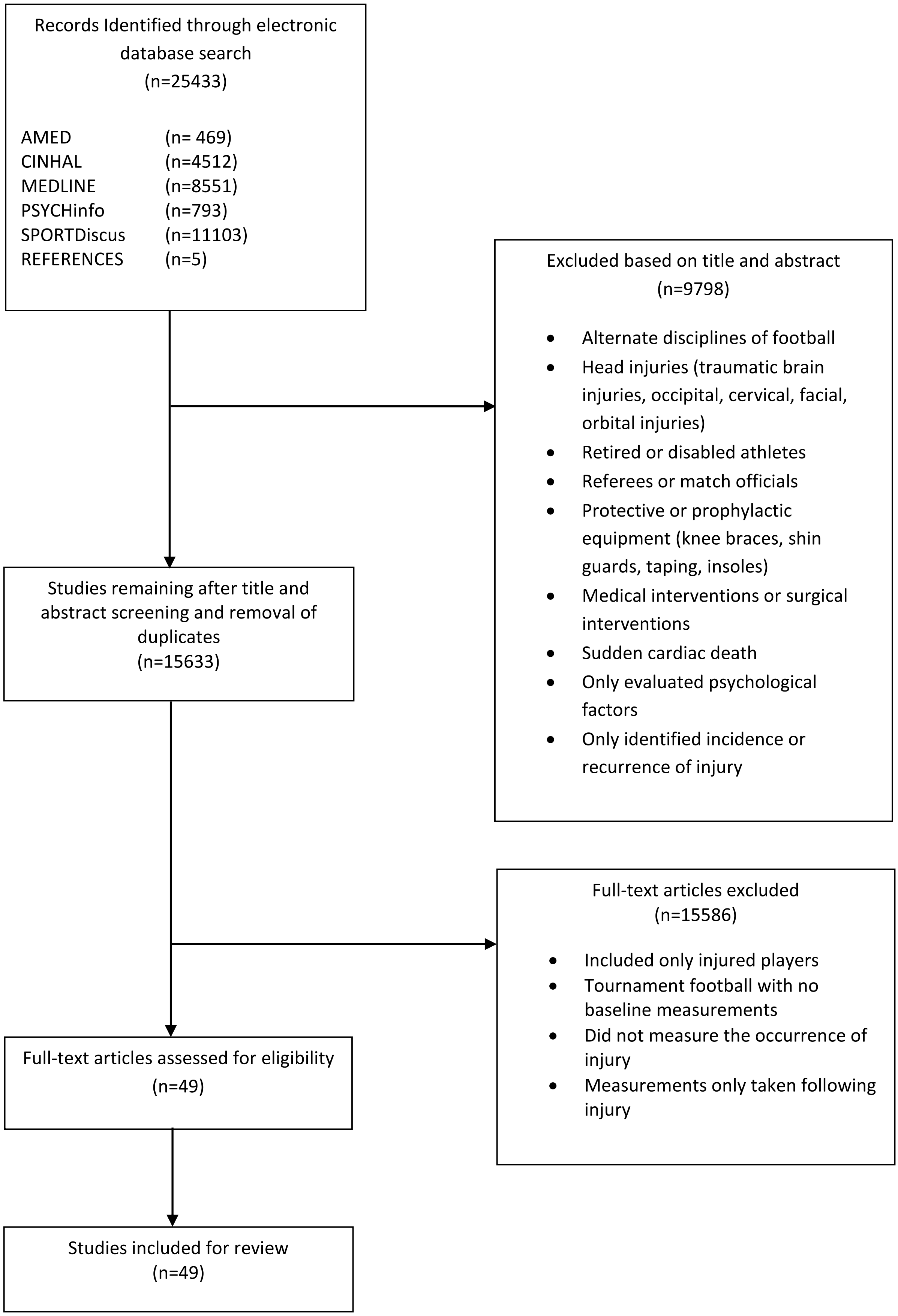
- (Risk OR Predict OR Recurrence OR Prevent OR Model OR Performance OR FMS) AND Injury AND Sport

Results of the initial search were imported into Reference manager v 12.0.3 where duplicates were removed and the remaining studies screened by title and abstract based on the inclusion and exclusion criteria listed below (table 1.1). An additional five papers were included following scanning of references of the included papers.

Table 1.1 Inclusion and exclusion criteria for search strategy

Inclusion criteria	Exclusion Criteria
Papers were included if they were: • Peer reviewed • Included male participants • Published in English or able to obtain suitable translation • Identified injury as an outcome measure • Included association football	Papers were excluded if they were: • Included multiple sports from which football could not be differentiated • Head injuries (traumatic brain injuries, occipital, cervical, facial, orbital injuries) • Retired or disabled athletes • Referees or match officials • Protective or prophylactic equipment (knee braces, shin guards, taping, insoles) • Medical interventions or surgical interventions • Sudden cardiac death • Only evaluated psychological factors • Only reported on incidence or recurrence of injury • Not published in English or unable to obtain suitable translation

Figure 1.5 Flow chart showing selection of studies



The process for screening has been shown in figure 1.5. The search strategy was implemented for each database without any limitations. This returned a large number of studies (25428). In accordance with the exclusion criteria, studies were screened according to their title and abstract. Following removal of duplicates a total of 9798 studies were excluded resulting in a remaining 15630 studies for full text screening. After full-text screening a further 15586 studies were excluded as they included only injured players, consisted of tournament football with no baseline measurements, no measurement of injury occurrence and only recorded measurements following injury. A remaining 49 studies were therefore included in the review.

Given that numerous factors have been proposed for injury causation, many screening tests have also been developed in an attempt to identify causative factors, despite paucity of accurate and detailed injury mechanisms within the literature. Anthropometric measurements as well as "Functional" tests of range of movement, balance, proprioception, jumping, isokinetic strength testing, asymmetries and tests of fitness have all been suggested as factors for injury. However, their efficacy in the prediction of injury has been poorly reported on. These factors for injury, which will be discussed in the section that follows, have been categorically divided into intrinsic and extrinsic risk factors and within the intrinsic category; factors can have been subdivided into modifiable and non modifiable risk factors for injury (table 1.2).

Table 1.2 Risk Factors for injury identified in literature search

Intrinsic Risk Factors		Extrinsic Risk Factors
Non-modifiable	**Modifiable**	
Age Biological Maturity Previous injury Height Posterior tibial slope Laxity (Hypermobility and Joint instability)	Range of movement Weight Body fat percentage Body mass Index Balance and Proprioception Fitness Muscular conditioning/ strength	Training exposure Training duration Training Intensity Fixture congestion Surface type

Whilst several risk factors have been identified for predicting injury in football, the supporting evidence is limited, with single studies evaluating a wide breadth of risk factors and same datasets being used for multiple studies with repetition of results (Anson et al 2004; Dvorak et al 2000; Ekstrand and Gillquist 1983a; Ekstrand and Gillquist 1983b; Ekstrand et al 2011; Ekstrand et al 2013; Kofotolis et al 2007; Venturelli et al 2011).

1.2 Intrinsic risk factors

1.2.1 Biological maturity

In order to identify and model causes for injury occurrence, it is necessary to establish at which point within a footballers' development the injury occurred. It may be assumed that prior to the uptake of football, at a young age, regardless of skill level; players will be free from injury. Presence of an injury would otherwise prohibit them from engaging in the sport. Footballers can therefore be assumed to start injury free but be predisposed or be exposed to factors that will result in injury. There is a trend for the incidence of injury to increase with age by approximately 4.0/1000h between the age groups of 14 to 16 years, 16 to 18 years and older than 18 years (adult) (Junge and Dvorak 2004; Peterson et al 2000). Some studies have reported higher injury rates in the 16 to 18 category compared to the adult category, although there seems to be agreement that at approximately 17 years of age, injury patterns then follow a similar incidence to that of adults (Junge and Dvorak 2004; Peterson et al 2000). As players progress through the relevant age groups, certain changes occur within the demands of the game. There is an increase in pitch sizes, match duration, ball size and players on the field. The increases in exposure and physical demands may contribute to the increase in injury incidence. Another proposed factor for increased injury risk between age groups is biological maturity. Given that football is played throughout a variety of ages, it has been identified that during puberty, boys may mature at different rates despite being the same chronological age. Knowing biological maturity may allow for the appropriate stratification of players to ensure the appropriate amount of exposure time in training and matches is provided. Although sufficient time is required for athletic development, time spent in training and matches may be limited to avoid overtraining which would be detrimental to athletic development.

Biological maturity can be assessed either radiographically to determine skeletal age, or clinically by evaluating secondary sex characteristics such as pubic hair development and testicular volume as in the Tanner staging method. In order to assess skeletal age, an x-ray of the left hand and wrist is required, from which, depending on the selected interpretation method, the radiograph is evaluated and the skeletal age derived. From the papers identified varying methods were used in the assessment of skeletal age. Johnson et al (2009) and Le Gall et al (2007) used radiographs. Skeletal age was then determined by the Fels method and the Greulich and Pyle method respectively. Within both studies footballers were then categorised as either early (skeletal age that is older than chronological age by more than one year), normal (skeletal age that is within one year of chronological age) or late maturers (skeletal age that is younger than chronological age by more than one year). Alternatively Backous et al (1988) assessed maturity by means of grip dynamometry. Physically mature footballers were defined as those who achieved grip strength of 25kgf or above (Tanner stages four to five) and physically immature footballers were defined as those whose grip strength was below 25kgf (approximately 245 newtons) (Tanner stages one to three). Population age, size, length of follow up and injury rates varied between studies (table 1.3).

Table 1.3 Study characteristics for biological maturity

Study	Population	Method	Length of follow up	Overall injury rate/1000h
Johnson et al (2009)	292 boys aged 9 to 16	Radiographs – Fels Method	6 years	2.23
Le Gall et al (2007)	233 boys Aged 14 and under	Radiographs - Greulich and Pyle method	10 years	5.6
Backous et al (1988)	681 boys aged 6 to 17	Grip Dynamometry correlated with Tanner staging method	5 weeks	7.3

Within all the aforementioned studies, biological maturity was not a significant risk factor in the overall injury rate between categories of maturity status. Johnson et al (2009) did not report on the injury type and location. Differences in injury trends and type have been identified between Backous et al (1988) and Le Gall et al (2007), although a true comparison is not possible. Backous et al (1988) observed injury in a summer soccer camp consisting of five one week sessions. Within these sessions there was mixed integration between boys and girls for football training and matches. It has already been identified that between gender differences exist for injury trends and types. This may therefore confound the injury incidence and trends for that sample. Additionally, the sampling frame and duration is not comparable with that of Le Gall et al (2007) who evaluated only male footballers under 14 years of age, over 10 consecutive seasons. The methods of classification for biological maturity used by Backous et al (1988) are also questionable given that justification for the stratification was carried out based on unpublished findings. Additionally, Backous et al (1988) have evaluated only a part of the Tanner-Whitehouse method and infer that upper limb strength is correlated to lower limb strength which is assumed as being an indicator for maturity. An increase in strength is associated with adolescent development in males; however the argument that strength thresholds are indicators for maturity by Backous et al (1988) relies too much on inference. It is hard to confirm the relationship between weaker grip and weaker lower limb strength resulting in injury without having evaluated the strength of the muscles involved. No reliable conclusions or comparison of injury incidence or trends can be extrapolated from the study by Backous et al (1988) given its methodological flaws.

As previously stated, whilst no difference for overall injury incidence was reported by Le Gall et al (2007) for early, normal and late maturers (approximately 5.7/1000h, 95% CI 4.6 - 6.5/1000h), some differences for injury severity, injury location, injury subtypes and repeat injuries were reported. Le Gall et al (2007) identified the incidence of major injuries (> 28 days absenteeism) was statistically significantly higher ($p=0.039$) in late maturers (0.9/1000h, 95% CI 0.5 – 1.4) than in early maturers (0.3/1000h, 95% (0.1 – 0.5). However, later in this study this same result is reported as non-significant, alongside inconsistent reporting of values. This result should therefore be interpreted with caution. A difference in injury incidence of 0.6/1000h between early and late maturers is not clinically significant, and in light of the contradicting presentation of their findings, this conclusion is questionable. It was however identified that early maturers had on average less days lost per injury (13.4 days) when compared to normal and late maturers (18.4 and 20.7 days respectively). Despite having fewer days lost to injury on average, early maturers were reported as having a statistically significantly higher repeat injury rate compared with other groups (early 0.35/1000h versus normal 0.12/1000h versus late 0.08/1000h, post hoc early versus all groups ($p<0.05$). Whist statistically significant differences for early maturers having increased incidences of repeat injury, thigh, groin and tendinopathy subtypes have been reported, the differences are less than 1 injury per 1000h between groups. This is arguably not a clinically meaningful difference, and so based on the results reported within this study, is not possible to identify clear injury trends for footballers based on the categories used for biological maturity.

Johnson et al (2009) evaluated other factors for injury alongside biological maturity. Johnson et al (2009) used a general log linear analysis in a Poisson model on mean data over six seasons to evaluate the effect of mean training time, mean match play time and mean difference in chronological maturity (chronological age minus skeletal age) on the effect of mean injury occurrence. All three were significantly associated with injury occurrence ($p<0.05$) (t ratio= 3.84 for mean training time, 2.03 for mean match play time and -2.65 for mean difference in chronological maturity). It can be argued that these factors are not a specific predictor of injury as increased exposure to training and matches will lead to increased risk of injury.

It may be concluded that biological maturity is not a predictor of the total incidence of injury. A possible cause for this may be due to the x-ray image interpretation methods and scales used to determine skeletal age. There is poor agreement between methods and skeletal age has been shown to be under and overestimated by up to two years depending on the selected method (Bull et al 1999; van Lenthe et al 1998). Johnson et al (2009) acknowledged that within their study the Fels method overestimated skeletal age. The categories used to determine biological maturity may provide insight into injury patterns within adolescent footballers, although the use of maturity status in the prediction of injury is arguably poor. This is partly attributable to the error associated with radiograph interpretation when determining skeletal age. No study explained the mechanism of injury and whether the biological maturity of the player was a factor within injury causation. Given that the biological maturity was determined during pre-season in the studies, the maturity status of a player may change throughout the season due to the process of puberty. It is therefore difficult to establish whether the maturity of the player at the time of injury was the same level of maturity that was determined in pre-season. Whilst the aforementioned studies demonstrate an association between biological maturity and injury, there is no evidence of causality.

1.2.2 Age

As stated, there is a trend for the incidence of injury to increase with age (Junge and Dvorak 2004; Peterson et al 2000). In the adult population, age has been associated with varying subtypes of injuries, although the papers that reported a relationship between age and injury were far fewer than those which did not (Arnason et al 2004, Hagglund et al 2006, Hagglund et al 2012, Gajhede-Knudsen et al 2013). Hagglund et al (2006) reported an increase in age was associated with increased risk of hamstring injury although did not report values for this. Arnason et al (2004) also reported an increase in the overall incidence of injury with age 23.4±0.3 (uninjured) versus 24.8±0.4 (injured) ($p=0.005$), as well as increased risk of hamstring injuries with age 23.8±0.2 (uninjured) versus 27.8±0.9 (injured) ($p<0.001$). Arnason et al (2004) identified that for every increase in age by one year, players had an odds ratio of 1.4 (95% CI 1.2 - 0.4) of developing a hamstring strain. It is noted that the reported 95% CI may be erroneous[1] and therefore interpretation of these results is difficult. Gajhede-Knudsen et al (2013) reported an increase risk of achilles tendon disorder, mainly tendonopathies, associated with increased age mean age 27.2±4 versus 25.6±6 years ($p<0.001$). Although reported as significant, the range in which achilles disorders occur is fairly broad and may be of little clinical use in identifying those at risk of injury. Hagglund et al (2012) identified age was a significant factor for injury in calf injuries although this was in addition to previous injury. Some muscular injuries were associated with age although previous injury was also significantly associated with an increase in injury. Age as an individual factor for injury may therefore be of limited value given that the reported differences in age associated with injury are small. From the studies identified the incidence of injury shows a positive correlation with age. Older players would be expected to have higher total of match and training exposure, given that they have been involved in football for longer. Therefore, previous injury, the amount of hours played or overall exposure may be a significant confounder in the occurrence of injury and a better predictor than age.

1.2.3 Previous injury

Despite causes of initial injury being poorly understood, within a single season, recurrent injuries can account for up to 30% of the total injury burden (Hagglund et al 2005). A proposed risk factor for injury is previous injury. The existence of a previous injury has been identified as a specific risk factor in relation to injury type and location. This has been identified in strains of the thigh, hamstring, groin and calf (Arnason et al 2004; Dvorak et al 2000; Engebretsen et al 2010b; Hagglund et al 2013, Venturelli et al 2011). The reported odds ratio for hamstring injuries as a result of previous hamstring injury is 11.6 (95% CI 3.5 - 39.0) (Arnason et al 2004). Previous injuries as causes for a recurrent injury has also been identified in sprains of the knee and ankle, odds ratios 4.56 (95% CI 1.6 - 13.4) and odds ratio 5.31 (95% CI 1.5 - 19.4) (Arnason et al 2004;Dvorak, Junge et al 2000; Ekstrand and Gillquist 1983b; Engebretsen et al 2010a; Kofotolis et al 2007).

[1] The reported odds ratio falls outside of the 95% CI ranges

Some papers collected data concerning previous injuries by questionnaires or from the past medical history of players obtained during the pre-season medical examination (Engebretsen at al 2010b; Frisch et al 2011). It has been identified that these methods are subject to recall bias as inconsistencies have been shown to exist even for injuries sustained in the previous season (Junge and Dvorak 2000). The role of previous injury for further injury may therefore be underestimated. As a consequence, this may allow for a false association of other proposed risk factors present at the time of injury. In order to limit the effect of recall bias on the effect of previous injury as an injury risk factor, Hagglund et al (2006) prospectively recorded injury occurrence within 197 footballers over two consecutive seasons. In the first season 151 participants sustained an injury out of 197 participants. In the second season 131 of the 151 previously injured participants sustained a further injury resulting in a hazard ratio of 2.7 (95% CI 1.7 – 4.3). The most common injuries sustained were hamstring, groin, knee and ankle injuries. Previous hamstring, groin, knee or ankle injuries were significant risk factors for sustaining a further injury within their relevant location subgroup. Previous injury was also significant for the occurrence of injury in locations not previously exposed to injury. It was also identified that the more injuries sustained by a player the greater the risk of injury. Similarly, Dvorak et al (2000) observed players who had more than six previous injuries were more at risk of sustaining further injury than those with fewer injuries (odds ratio 2.7, 95% CI 1.1 - 6.0).

It has also been identified that more significant injuries within football have been preceded by minor injuries or acute complaints. Ekstrand and Gillquist (1983b) also reported that out of 97 injuries, 13 moderate or major injuries occurred within two months of a minor injury. It is apparent that previous injury is a risk factor for further injury. Ekstrand and Gillquist (1983b) attributed the occurrence of major or moderate injuries to inappropriate rehabilitation, although the rehabilitation process for return to play was not evaluated. Gajhede-Knudsen et al (2013) identified that 27% of tendinopathies were recurrence injuries associated with a recovery period of less than 10 days following initial injury. Insufficient rehabilitation time may be explained by a poor understanding of risk factors in addition to the competitive league and external pressures associated with professional football. Players may have had shorter recovery time due to required participation in important games; as a result they may not achieve sufficient recovery or complete the full rehabilitation process. It may also be argued that recurrence of injury was due to inappropriate rehabilitation as proposed by Ekstrand and Gillquist (1983b). Given that initial mechanisms for injury are poorly understood, it appears the ability to predict the recurrence of a more significant injury from initially minor or acute injuries is also poorly understood, as no accurate markers or factors have been identified. Some studies have sought to investigate the mechanisms by which previous injury contributes to recurrent injuries and these will be discussed in the following sections.

It has been identified that previous injury is a risk factor for future injury and should be considered for prospective injury modelling. Previous injuries may be underreported and could be a confounder when considering other variables for injury prediction.

1.2.4 Laxity

Excessive movement within a joint is thought to contribute to initial and recurrent injuries; this has been proposed as a factor for knee and ankle sprains within football. Excessive movement is known as laxity, which can be congenital or arise from a traumatic event. Whilst the term laxity can be used to describe both of these, it has been identified that within the literature, increased laxity deriving from a traumatic episode is referred to as joint instability whilst congenital laxity is referred to as hypermobility. The following two sections will evaluate the role of laxity in injury causation. Laxity has been classified in keeping with the existing literature.

1.2.4.1 Joint instability

The stability of a joint is often assessed routinely in clinical practice through tests that place the stabilising ligaments under stress. Several tests exist to examine laxity of the knee and ankle joint structures. These tests are advocated by professional bodies and are included as part of the FIFA medicine manual for injury, under the section of prevention (F-MARC 2009). For the knee, tests which evaluate instability caused by disruption to major ligaments such as the anterior cruciate ligament (ACL) have a reported sensitivity as low as 66% (Makhmalbaf et al 2016). The stiffness and elastic properties of other soft tissues around the joint can also affect the test. The sensitivity of the tests have been shown to increase from 66% to 91% when patients are placed under anaesthetic and are therefore unable to respond to pain or contract the soft tissues. For some of these tests the joint instability or laxity is graded according to the level of displacement measured, with a clinically significant difference being considered more than two millimetres between limbs in clinical practice (Malcom 1985). When considering that these tests require the handling of patient's limbs by the clinician and application of a force to test the integrity of the ligaments, it is likely that the tissues will undergo a deformation of more than two millimetres. Whilst arthrometers are reportedly able to measure the amount of displacement, soft tissue deformation will still occur and the error of measurement is likely to be larger than the levels of displacement that they are trying to measure. It has been identified that the accuracy and reliability of these devices is inferior for intrarater and interater reliability when compared to clinical tests such as the Lachmans test (Weirtsema et al 2008).

Given the reported sensitivity of these tests and their susceptibility to error, the use of such tests in quantifying instability and for prediction of injury is limited. Additionally, previous injury should be considered as a confounding variable when evaluating joint instability for prospective injury modelling, given that the occurrence of instability stems from a traumatic event. The findings of the reported literature are presented below and studies which advocate joint instability for injury prediction should be interpreted in light of the identified shortcomings of the methods used.

The existence of laxity within studies identified was recorded as either being present or absent. Ekstrand and Gillquist (1983b) identified 26 footballers with knee instability from previous injury. The types of instability identified were antero-medial rotary instability (n=21), anterolateral rotator instability (n=3) and straight posterior instability (n=2). Antero-medial rotary instability, anterolateral rotator instability and straight posterior instability were determined by external rotation of the tibia, pivot shift test and posterior draw sign respectively. All three players with antero-lateral rotary instability sustained knee injuries, and 18 moderate or major traumatic knee injuries occurred in players who had a previous knee sprain with instability. Arnason et al (2004) used similar clinical tests to evaluate the presence of joint instability. In the knee, the Lachmans, valgus stress, varus stress and posterior draw tests were conducted. In the ankle the anterior draw test and talar tilt tests were used. Although joint stability was not a factor for injury within their analysis it was identified that medial instability of the knee was higher in those with previous knee sprains ($p<0.05$) and lateral instability was higher in those with previous ankle sprains ($p<0.05$). Similarly, Engebretsen et al (2010b) assessed 817 participants' ankles with the anterior draw test. The ankle joint was classified as normal or pathological depending on the clinical assessment of joint instability. In 817 players, 427 players had pathological findings and within the pathological group 20 were injured. In the normal group of 390 players, 16 players sustained an ankle injury (odds ratio 3.0, 95% CI 1.5 – 5.8). Joint stability was not identified significant factor for injury in the ankle.

Fousekis et al (2011) used an arthrometer (KT-1000) to measure knee laxity as a factor for non-contact hamstring and quadriceps strains in 100 professional footballers. In addition to laxity, measures of isokinetic strength testing, range of motion, anthropometrics and proprioception were recorded. Knee laxity was not found to be a significant factor for non-contact hamstring or quadriceps injuries. This may be expected as increased laxity has been proposed as a factor for knee and ankle sprains as opposed to muscular strains and these were not reported. Additionally, given the previous argument regarding error of measurement associated with this device, it cannot be considered a reliable measurement.

The presence of joint instability following injury as identified by Arnason et al (2004) and Ekstrand and Gillquist (1983b) may provide insight into possible changes that occur post injury. However, it can be concluded that existing methods for assessing and quantifying joint instability are not suitable for prospective injury modelling, given the previously identified limitations and existence of confounding factors such as previous injury.

1.2.4.2 Hypermobility

Hypermobile joints are considered to be joints with a range of motion (ROM) that is excessive, taking into consideration the age, gender and ethnic background of an individual (Grahame 2003). Collinge and Simmonds (2009) and Konopinski et al (2012) investigated hypermobility as a factor for injury in 35 and 54 professional male footballers respectively. Frisch et al (2011) investigated hypermobility in 60 youth footballers. For all studies, hypermobility was determined using the Beighton scale. In the Beighton scale, a point is given for each side in which the participant achieves the movement criteria. The movements conducted and associated criteria are passive extension of the fifth metacarpophalangeal joint greater than ninety degrees, passive apposition of the thumb onto the anterior aspect of the forearm, passive hyper extension of the knees and elbows greater than ten degrees and actively placing hands flat on the floor without knee flexion. Hypermobility was determined by scoring a minimum of four out of nine on the Beighton scale.

Players were assessed during pre-season with subsequent injuries being monitored and recorded throughout one competitive season. Significance of inury rates varied between studies. Collinge and Simmonds (2009) observed no statistical significance (χ^2 p=0.22) in injury rates between the hypermobile (6.2 injuries /1000h) and non hypermobile (6.3 injuries/1000h) groups, similar to Frisch et al (2011). However, in a sample of 54 footballers, Konopinski et al (2012) reported injury rates with a statistically significant mean difference 15.65/1000h (95% CI 9.18-22.13) ($p<0.05$) between the hypermobile (21.79/ 1000h ± 12.50) and non hypermobile (6.32/1000h ±6.06) groups. The relative risk of a hypermobile participant sustaining at least one injury was 1.31 (95% CI 1.04 -1.64) with an odds ratio 6.55 (95% CI 0.76-55.83) (Konopinski et al 2012). Injury between studies and groups was predominantly located in the lower limbs, with a majority of injuries occurring at the knee joint in both groups.

Frisch et al (2011) did not report on injury severity, injury type or location subtype between hypermobile and non hypermobile participants. Konopinski et al (2012) reported a difference in training days missed between the hypermobile (68.28±49.9 days) and non hypermobile (11.33±15.76) groups respectively ($p<0.05$). Additionally a statistically significant mean difference in match days missed 11.3 (95% CI 5.96 - 16.53) between the hypermobile (14.0±10.1 days) non hypermobile (2.75±5.44 days) group ($p<0.05$) was identified. Although Collinge and Simmonds (2009) failed to show statistical significance (χ^2 p=0.21) in games missed from injury between groups, on average the hypermobile group missed 12 games compared to 5 in the non hypermobile group. A trend towards increased days missed of training followig inury was also identified in the hypermobile group. Within all the studies identified training exposure between groups did not differ significantly.

From the studies evaluated, an injury occurring within a hypermobile footballer, as classified by the Beighton scale, is more likely to result in a longer absence from training and games. Konopinski et al (2012) also attributed hypermobility as a factor for repeat injury with relative risk of 0.55 (95% CI 0.34-0.87), odds ratio of 11 (95% CI 2.45-49.31). As stated previously the role of laxity, hypermobility or instability in the modelling of injury is inconsistently supported by the literature. In addition, the use of clinical tests for identifying joints with laxity or instability vary in sensitivity and are prone to error. No threshold at which excessive laxity or instability causes injury has been identified. The role of instability or laxity as identified by clinical tests and arthrometers is not adequate in prospective injury modelling.

1.2.5 Range of movement, muscle length and muscle flexibility

Excessive range of movement (ROM) caused by joint instability, increased laxity or hypermobility has been identified as a possible factor for injury. Collinearity between ROM and laxity may therefore be a problem in prospective injury modelling. Measurements of ROM for players with previous injury or for players undergoing growth may be affected by additional confounders. A reduction in ROM is also thought to contribute to injury, as limitations arising from the joint do not allow for the required movement or appropriate distribution of force. As a result of this, injury is postulated to occur as the joint or other surrounding structures are unable to cope with the load they undergo. Some of the papers identified reportedly measured muscle length, muscle tightness and flexibility (Arnason et al 2004; Ekstrand and Gillquist 1983b; Rolls and George 2004; Witvrouw et al 2003). However, on further reading it is evident that magnitude of ROM was measured as opposed to the aforementioned categories of muscle length, muscle tightness and flexibility. The interaction of the articulating surfaces and soft tissues that cross the joint such as muscles, tendons, fascia and nervous tissues can influence the ROM available at a joint. Magnitude of ROM is measured in degrees and from the studies identified, the most commonly used methods for measuring ROM were goniometers and two dimensional (2D) image based analysis systems.

When measuring ROM with goniometers the centre of the joint is estimated by anatomical landmarks. The distal and proximal arms of the device are also aligned with other anatomical landmarks depending on the joint being measured. Although several studies shared similarities in the use of goniometers to measure ROM, there was variation in the reporting of methodology and protocols of goniometer placement (Ekstrand and Gillquist 1983b; Engebretsen et al 2010b; Fousekis et al 2011; Ibrahim et al 2007; Rolls and George 2004; Venturelli et al 2011; Witvrouw et al 2003). Variaiton in placement of the arms for goniometery will affect the results observed. For example, when comparing methods of measurement for hip ROM with goniometery between by Witvrouw et al (2003) and Rolls and George (2004). Witvrouw et al (2003) placed the stationary arm parallel to the table with the moving arm aligned to the lateral epicondyle of the femur, where as and Rolls and George (2004) placed the stationary arm along the mid axillary line and the moving arm along the shaft of the femur. Whilst arguably the differences may be small, none of the aforementioned papers reported the error of measurement associated with use of the goniometer. Within the literature, the reported error of measurement for use with a goniometer ranges from approximately five to 15 degrees (Boone et al 1978, Gajdosik and Bohannon 1987). Therefore when interpreting the results of these papers, the effect of the error of measurement must be taken into consideration as, for example, Ibrahim et al (2007) reported a mean difference of three degrees as statistically significant difference between injured and uninjured players. This value is smaller than what would be expected for the error of measurement and is not a clinically significant difference. The results of the studies evaluating ROM as measured by goniometry for Ekstrand and Gillquist (1983b), Ibrahim et al (2007) and Witvrouw et al (2003) will therefore be excluded given that despite reporting statistically significant differences for decreased ROM between injured and uninjured groups, the observed differences were less than the error of measurement. Additionally these studies were subject to similar flaws as per the studies discussed below.

Rolls and George (2004) found no statistically significant difference between injured and uninjured players in all of the five tests they performed for measuring ROM of the lower limbs ($p>0.01$). The largest mean difference between groups was 11 degrees for the sitting active knee extension test (knee ROM). There was also no statistical significant difference in injured and non injured legs of the same players, with the largest mean difference being four degrees for the passive knee extension test (passive knee ROM). Similarily, Venturelli et al (2011) also reported no relationship between the sit and reach test and muscular strain injuries. Neither tests reported a relationship between the occurence of muscular injuries and the tests used. A reason for this may be the erroneous assumption that any limitation to ROM is resultant form insufficent muscular length. The validity of the tests to acurately measure muscluar length is questionable as the test are not specific to one group of muscles or soft tissue structures. As identified by Rolls and George (2004) the sit and reach test is not specific to the hamstring muscles or the hip joint, as factors such as upper limb length, scapula abduction, shoulder protraction or movement within the spine may influence results. Rolls and George (2004) made significant effort to reduce the involvement of compensatory movements in order to reduce confounding factors. The end point of ROM of movement for these tests was determined by either a subjective report of tightness from the participant or the tester feeling resistance. Therefore, factors such as variability in the therapist application of force, limb mass, soft tissue compliance and active interference may affect the perceived end point for ROM. These factors may account for some of the variability observed within and between subjects. Therefore interpretation of results which demonstrate small differences must be done so with caution. The remaining studies shared similar methodological processes and reported no relationship between lower limb muscular injuries and decreased ROM (Engebretsen et al 2010b; Fousekis et al 2011)

Some studies were identified as using 2D image based analysis, as validated by Selfe (1998), for measuring ROM at the hip and knee (Bradley and Portas 2007, Henderson et al 2010). For both studies no error of measurement was identified. Both studies considered a difference of three degrees between either the dominant and non dominant legs of players (Henderson et al 2010), or hip flexor ROM between uninjured and injuried players (Bradley and Portas 2007) to be statistically significant. ROM was measured clinically and as stated previously, this method is subject to variability stemming from variability in the therapist application of force, limb mass, soft tissue compliance and active interference. Such small differences are within the error of measurement and therefore cannot be considered for use in determining whether ROM is a risk factor for injury prediction.

Only the study by Arnason et al (2004) used goniometers, 2D image analysis as well as a the application of a consistent load when measuring passive ROM in the passive knee extension, knee flexion and hip abduction tests. They identified no relationship between ROM and hamstring strains or knee and ankle sprains. Only reduced ROM in the adductor group was identified as a significant risk factor for injury, although this was in addition to previous injury, which is known to be a confounding variable in prospective injury modelling. Given that an appropriatte sample of 306 male footballers was assessed over a 4 month competitive season, the results of this study can therefore be considered for informing decisions around the use of ROM in prospective injury modelling.

Based on the existing literature, the role of preaseason ROM in prospective injury modelling is not clear and may be of limited value. It has also been identified that the methods used to measure ROM may not be sufficiently accurate in identifying thresholds at which a reduction in ROM is causative in injury. ROM cannot therefore be advocated for use in prospective injury modelling based on the existing literature.

1.2.6 Anthropometric measures

Within a majority of the studies evaluated, anthropometric measurements of height, weight, body mass index and body fat percentage have not been identified as risk factors for injury (Arnason et al 2004; Frisch et al 2011; Fousekis et al 2011; Gajhede-Knudsen et al 2013). Only three studies identified anthropometric measurements as risk factors for injury with no consistent physical attribute being associated with injury. Salokun (1994) looked at the occurrence of injury over eight weeks within varying somatotypes. One hundred and eighty male footballers from six different teams, "*highly rated clubs*", were investigated and stratified into the categories of ectomorph, meso-ectomorph, ecto-mesomorph and mesomorph. Measurements of height, weight, bi epicondylar diameters of the humerus and femur, calf, flexed biceps and waistline girths were recorded according to a standardized protocol. In addition skinfold thickness from the triceps, subscapular, suprailiac and calf were taken. Injury information was collected by means of a questionnaire completed by the players. The statistical significance of injury and somatotype was not reported on and no data was available for further review of the results. Therefore the conclusions of this paper should be interpreted with caution. Soluken (1994) report that 85% of the ectomorph group sustained injuries compared to the other groups where no more than 50% sustained an injury. A trend in increased injury prevelance was identified as player somatotype became smaller, with mesomorphs having the lowest occurrence of sprain, strains, bruises and dislocations, whilst ectomorphs had the highest prevelance. The short follow up period of eight weeks may not allow for a representative injury pattern that may be expected throughout the season. Additionally, Soluken (1994) attributed increased strength with increasing somatotype size despite not testing strength; this is a poor argument as there may be additional factors important to injury causation apart from size. Soluken (1994) suggest that players who are smaller than their associated team mates or opposition may be more likely to sustain injury.

Similar observations were reported by Henderson et al (2009) who used a logistic regression model for identification of risk factors for hamstring injury in 36 professional footballers (mean age 22.6±5.2 years). Players with a lower lean mass were reported as reported having an increased propensity for injury with an odds ratio of 0.8 (95% CI 0.7 - 1.0). It was however identified that within the model that lean mass did not make a uniquely significant contribution, and that age was the only predictor independently related to injury risk. Therefore lean mass cannot be considered an independent predictor of injury risk. Additionally Henderson et al (2009) did not find an association between previous injury and hamstring injuries, although as reported on earlier, previous injury has shown to be evident in the occurrence of further injury. Their findings are not consistent with the reported literature and conclusions regarding risk factors for injury should be interpreted with discretion.

Whilst Soluken (1994) and Henderson et al (2009) identified increased injury risk for players of a smaller stature (body type and lean mass respectively), Venturelli et al (2011) identified elite players of a taller stature, aged between 13 to 18, (height range 163 to 191cm) were more likely to sustain a partial thigh tear injury (hazard ratio 1.2 ±0.07, 95% CI 1.1-1.3). Within this study, it was recognised by the authors that a limitation of their study was the number of injury cases used in the modelling process (27). Additionally the injury subgroup used (thigh strains), was comprised of further injury subgroup locations, each of which has been proposed to have separate risk factors for injury (quadriceps (n =6), adductors (n=7) and hamstrings (n=14). It is not possible to therefore decisively conclude that increased height is a risk factor for partial thigh strains.

No consistent anthropometric traits were identified for use in prospective injury modelling. Whilst some studies identified anthropometric characteristics of ectomorph body type, lean mass and increased height to be considered risk factors for injuries, these must be interpreted within the injury subgroups they were modelled on and within the context of other confounding variables. The conclusions of the aforementioned studies identifying differing anthropometric measures as risk factors for injury are also not consistently supported by other studies (Arnason et al 2004; Frisch et al 2011; Fousekis et al 2011; Gajhede-Knudsen et al 2013). Based on the existing literature, the role of anthropometric characteristics in injury occurrence is therefore not clear and its role in prospective injury modelling may be of limited value.

1.2.7 Strength

Muscular strength has been proposed as a factor for injury within football. Within the literature, isokinetic testing, mainly in the quadriceps and hamstring muscle groups is the most commonly used assessment tool. The use of isokinetic strength testing in injury prediction is limited. This is due to the possible confounding factors associated with the isokinetic method of testing, its questionable validity for application and absence outside of the clinical environment. This may explain the inability of results obtained in isokinetic testing for injury prediction in football. Isokinetic testing may be useful in identifying pathological patterns of force production within the concentric and eccentric phases of muscle contraction. However, this may be achieved without the use of an isokinetic testing apparatus. In any sport or daily functional tasks, people and muscles do not to work isokinetically and so this brings into question the validity and practicality of such testing. In addition the speed at which the limb moves during testing is predetermined by the isokinetic machine. The velocity of the testing limb is therefore limited and controlled during a maximal effort by the participant. It is unknown what effect this has on the behaviour of the individual, their testing limb and the associated musculature.

Frisch et al (2011) and Henderson et al (2009) did not report muscle strength as assessed by isokinetic testing as a risk factor for injury. Fousekis et al (2011) tested 14 isokinetic variables in 100 professional footballers, with only 11% (95% CI 4.8 - 17.1) of the participants showing normal isokinetic muscle strength profiles (with asymmetries less than 15% between limbs). In the isokinetic testing, at least one muscle strength asymmetry was detected in 68% (95% CI 58.9 -77.1) of the players for concentric measures and 73% (95% CI 64.2 - 81.7) of the players for eccentric measures. Eccentric muscle strength asymmetry was reported as a factor for injury (odds ratio 3.8, 95% CI 1.13 -13.23). Interestingly the presence of previous hamstring in this study was identified as a significant factor in reducing hamstring injury risk (odds ratio 0.15, 95% CI 0.03 - 0.79). The results suggest that an eccentric strength asymmetry as opposed the overall strength of the muscle is a risk factor for injury. Given the high percentage of asymmetries present on isokinetic testing and presence of previous injuries, it is unclear whether the asymmetries are a consequence of previous injury or a marker for future injury. The presence of asymmetry between limbs is normal given that they are used for different purposes within the game. This is evident in football as within the literature it is common practice to record the preferred kicking leg. Thus the existence of asymmetry in a sport such as football may be a reflection of motor control contributing to performance as opposed to injury.

Engebretsen et al (2010b) tested isometric strength of the adductor muscles with hand held dynamometry in 508 players in 31 amateur teams over one season. In supine, participants were required to perform two maximal contractions with the dynamometer placed five centimetres proximal to the medial malleolus of the ankle. Measurements of strength were categorised as strong or weak within the study with no numerical measure of performance. Within this study it is therefore hard to provide a threshold at which weakness in the adductors is causative of injury. Within this study previous injury, presence of pain at external rotation of the hip, reduced range of motion in external rotation, total scores of "soreness" and "pain" on questionnaires, pain of functional testing of the illiopsoas muscle and weakness of the illiopsoas muscle with clinical tests were associated with injuries. The weakness observed in tests of strength of the illiopsoas and adductor muscles may be attributed to previous injury or the presence of pain, which was identified as being present with the use of questionnaires and clinical tests and so no quantifiable measures of performance were available.

No threshold of muscular weakness determined, isometrically, isokinetically or clinically was identified as a risk factor for injury. Despite muscular weakness being associated with injury by Engebretsen et al (2010b) and Fousekis et al (2011), the concurrent existence of previous injury and pain again raises the issue of whether the weakness is a consequence of pain and previous injury, or if weakness identified by testing is causative of injury. The role of muscular strength as measured by the aforementioned methods is not clear and may therefore have a limited role in prospective injury modelling.

1.2.8 Clinical screening tests

It is apparent within the literature numerous varied individual tests and combinations of tests exist to try and identify injury risk factors that may be associated with intrinsic factors. Given the numerous proposed risk factors for injury, some screening tests have been established that reportedly incorporate numerous markers for injury in a single or series of tests.

1.2.8.1 The Functional Movement Screen (FMS)

On review of the risk factors, screening tests and preventative measures used in 44 professional football teams, it was identified that the FMS was the most commonly used screening test, despite a lack of quality research to support its validity (McCall et al 2015). The FMS is a screening tool, introduced in 1998 with the original purpose of rating and ranking movement patterns in high school athletes (Functional Movement Systems and Gray Cook 2012). Application of the FMS has since been established within multiple sporting and occupational disciplines, with the reported measurement capabilities of the FMS being that it is a:

a) Scale for rating and ranking movement patterns
b) Method for assessing muscle strength, range of motion, asymmetry, balance and kinaesthetic awareness
c) Indicator of injury risk through identification of a final composite score

(Cook et al 2006a, Cook et al 2006b, Cook et al 2010, Functional Movement Systems and Gray Cook 2012, Kiesel et al 2007)

Fundamentally, the FMS is a series of seven exercise tests (Deep Squat, Hurdle Step, Inline Lunge, Shoulder Mobility, Active Straight-Leg Raise, Trunk Stability Push-Up and Rotary Stability tests) which evaluates an individual's ability to perform a series of movements against set criteria. Based on performance, participants are awarded a score in which a three is the highest score corresponding to a high quality of movement; a lower score indicates poorer quality of movement, and a score of zero is give in the presence of pain. (Full descriptions of the FMS tests and scoring criteria have been provided in Chapter 5). Some of the exercise tests are informed by additional clearing tests performed after the exercise tests (shoulder, spinal flexion and spinal extension). These tests evaluate the absence or presence of pain during a specified movement and are scored nominally i.e. pain or no pain. However if pain is identified on the clearing test a score of zero is given for the associated exercise test (Functional Movement Systems and Gray Cook 2012).

For this review, the study by Kiesel et al (2007) has been included given that it was the seminal paper on which, justification for use of the FMS and identified thresholds for injury screening was established. The ability of the FMS to predict a severe time loss injury (>3 weeks) in 46 professional American football players (National Football League) over a four and a half month period was investigated. A score of 14 was identified as the threshold for identifying players at risk of injury. Those who scored below a 14 were more likely to sustain a severe injury (odds ratio 11.67, 95% CI 2.47-54.52) with a sensitivity of 0.54 (95% CI 0.34-0.96) and specificity of 0.92 (95% CI 0.83-0.96). Through the use of the FMS, it is suggested that "*dysfunctional fundamental movement patterns*" as indicated by low scores on the FMS, are predictive of non-contact injury. There is therefore a hierarchy to the performance metrics, as according to this rationale, people who achieve higher scores will have less dysfunctional movement patterns and a reduced risk of injury. Within this study training volume, exposure and previous injury were not reported on and may contribute to injury causation.

For association football (soccer), three papers were identified as having evaluated the ability of a FMS composite score (threshold of 14) in injury prediction (Zalai et al 2014, Rusling et al 2015, Schroeder et al 2016). No association between the final FMS score and injury was identified in any studies for amateur (Schroeder et al 2016) or professional footballers (Zalai et al 2014, Rusling et al 2015). From the aforementioned studies, the subtests of Deep Squat, Hurdle step and Trunk stability were reported as being statistically significantly correlated with injury sub locations of the lower limbs. Whilst some subtests of the FMS have been correlated to injury, it is not clear which components of the subtest are related to injury, given the varied criteria associated with each scoring category of the same subtest. Before the total score and sub scores of the FMS can be considered for prospective injury modelling in football, a better understanding of the FMS measurement scales performance is required. Whilst the FMS final composite score has not been identified as a predictor of injury in association football, differences between the results of Kiesel et al (2007) and Zalai et al (2014), Rusling et al (2015) and Schroeder et al (2016), are likely to stem from the different injury subgroups on which the predictive ability of the score was based. Kiesel et al (2007) evaluated the use of the FMS for the injury subgroup of non-contact severe injuries; where as the other studies evaluated the use of the FMS on a mix of injury subgroup types and severity's. Whilst it is recognised that the sporting disciplines are different, arguably within the context of non-contact injuries, the demands between disciplines are similar in that both require an ability to perform intermittent efforts of running. The FMS may therefore play a role in helping to identify severe non-contact injuries.

Valid clinical measurements are necessary for monitoring changes in performance related to injury risk, informing injury prevention programs and evaluating the efficacy of current treatment approaches in rehabilitation (Pandyan et al 1999). It is therefore imperative to have appropriate knowledge of a measurement scales performance characteristics and limitations, as these play a part in data interpretation and analyses (Pandyan et al 1999). For example, based on the FMS score, an assessor using the scale may change a characteristic of the participant's movement. This is achieved through introduction of an exercise or through coaching of a movement pattern; both with the desired outcome of scoring higher on the FMS (Functional Movement Systems and Gray Cook 2012). The FMS therefore assumes that the movement patterns associated with the higher scoring criteria have an inverse relationship to injury risk.

Several studies have sought to investigate the validity and sensitivity of the FMS through an evaluation of the final composite score which acts as a threshold for predicting the occurrence of injury (Zalai et al 2014, Bakken et al 2016). A score of 14 has been identified as the most commonly used threshold, although selection of alternate thresholds for determining injury risk (final score 17) has been identified in other sporting disciplines and physical occupations (Wiese et al 2014, Letafatkar et al 2014, Shojaedin et al 2014, Knapik et al 2015, Kodesh et al 2015, Moran et al 2017). With this method, the *validity* of the FMS as a predictive measure is therefore dependent on the threshold selected and definitions of injury. *Validity* within this context relates to the ability of a scale or system to accurately measure what it claims to measure or is expected to measure (Payton 1994). Use of the final score as a metric for assessing the validity of the FMS does not address the performance characteristics of the measurement scale which informs it, or the reported capabilities of the FMS. This is because the final score is determined by the subscores, which are in turn determined by rules that are individual to each subtest and rules common to all subtests. Additionally this approach does not fully address other components related to the *validity* of the FMS, such as its' "level of measurement" and the performance properties. The validity of the FMS an assessment tool is therefore dependant on its performance as a measurement scale, as this is the fundamental principle on which the FMS has been based.

Based on this review it has been identified that existing studies interpret the FMS scoring criteria as either an ordinal or ratio level scale (Wiese et al 2014, Letafatkar et al 2014, Shojaedin et al 2014, Knapik et al 2015, Kodesh et al 2015, Moran et al 2017). However this has not been proven and the FMS has not been systematically studied. Whilst the validity of the FMS as a predictive indicator has been demonstrated within American football, the evidence is poor. Additionally, within association football there is no evidence to support its use and despite this, it still remains the most commonly used screening test in professional football (McCall et al 2015). A further understanding of the FMS framework and measurement scale, alongside additional risk factors for injury, may help in providing reliable markers for injury prediction in football. However, based on the existing literature, it is apparent that use of the FMS final score or subtest scores for prospective injury modelling is not fully understood.

1.2.8.2 Jump testing

Other screening tests were identified and have been discussed in the sections below (Frisch et al 2011; Venturelli et al 2011). As mentioned previously, these studies conducted and evaluated numerous measures and screening tests in order to identify causes of injury. Within the studies that applied several methods of screening, no consistent markers or factors for injury were identified. The use of numerous tests that ultimately provide no insight into injury causation highlights a poor understanding of injury risk factors. Although pre-season screening tests cover a large array of proposed risk factors for injury, there is still a lack of understanding and adequate evidence to confirm the proposed risk factors for injury as well as the mechanisms of injury.

Jump tests have been proposed as a method for identifying injury. In all jump tests reported the actual jump height was not recorded, but rather flight time. Jump height is a product of flight time and may be influenced by several confounding variables which will be elaborated on later. The most commonly used jumps were countermovement jump and the squat jump also referred to as the non-counter movement jump. From standing the countermovement jump requires participants to start with their hands on their hips and squat down until their knees are flexed to 90 degrees, at which point a maximal jump is carried out. The squat jump follows the same procedure although a pause is required once knee flexion at an angle of 90 degrees is achieved. Jump tests were either conducted on an electronic pressure mat or Optojump device which uses photocells. A formula is used to predict jump height with the use of flight time.

The squat jump, countermovement jump and one legged countermovement jump performed on a contact mat were not significant factors for injury as identified by Arnason et al (2004). Similarly, Frisch et al (2011) found no significant association of the best recorded squat jump and countermovement jump with injury on a force plate. Some studies identified a significant association with jump tests and injury although no one jump test was consistently associated with injury. Engebretsen et al 2010b) found an association between the best recorded countermovement jump and the risk of groin injury in a univariate analysis. Hederson et al (2009) conducted the squat jump and countermovement jump on an electric pressure mat and identified that the non countermovement jump/squat jump was associated with hamstring injury in the kicking leg of footballers (odds ratio 1.47, 95% CI 1.02 - 2.12). The jump tests used within this study were conducted bilaterally and so it is questionable whether the results obtained are applicable in determining injury in a unilateral lower limb. In addition, despite being reported as significant the recorded non counter movement jump heights were 42 (±4) cm and 39 (±4) cm for the injured preferred kicking legs and non injured preferred kicking leg groups respectively. Clinically this is a small difference in heights between groups and is arguably not significant. Venturelli et al (2011) used the photocell Optojump system and conducted the squat jump and countermovement jump. In addition the change in jump height was also used as a factor for injury based on their selected formula[2]. In the univariate analysis the change in jump height and squat jump were associated as factors for thigh strain injury (hazard ratio 0.8±0.04, 95% CI 0.7-0.9 and hazard ratio 1.1±0.1, 95% CI 1.0-1.3 respectively). However in the multivariate analysis only a low change in jump height was a significant factor for a partial thigh strain injury (hazard ratio 0.8±0.04, 95% CI 0.7 -0.9). For the studies by Henderson et al (2009) and Venturelli et al (2011) it has been identified that relative to the number of predictors used the sample used for modelling was small (10 hamstring strains and 27 thigh strains respectively). The limitations of the small sample have been discussed previously and the conclusions of these studies must therefore be interpreted with discretion.

[2] (CMJ-SJ)x SJ-1x100 (10^{18})
Where: CMJ = Countermovement jump, SJ = Squat jump

Given that a majority of the tests used flight time as a predictor of jump height, variables such as knee flexion angle may affect the predicted jump height. The tests and subsequent analysis also assume that limb symmetry at landing is equal, although this has been disputed (Edwards et al 2012). Furthermore it is unclear if the desired 90 degree knee flexion angle was achieved consistently when completing the relevant jumps. The tests may be a valid tool used in the assessment of jump height; however the tests are more arguably a measure of performance as opposed to a predictor of injury. No one type of jump has consistently been associated with injury and the reliability of the tests themselves may affect the results produced. Furthermore no study was identified explaining the mechanism of jump height performance and the occurrence of injury. Based on the existing literature it is not possible to advocate the use of jump tests for prospective injury modelling.

1.2.8.3 Balance and proprioception

Several studies measured sway by evaluating variability in the centre of pressure (Tropp et al 1984; Fousekis et al 2010; Frisch et al 2011). However within the studies identified, measures of sway were reported as measures of proprioception (Tropp et al 1984; Fousekis et al 2010), static balance (Frisch et al 2011) and dynamic balance[3] (Frisch et al 2011). Fousekis et al (2010) reportedly measured neuromuscular control and proprioception by getting participants to cover five traces of a circular route with a cursor controlled by lower limb movement.

The only study to report an association between stabilometric recordings and injury was Tropp et al (1984), in which the odds ratio for players with a "pathological stabilometric value" compared to those without was 5.5 (95% CI 2.1 - 14.7). Tropp et al (1984) defined a "pathological" stabilometric value as an area exceeding the reference group area by two standard deviations or more (Sahlstrand et al 1978). The reference group for this study comprised of 30 medical students with no previous injury. Given that the classification for "pathological" or "non pathological" is dependant on the reference group, the one used in this study is not

[3] "Dynamic balance" determined from the three dimensional reaction forces recorded over the first second of landing on a single leg. Wilkstron et al (2005)

a true representation of a football population. Participants may have therefore been classified as pathological due to the reference group used as opposed to the true presence of pathology. Increased sway cannot be considered a determinant of pathology given that sway is a natural behaviour within humans and people with increased sway may have greater control. It has also been identified that the sensitivity of this method for detecting injury is 52.2% and therefore cannot be considered appropriate for use in injury prediction. Characteristics of sway measured by stabilometry and excursion of centre of pressure are sensitive to variations in sampling duration and frequency (van der Kooij et al 2011). Interpretation of results in order to draw clinically meaningful conclusions between studies utilising differing sampling durations and frequencies is therefore difficult. The excursion of centre of pressure is therefore a poor measure and of limited value in injury prediction given its susceptibility to variation. As a result of these methodological shortcomings, the results of the studies by Tropp et al (1984) and Frisch et al (2011) will be disregarded.

Proprioception is a sense informed by numerous cutaneous receptors located in the skin as well as mechanoreceptors located in within muscles and tendons. These receptors are integral in providing information to the brain about kinaesthetic awareness which includes movements of the limbs, muscles, joint positions and pressure (Carpenter 1990). Proprioception informs kinaesthetic awareness, and given proprioception is an input to the brain it cannot be measured directly. Fousekis et al (2010) reported measuring neuromuscular control and proprioception, although arguably they looked at tasks aimed at challenging kinaesthetic awareness. The test required participants to cover five traces of a circular route with a cursor controlled by lower limb movement. It is debatable if the performance within the selected test is indicative of the required performance needed to prevent injury, and if the test is a valid measure of proprioception and neuromuscular control (Fousekis et al 2010). This may also be true of the tests conducted by Engebretsen et al (2009), in which a clinical scale ranging from five to one was used to assess balance. A score of five indicated the player was able to balance on one leg for 60 seconds with eyes opened and an additional 5 seconds with eyes closed with "*compensatory movement*" only allowed to occur at the ankle throughout the test. A lower score was given according to time thresholds, amount of additional upper body involvement "*further compensation*" and amount of time the opposite lower limb was used to touch the floor. A score of one was indicative of a player not being able to maintain single leg balance for more than a "*short length of time*". The scoring categories are not reliable enough to accurately identify deficits in balance and proprioception as they rely on clinical observation. The criteria which inform the scoring process are also ambiguous, with no quantification of thresholds e.g. "*short length of time*". They are therefore subject to interpretation which would result in misclassification. Furthermore it is questionable if the perturbations or "*compensations*" used to assess balance and proprioception are the appropriate markers for injury. The methods used by Engebretsen et al (2009) and Fousekis et al (2010) are not valid methods for assessing balance and proprioception and should therefore be disregarded.

Based on the literature, the existing methods identified as measures of balance and proprioception cannot be advocated for prospective injury modelling. Deficits in balance and proprioception may be predictors of injury; however existing methods for measurement of these variables is not valid and cannot therefore be used for injury prediction.

1.2.9 Posterior tibial slope

Only one study identified posterior tibial slope as a marker for ACL injuries (Senisik et al 2011). Posterior tibial slope was measured with a goniometer on lateral knee radiographs in 64 male healthy footballers and 45 sedentary controls aged between 20 to 30 years. The angle was determined between the tibial mid diaphysis line and the line between the anterior and posterior edges of the medial tibial plateau. Tibial slope angles for both dominant and non-dominant legs between soccer players and sedentary controls were similar (approximately 9 (±2) degrees). Players with a posterior tibial slope greater than 9.58 degrees in their kicking leg had an odds ratio of 5.6 (95% CI 1.2 - 27.2) for sustaining an ACL injury compared to soccer players with posterior tibial slope less than 9.58 degrees. No justification for the selected threshold is provided and additionally the confidence intervals for this result are wide. The conclusion regarding tibial slope of greater than 9.57 for ACL should therefore be interpreted with caution.

As a standalone risk factor, increased posterior slope may assist in highlighting players who are more at risk of sustaining a non-contact ACL injury. However, as this is arguably a non modifiable risk factor, no preventative strategy has been proposed. The role of posterior slope in prospective ACL injury modelling is not clear and before it can be considered for use in prospective injury modelling, further evidence is required to support this relationship and selected threshold value used.

1.3 Extrinsic risk factors for injury

The investigation of risk factors for injury to be used in prospective injury modelling requires evaluating a range of inter-related factors. There is a complex interaction between the range of external and internal risk factors proposed for injury risk. When considering external risk factors for injury alone, a complex interaction of proposed risk factors still remains. For example, if surface type has been proposed as a risk factor for injury, the total exposure time or rate at which training intensity increases may both independently affect injury rate. The existence of collinear or confounding variables may therefore be a problem when evaluating these variables for prospective injury modelling or identifying their role in injury causation. Whilst a single external risk factor for injury may be identified, it needs to be considered within the context of other factors that may influence overall injury or injury subtypes. Furthermore, the numerous combinations in which injuries can be clustered makes evaluation of these factors and interpretation of results between studies difficult.

1.3.1 Surface type

The interaction between the player and the playing surface is a proposed risk factor for injury. Ekstrand and Nigg (1989) reported that 24% of injuries could be associated with unsatisfactory playing surfaces. Between grass surfaces or natural turf, variations exist in the evenness of surfaces, grass type, ground hardness, grass surface compaction and drainage (Williams et al 2011). Some of these conditions are susceptible to change throughout the season due to the playing volume conducted on the pitch and changing climatic conditions. Adverse weather conditions may prohibit training and match play on natural turf. As a result of this; there has been an increase in the introduction and development of synthetic turf or artificial turf as an alternative to grass in football, given its robustness in varying weather conditions and lower maintenance costs (Williams et al 2011). There are currently four generations of artificial turf, although the most readily available is third generation surfaces which are becoming replaced by the fourth generation surfaces. As each generation of turf has succeeded the other, fibres have become thicker and longer, with a composite sand and rubber filling being introduced to more closely imitate a natural grass surface. Whilst for sports such as American football, the introduction of first and second generation artificial turf saw an increase in the incidence of injury, reportedly associated with the increased hardness, stiffness and frictional properties of the playing surfaces; this was not the case for soccer (Ekstrand and Nigg 1989, Williams et al 2011). Despite this, the development of third and fourth generation surfaces was aimed at reducing the incidence on injury for all sports, although its success in achieving this is still debated.

From the studies identified, there is no significant increased risk of overall injury incidence between artificial turf (third and fourth generation) and natural turf (grass), with the injury incidence ranging from approximately 2 to 20 injuries/1000h for both grass and artificial turf (Aoki et al 2010; Bjorneboe et al 2010; Ekstrand et al 2006; Ekstrand at al 2010; Fuller et al 2007;Kristenson et al 2013). Some studies evaluated the effect of surface type on injury subcategories of severity, location and type. Additionally, these were done with respect to training and matches. Whilst some studies have reported statistically significant differences between artificial turf and natural grass for injury subtypes, the reported differences are arguably not clinically significant. For example, Ekstrand et al (2006) reported higher incidences of lower limb muscle strain injuries during training for grass compared to artificial turf (6.2 compared to 3.8/1000h, rate ratio 0.6, 95% CI 0.4 -1.0). This was the biggest difference for injury incidence in this study, approximately 2.4/1000h. Similar differences or smaller were observed for studies by Ekstrand et al (2010), Fuller et al (2007) and Kristenson et al (2013). Whilst all the aforementioned results have been reported as statistically significant, the differences between injury incidences for surface types are small and arguably not clinically significant. Additionally there are no consistent trends for injury subcategories according to surface type. Almutawa et al (2014) and Bjorneboe et al (2011) found no significant difference in injury type, severity or location between surfaces.

The effect of surface type on injury incidence, location, type and severity shows variability within the literature. It may be concluded that there is no increased risk of sustaining an acute traumatic injury between third and fourth generation artificial turf, and natural turf. As stated earlier, surface type alone may not account for all differences in injury incidences and subtypes. Several other factors may influence the occurrence of injury on either artificial turf or natural grass. Climatic conditions, surface hardness and footwear/boot cleat design have all been proposed as additional factors in the occurrence of injury. No papers were identified that evaluated the effect of the aforementioned variables as a causative factor for injury within football.

It was also identified that some papers excluded overuse injuries in the analysis, as by definition they have no identifiable cause and so it would be difficult to attribute their causation to a specific turf type (Bjorneboe et al 2010; Ekstrand et al 2006; Kristenson et al 2013). The exclusion of overuse injuries in the analysis will result in a lesser injury rate and additionally omits information that is relevant to mechanisms preceding injury. Ekstrand et al (2006) reported 41% of injuries sustained were overuse but excluded these from the analysis. Exclusion of overuse injuries also highlights a poor understanding of injury mechanisms within overuse injuries, as studies only record the surface on which the injury occurred and attribute that to being causative. When overuse injuries were included in the analysis differences in injury type were observed (Aoki et al 2010; Kristenson et al 2013). Aoki et al (2010) reported a higher incidence of chronic lower back pain complaints resulting in injury for artificial turf (1.08/1000h, 95% CI 0.78 - 1.47) compared to grass (0.67/1000 ,95% CI 0.5 - 0.9), (incidence rate ratio 1.62, 95% CI 1.0 - 2.5). Total training hours was not a risk factor in this injury subtype although longer training sessions on artificial turf was identified as a risk factor. Kristenson et al (2013) identified that clubs with artificial turf at their home venue had significantly more muscle and tendon injuries attributable to overuse (rate ratio 1.5, 99%CI 1.21 - 1.89). The small differences in injury incidence for injury subtypes between surfaces are similar to those of previously identified studies (Ekstrand et al 2006; Ekstrand et al 2010; Fuller et al 2007 and Kristenson et al 2013). Therefore conclusions regarding the role of surface type in injury occurrence should be interpreted with discretion. The training load and the interchanging of surfaces may play a role in injury causation within football (Aoki et al 2010; Kristenson et al 2013). As stated by Aoki et al (2010) the duration of the individual training session as opposed to the total playing hours may be causative in overuse injuries, although Kristenson et al (2013) did not report on individual sessions. Clubs with access to artificial turf may be more inclined to train for longer as adverse weather events and pitch condition would not affect the training.

As previously stated, the existing framework allows for multiple variations in which injury subcategories can be clustered. This makes interpretation of results and comparison between studies difficult. The level at which subclassification becomes meaningful it also unknown. This means we are unable to make recommendations for the level of subclassification that should be used in order to maintain or further develop meaningful results. Furthermore, the nomenclature and framework associated with injury recording may not allow for the capture of relevant details that are important in the modelling of injury.

The overall incidence of injuries between surfaces does not seem significant and whilst some trends for differences in injury type and location have been identified, there is no agreement within the literature (Aoki et al 2010; Bjorneboe et al 2010; Ekstrand et al 2006; Ekstrand at al 2010; Fuller et al 2007;Kristenson et al 2013). The role of surface type alone in prospective injury modelling is unclear and may be confounded by training load and exposure.

1.3.2 Training load and exposure

A contextual definition for the term *load* is needed prior to describing the acute to chronic workload ratio. Load can be used to describe any quantifiable metric that is believed to be relevant to injury or performance, for example, total distance run, time spent in training, high speed running time (>19 km/h) or rate of perceived exertion. The acute to chronic workload can therefore be applied to any of these metrics. The acute to chronic workload ratio is an index calculated by dividing the most recent week's load (acute workload) by the average load of the previous four weeks workload (chronic workload) (Hulin et al 2014). The ratio is reported to evaluate the training load the athlete has performed relative to the training load the athlete has prepared for; this is done as a weekly rolling average (Hulin et al 2016). Within football, a ratio of greater than 1.75 for total distance has been associated with an increased injury risk (RR 4.98 95% CI 1.31 - 19.02) (Bowen et al 2016). The significant increase or 'spike' in training load is therefore regarded as a risk factor for injury (Hulin et al 2014). A ratio between 1.00–1.25 has been identified as a range in which the occurrence of injury is less likely within football (Malone et al 2017). This is similar to the 0.8 to 1.3 ratio range, reported by other sporting disciplines (Hulin et al 2014, Hulin et al 2016, Moller et al 2017). It is worth noting that the ratio within these studies has been applied to multiple aspects of load such as measures of distance, speed, activity time and rate of perceived exertion.

From the trends observed in injury patterns thus far, increased participation in football increases the risk of sustaining an injury. Other factors influencing injury may be the duration of training sessions, intensity of training, fixture congestions and time between events. The overall training structure and demand from competitive matches may influence injury occurrence. Football requires a level of fitness as well as technical and skilled ability. Training is aimed at developing the physical aspects of the player as well as the tactical and technical ability of the team and individual players. Ekstrand et al (1983c) reported a correlation between team success and training hours. Training load should be such that a physiological overload is reached to achieve physiological benefits that aid performance. If the load is excessive it may be detrimental to performance and may result in injury. Ekstrand et al (1983c) reported a non-linear relationship between injuries and training hours. Within this study only, no data was available to compare between groups. The average training hours was approximately 1400 hours and teams with less than average training (<1400/hr) showed an increasing number of injuries with increased training, whilst teams with more than average (>1400/hrs) showed a decrease in injures with increased training ($p<0.05$). Teams with more than average training had significantly fewer traumatic injuries per training hour than compared with teams who had less than average training hours ($p<0.05$). The occurrence of overuse injuries was equal between the two groups. It therefore seems there is an optimum level of training which is beneficial to performance and injury rate. Inadequate training may increase risk of injury due to insufficient fitness when competing against participants of similar or higher performance levels. As well as the physical demands of football there is also a level of technical ability and skill that is required. A footballer may be able to increase their fitness, speed and strength although ultimately if there is not an ability to perform during matches, this may affect their technical performance and may influence injury. Peterson et al (2000) compared teams of similar ages but varying competitive league levels, the level of competition was associated with skill level of the players. Between skill levels, lower level youth players (aged 14-16 years) had less exposure but a higher incidence of injuries per 1000h, per player compared to higher lever youth players (11.4/1000h compared to 6.0/1000h). Lower level youth players sustained twice as many injuries per 1000h whilst lower level adults sustained up to four times as many injuries per 1000h when compared to those in higher levels (20.2/1000h compared to 5.6/1000h). There was a trend for lower level players to sustain more severe injuries and most of the injuries were sustained in games. It may be argued that players within a higher league may have access to better facilities and coaching resulting in better conditioned players which would affect injury occurrence. Even though coaching techniques may aid the development of player skills and tactical awareness, assisting in the reduction of injury, a player may not have the required adaptability or rate of skill acquisition that is required to continue participating with their peers, thus limiting their performance. Given that lower level players also had less exposure, it may be argued that they has insufficient training which Ekstrand et al (1983c) attributed to injury.

Players who do not achieve sufficient training may not develop the required level of fitness. This in turn may not allow the player to maintain a level of performance that is required to reduce to occurrence of injury. Common practice is to assess player fitness during the pre-season periods and at selected times throughout the season. This can be done through varying forms of maximal and sub maximal exercise tests. Eriksson et al (1986) investigated the effect of player fitness injury occurrence. The test used for fitness was assessed on an electrically braked bike with incrementing stages of 50W (305kpm/min) until a heart rate (HR) of more than 150 beats per minute was reached. Heart rate was monitored by an electrocardiogram and the maximal oxygen uptake was estimated according to Astrand and Rhyming (1954). Participants were then ranked and stratified post hoc according to their estimated Vo2 max i.e. group one (5.6 – 4.4 l/min), group two (4.4 – 3.8 l/min), group three (3.8 – 2.7 l/min). Estimated Vo2 max had no significant effect on overall injury incidence although participants in group 3 sustained significantly less overuse injuries compared with those in group one and two combined (12 overuse injuries for groups one and two combined compared with one overuse injury in group three). It was postulated that fitter players sustained more overuse injuries due to an ability to achieve a higher work rate by covering more distance at higher speed and intensity. Frisch et al (2011) assessed Vo2 max by a shuttle run test although this was not significant in identifying those at risk of injury (hazard ratio 1.03, 95% CI 0.96 - 1.1). Similarly, Arnason et al (2004) assessed peak oxygen uptake and carbon dioxide production in a treadmill test. The speed was increased by 0.5 meters per second every minute until 4 meters per second was achieved, at which point the treadmill incline was increased by 1.5 degree every minute until volitional exhaustion. Heart rate was monitored by a pulse meter and the meters were calibrated by the Scholander technique (Scholander 1947). Within this study peak oxygen uptake was not an indicator for injury (>1 SD below the mean, odds ratio 1.1 (95% CI 0.5 - 2.1), >1 SD above the mean, odds ratio 0.7 (95% CI 0.3 - 1.4). Venturelli et al (2011) evaluated player fitness through a shuttle run test known as the Yo-Yo intermittent recovery test. The Yo-Yo test is a shuttle run test comprised of two x 20 meter runs and a 10 meter recovery period. Audio signals control the speed of the test and as the test progresses; the speed of the shuttle runs increases. There are two variations of the test, the intermittent recovery 1 (IR1) and intermittent recovery 2 (IR2). The IR2 progresses at a quicker speed than the IR1 and the IR2 test anaerobic capacity (Bangsbo et al 2008). The simplicity and reproducibility of the test has led to it being a commonly used fitness tests in football as it is effective in testing several players simultaneously and it is argued that the test is specific to sports that involve intermittent episodes of high intensity running (Krustrup et al 2003; Bangsbo et al 2008). Venturelli et al (2011) identified the score achieved on the Yo-Yo IR2 as a risk factor for injury the univariate analysis (hazard ratio 0.7±0.09, 95% CI 0.5 - 0.9), with higher Yo-Yo scores being associated with a lower risk of injury, although in the multivariate analysis for partial thigh tears this was not significant.

Within the literature the use of fitness tests for injury prediction is not clear and inconsistently supported. Arguably the tests were designed to evaluate player fitness and are therefore useful in identifying players who have not achieved the required level of conditioning. Players who have not achieved the required levels of fitness may be at risk of sustaining injury if the requirements of the game or training exceed their functional capacity. However, in isolation the tests may be unable to differentiate between a player with reduced performance due to overtraining or a player who is not reaching the required level of fitness. The relationship between training load, exposure and fitness may result in the existence of collinearity between variables, or result in some variables being considered as confounders in prospective injury modelling. It is evident within the literature, that these factors are interrelated and there are multiple methods used for measuring training load, exposure and fitness. Despite this, no one method or metric has been consistently associated with injury prediction and the role of these variables in predicting injury remains unclear.

1.3.3 Subjective scales of fatigue and injury

Fatigue may occur as a result of inadequate training that is manifested in match play or as a consequence of overtraining which may affect a player in either training or match play. Monitoring of exposure seems to have been well conducted within the papers identified, although as stated there are several other components and variations apart from duration associated within training and matches. Monitoring of players is therefore important to identify those who are at risk of sustaining injuries. Frisch et al (2011) identified physical fatigue, which was assessed by a questionnaire with a yes or no response, as a significant factor in time loss injuries of more than 3 days (hazard ratio 2.0, 95% CI 1.0 - 3.8). Similarly, Brink (2010) reported physical stress as being a component in acute injuries for elite youth soccer players. Physical stress was comprised of by two factors, an objective measure of match and training duration, and a subjective measure of the players rate of perceived exhaustion (RPE) according to the Borg 15 point scale (Foster 1998). The training load within this study was achieved by multiplying the duration of the session by the session RPE. The weekly load was the sum of all the sessions over one week. All four components of physical stress (duration, load, monotony and strain) were higher for players who sustained a traumatic injury in the preceding week. The largest odds ratio observed was for monotony 2.6 (95% CI 1.2 - 5.5) and the smallest odds ratio was for strain 1.01 (95% CI 1.00 - 1.01). All variables are reported as statistically significant however an odds ratio of 1.01 with (95% CI 1.00 - 1.01) is arguably not significant and their conclusions should be interpreted with caution. No significant difference was found in overuse injuries. Dvorak et al (2000) used a scale to measure exhaustion (1 = exhausted to 5 = recovered) and levels of aching or stiffness (1 =never to 5 = recovered). Compared to uninjured players, severely injured players felt more exhausted (mean 3.6 (±0.8) compared to 3.9 ± (0.8)) and reported more aching or stiff muscles before a game (mean 2.2 ± (0.8), compared to 1.8 (±0.7).

It may be assumed that a subjective player report of fatigue or increased stiffness is a factor for injury prediction. However the conclusions of the aforementioned studies must be interpreted with discretion given the small differences that exist between injured and uninjured groups. It has also been identified that there appears to be no relationship between physical markers of performance or injury mentioned so far and the subjective reports of footballers. Other questionnaires and subjective measures have been associated with injury. Engebretsen et al (2010a) and Engebretsen et al (2010b) found a relationship between questionnaires for groin and ankle symptoms recorded during preseason and injury. Engebretsen et al (2010a) identified total groin outcome score (odds ratio 1.3, 95% CI 1.0 - 1.5) and subscores of symptoms, soreness and pain were associated with groin injuries. Engebretsen et al (2010b) identified for the foot and ankle outcome score, the subscore pain was associated with injury (odds ratio 0.9, 95% CI 0.7 - 1.2). The identification of existing pain, soreness and symptoms is more indicative of an existing injury. The groin and foot and ankle outcome score may therefore useful tools in the identification of previous injury which is associated with future injury.

Within the literature identified subjective reports and measure of fatigue or stiffness may be associated with acute injury occurrence although the effectiveness of these tools still remains unclear. Additionally questionnaires that evaluate player's symptoms such as pain may help to identify players at risk of future injury, although arguably pain may highlight an existing or previous injury. These measures may therefore be confounded by previous injury. The role of subjective scales of fatigue and injury for prospective modelling remains uncertain.

1.3.4 Match play

Matches have been identified as having an injury rate seven times higher than when compared to training, with the incidence of traumatic injuries showing an increased tendency over time in the first and second halves of matches (Ekstrand et al 2011). Foul play can account for 20% of injuries sustained and non-contact injuries can account for between 26% and 59% (Junge and Dvorak 2004). Fixture congestion and physical effort have been identified as factors that may increase the risk of injury.

Carling et al (2010) used a multiple camera player tracking system to evaluate the effects of physical performance prior to injury in professional footballers. Ten injuries were sustained with the most commonly affected sites being the ankle (50%), upper leg (30%) and the knee (20%). Eighty percent of the injuries were classified as moderate severity, with the remaining 20% being major. Sixty percent of the injuries were sustained as a result of contact. From the 10 injuries identified, eight involved efforts of a previous high intensity run (>19.1 km/h), with the final speed within a moderate range, approximately 17km/h. No significant difference in total distance and movement intensity five minutes prior to the time of injury was identified. Despite the lack of significance, it was noted that the final high efforts that led to injury were almost double the length and duration of the usual efforts. There was also a trend for players to cover a third more distance at high intensity running prior to sustaining an injury compared to typical performance over a 5 minute period. In addition the recovery time between the penultimate high intensity effort and high intensity leading to injury was shown to be significantly shorter compared to the normative recovery time between efforts, with a mean difference of -63.2±26.6 seconds, effect size of 3.5. It may be argued that the injury occurs as a result of insufficient recovery brought about by physical demands of the high intensity runs. Fatigue may influence the occurrence of injury which may provide some explanation as to why throughout studies the risk of injury increases towards the end of the match halves. Whilst fixture congestion has been suggested as a risk factor for injury, the existing literature is contradictory and confounded by other variables such as the varying intensity that would exist between matches. The high physical demands and insufficient recovery has also been proposed as a factor for injury between games as a consequence of fixture congestion. Dupont et al (2010) identified that players who undertook two matches in one week compared to those who undertook one match had an increased injury incidence (25.6, 95% CI 20.8 -30.5, compared to 4.1 (95% CI 3.0 - 5.1). However it was also identified that within this study there was no degradation to match related physical performance in players engaged in two games a week. Similar results were identified by Dellal et al (2013). Bengtsson et al (2013) identified matches played with four days or less of recovery had an increase in total injury rate (rate ratio 1.1, 95% CI 1.0 - 1.2) and muscle (hamstring and quadriceps) injury rate (rate ratio 1.3, 95% CI 1.2 - 1.5) when compared to matches with six or more day's recovery. As identified with previous studies, some differences have been reported as significant despite the difference between groups for injury rate being less than 3/1000h. This cannot be considered clinically significant. No difference was identified in overall muscle or ligament injury rate between matches played with three days or less recovery, or four days or more. Similarly, Carling et al (2012) investigated the effect of a prolonged fixture period (8 games in 26 days) on injury rate and physical attributes of match performance. There was no significant difference in the incidence of injury during the period of fixture congestion and those outside of the study period. In addition Carling et al (2012) identified no difference in the overall distance run, varying running intensities and individual possession of the ball in the first and second halves of matches played before, during and after the prolonged period of fixtures. Insufficient recovery may be attributable to injury as identified by Bengtsson et al (2013), although there is a lack of objective markers within the literature that have the ability to identify this. Markers of physical performance such as distance run and running speed intensity may be poor markers for injury prediction, as footballers at higher levels may adopt compensatory mechanisms to allow for the continuation of play.

It has been identified that the injury incidence is higher in matches than training. This indicates that causative factors of injury within match play are poorly understood. There may therefore be unidentified factors for injury during match play that could be used for predicting injury. Contradictions exist within the literature regarding the roles of physical activity efforts and fixture congestion for prospective injury modelling. Their roles as predictors for injury remain unclear.

1.4 Conclusion

Despite the incidence of injury within football being well reported on there is still inadequate data from which causal factors can be identified in the modelling of injuries. Whilst some risk factors have been identified as significant for injury, it is evident that despite being reported as statistically significant, the differences between injured and uninjured groups for these variables is small and not clinically significant. Failure to identify mechanisms for injury may stem from existing methodology omitting factors that precede injury, as well as other relevant factors present at the time of injury. A lack of understanding surrounding injury mechanisms is highlighted by the existence and implementation of numerous pre-season tests in which many had no association with injury (Venturelli et al 2011 and Frisch et al 2011). It was also identified that several studies took variable measures of what was titled as power, balance, muscle length and numerous others. These were identified as being erroneous, for example Arnason et al (2004), Ekstrand and Gillquist (1983b), Rolls and George (2004) and Witvrouw et al 2003) reported measuring muscle length or flexibility when they really measured magnitude of ROM. It is apparent that consistent valid and reliable ways of measuring proposed risk factors is yet to be developed. In addition individual risk factors and screening tests that have been associated with injury require further research in order to evaluate their validity and reliability in consistently identifying injury risk. Furthermore, the reason for which individual and multiple risk factors play a role in injury causation needs further investigation. It is apparent that previous injury is a significant factor for further injury and there is a tendency for increased injury risk with further injuries. The presence of previous injury makes it difficult to model and understand the effect of other potential risk factors in the occurrence of injury. In addition, it appears that the occurence of minor complaints or injuries and their role in more moderate or severe injuries is poorly understood, due to high rates of recurrent injuries. Underlying reasons and appropriate markers for high rates of recurrent injuries are also yet to be consistently identified within the existing literature. Performance within football may be measured by physical parameters or by a player’s ability on the football field. It appears that a decline in performance, either physically or in game results, is not a factor in the occurrence of injury, although it has been documented that injury rates can affect the team performance (Haggland et al 2013). The effect of turf type has been identified as having no effect on the overall injury rate although the exclusion of overuse injury rates in a majority of the studies may underestimate the role of surface type on injury. The inability to appropriately associate overuse injuries with an identifiable initial cause or mechanism highlights the inability of current nomenclature or measures to capture injury detail. As a consequence numerous different injury types such as tendonopathies, bursitis and stress responses are all assumed to have common mechanisms with no identifiable cause despite this having been proved false, further complicating injury modelling processes (Aoki et al 2010). It was identified inadequate or excessive training load is associated with injury and may play a role in the occurrence of acute and overuse injuries alike. Insufficient recovery and fatigue brought on by training duration, fixture congestion and poor physical conditioning have been associated as factors for injury although only subjective measure of fatigue have been identified.

A footballer's performance will be determined by their innate abilities as well as skills acquired and developed during training. As stated there may be a level of control and adaptability that is required to prevent injury. Within a match situation players are required to make decisions in a constantly changing environment within a short period of time. A footballer's ability to make positive decisions and execute skilled motor movements is informed by their motor control abilities (Schmidt and Wrisberg 2000). From the evidence identified it is still unclear what role fatigue, player error, insufficient conditioning, poor technical training and changing environmental factors have on the occurrence of injury. There is a wide variation in methods and measures used in the identification of injury. The existing framework allows for multiple variations in which injury subcategories can be clustered. This makes interpretation of results and comparison between studies difficult. The nomenclature and framework associated with injury recording may not allow for the capture of relevant details that are important in the modelling of injury and there may therefore be a need to modify the existing taxonomy. In addition, correct identification and ongoing evaluation of objective measures associated with injury is required, as several measures were incorrectly titled adding confusion to factors associated with injury.

2 AIMS AND OBJECTIVES

At the end of the literature review the following objectives had been identified. The incidence of injuries was well reported within the existing literature, attributable to the implementation of a consensus statement in 2006 which has resulted in greater consistency between studies (Fuller et al 2006). Despite this, the existing framework still allows for multiple variations in which injury subcategories can be clustered and reported. This makes interpretation of results and comparison between studies difficult. Several studies sought to retrospectively identify injury risk factors which have then been advocated for prospective injury modelling. Existing models for injury prediction are not suitable and currently, we are unable to accurately predict injuries in football. The inability to predict injuries using existing methods may stem from a lack of agreement around which factors can be used for predicting injury. Additionally, injury occurrence is multifactorial and complex; existing models fail to incorporate all relevant factors which may precede or occur at the time of injury.

The first aim of this thesis was therefore to explore why existing models are not working and to investigate whether injuries can be prospectively modelled using variables identified in the literature. In order to achieve this aim, it was necessary to replicate current practice, develop a database and prospectively collect variables recommended within the literature. As we are modelling injury, it was necessary to check if the injury patterns of the sampled population were comparable to the reported literature. This has been carried out to ensure performance of the model was not compromised as a result of a non-representative sample (Chapter 7). Following this processes, it was then possible to develop a model for identifying if injuries can be prospectively modelled as per the research question and first aim of this thesis (Chapter 8).

In order to meet the first aim, it was identified that before progressing to the modelling stages (Chapters 7 and 8), it was important to evaluate the validity of the FMS, which had been identified in the literature review as a significant component of the injury prediction and modelling process. **The second aim** of this thesis was therefore to evaluate the validity of the FMS for its use in injury modelling processes. This required operationalisation of the FMS is rules as carried out in Chapter 5. The results of the FMS validation process following operationalisation have been reported in Chapter 6.

In order to meet the second aim and evaluate the validity of the rules that govern FMS from first principles, it was necessary to establish a suitable methodology by which the operationalised FMS processes could be evaluated. **The third aim** of this thesis was therefore to establish a suitable methodology for comparison of the FMS. In order to meet the third aim a comparison was made against the kinematic measures obtained from the Vicon system (©Vicon Motion Systems Ltd) (VICON). The VICON system was selected as 3D motion analysis systems are considered the gold standard for movement analysis. This method of data collection using the VICON has been described in Chapter 3. Additionally selection of an appropriate marker set and model was required for the kinematic analysis as described in Section 3.1. In order to ensure that the results obtained from the VICON were reliable, the assessor had to be tested for reliability, given that factors such as marker placement can affect the kinematic outputs of the selected marker set and model. This methodology and results have been reported in Chapter 4.

The order of the aforementioned processes allowed for all three aims of the thesis to be addressed in a systematic way. Establishment of an appropriate methodology (**aim three**), allowed for the operationalisation of the FMS rules and its' subsequent validity to be evaluated (**aim two**). Once aims two and three had been achieved, it was possible to investigate the efficacy of existing prospective injury models and address the **first aim** of this thesis. A summative conclusion and future work have been provided in Chapter 9 to bring together the discussions from individual chapters and allow for meaningful conclusions to be drawn.

3 USING THE VIDEO BASED MOTION ANALYSIS SYSTEM, VICON (© VICON MOTION SYSTEMS LTD) FOR DATA CAPTURE AS A PRECURSOR FOR VALIDATION OF THE FMS

3.1 Introduction

The VICON system uses infrared cameras to track the movement of reflective markers. The standard operating procedures for laboratory calibration, anthropometric measurements and marker placement will be described first, as they are required for running the Plug-in gait model. Segment definition and kinematic analysis were carried out according to the conventional Plug-in Gait model (Appendix VIII) (VICON LTD, Oxford). For any processes that differed from the conventional Plug-in Gait model, a justification and description of the processes has been provided in the main text. This includes the post capture analysis and processing methods used as a quality control measure. The methodology has been structured in this way to avoid duplication, as the anthropometric measurements, marker placement and model details are similar for several steps of the study. The individual stages of the study procedure will then be explained.

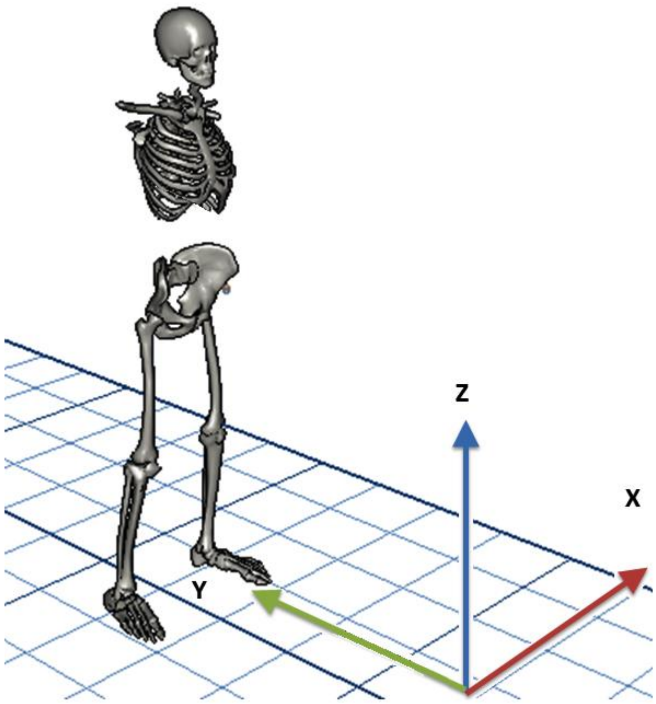
The process of using the motion capture system to validate the FMS followed these stages:

1. Camera calibration and laboratory orientation
2. Warm up (familiarisation of the FMS tests)
3. Anthropometric measurements
4. Marker placement
5. Static capture
6. Gait analysis as a quality control measure
7. Capture of the FMS screening test

3.1.1 Camera calibration and Laboratory orientation

Data capture was completed at the movement analysis laboratory located at Keele University. Prior to data collection the VICON camera system was "calibrated" as per the steps below. For this study the global axis of the laboratory was defined as per figure 3.1.

Figure 3.1 Laboratory orientation for global axis.



Camera calibration methods

There are two main steps to the system calibration process:

1. Dynamic calibration - This involves movement of a calibration wand throughout the whole volume. This allows the system to calculate the relative positions and orientations of the cameras. The dynamic calibration process also linearises the cameras and allows for the residual of each camera to be calculated.

   a. Residual threshold for each camera - The residual is the measure of the accuracy of a single camera. It is the root mean square of the distance between two rays; the first being that from the centre of the strobe ring to the centroid of the marker and the second being the reflected ray from the marker to the camera lens. The acceptable level of tolerance set within the VICON software was less than 0.1% of the distance from the camera to the centre of the capture volume.

2. Static calibration – The static calibration process requires the calibration wand to be placed on the capture volume floor. This calculates the origin of the capture volume and determines the orientation of the capture volume.

Markers were tracked at 100 Hz with eight VICON MX-T20 motion analysis cameras. A Woltring filter (Woltring 1986) as per the conventional Plug-in Gait model pipelines was used. VICON Nexus 1.8.5 was used for marker reconstruciton, labelling and application of the Plug-in Gait model in addtion to Body Builder 3.6.2. For the walking series results were analysed using VICON Polygon 4.1.2 and for the FMS tests data were analysed using MATLAB 2016A.

3.2 Measurements required for the Plug-in Gait model

Prior to the marker placement, the measurements required for the Plug-in Gait model were carried out as per table 3.1 below. In addition, measurements of tibial height and hand length were taken as required by the FMS. Standard operating procedure for anthropometric measures is taken from The Orthotic Research and Locomotor Assessment Unit (ORLAU) 3D movement analysis marker placement protocol (Reference MAS OP 111).

Table 3.1 Anthropometric measurement protocol and recording sheet

Name ____

ID reference ____

D.O.B ____

	Anthropometric measurements	Recording
1.	**Height** The participant will be tested in their shorts and therefore asked to remove pieces of clothing not required. They will then be asked to stand on the scales.	mm
2.	**Weight** Participants will be required to stand erect under the stadiometer.	kg
3.	**Inter ASIS distance** Subject supine the plinth a) For the palpation of each ASIS, stand on the side of the ASIS being palpated. b) Palpate the iliac crest to identify the general area of the ASIS. c) Palpate just below the ASIS, moving the hand up towards it. d) The first bony prominence should be the inferior edge of the ASIS: mark a dot on the middle of this inferior edge with an eye liner pencil.	mm
4.	**Leg Length** Measure with the patient supine, the knees maximally extended, and the operator stood on the side to be measured. Using a fabric tape measure hold the end on the point marking the ASIS with the proximal hand. Gently pull the tape taught on a direct line to the medial malleolus with the distal hand. Hold the tape here with a finger just distal to the MM. Gently slide this finger up the tape until a bony ledge is felt. At this point record the measurement. Repeat on the opposite side.	LEFT mm RIGHT mm
5.	**Knee Width** Identify and Surface Marking Knee Axis ***Lateral surface marking*** With the patient supine, stand at the side of the plinth, level with the knee. Flex the knee to 90^{o} and palpate the lateral joint line. Use the other hand to identify the lateral epicondyle of the femur by sliding the hand along the outside of the femur. Now palpate the dip of the popliteal groove between the epicondyle and the joint line. Move along the popliteal groove until between the tendon of biceps femoris and the lateral collateral ligament. The iliotibial (ITB) band should be above the palpating finger, and the lateral head of gastrocnemius should be below. Move anteriorly and proximally onto a bony nodule - the origin of the lateral collateral. Keep this point under the palpating finger as an assistant slowly extends the knee. Re-palpate (the ITB tends to obscure the point of palpation on extension). In extension mark this point. ***Medial surface marking*** With the patient supine, stand at the side to be palpated level with the knee. Flex the knee to 90^{o} and from the patella tendon palpate the medial joint line. Identify the broad tibial collateral ligament and grasp this loosely between the thumb and forefinger of the "distal" hand. Maintaining this grasp extend the knee with the other hand. Then run the flattened fingers of the proximal hand down the lower medial side of the thigh to find the adductor tubercle. Mark this with the middle finger and place the index finger on the mid-point of the line that joins the adductor tubercle to the middle of the collateral ligament at the joint line. This is a flat, rather featureless area, but a small depression may be felt. This should be distal and slightly anterior to the adductor tubercle. Remove the finger from this point and mark the same spot with a pen. The distance between the surface markings of the knee joint axis, measured using the callipers with the patient lying supine (cm)	LEFT mm RIGHT mm

Table 3.1 Anthropometric measurement protocol and recording sheet

	Anthropometric measurements	Recording
6.	**Ankle Width** Measure the widest part of the ankle malleoli measured using the callipers with the patient lying supine (cm).	LEFT mm RIGHT mm
7.	**Tibial torsion** The midpoint of the medial malleolus and the posterior tip of the lateral malleolus are marked with eyeliner pen. The subject is prone and knee flexed at 900 so that the shank is vertical and ankle dorsiflexed to900, or as close as possible. The goniometer is place on the plantar surface of the heel so that the first arm is in line with both marks. The second arm is aligned parallel to an imagined line between the midpoint of the knee joint axis and the hip joint centre – the mid-line of the thigh. The angle recorded is from the line perpendicular to the mid-line of the thigh	LEFT Degrees RIGHT Degrees
8.	**Shoulder offset** Vertical offset from the base of the acromion marker to shoulder joint centre	LEFT mm RIGHT mm
9.	**Elbow width** This is the distance between the medial and lateral epicondyles of the humerus.	LEFT mm RIGHT mm
10.	**Wrist width** This is the distance between the ulna and radial styloids.	LEFT mm RIGHT mm
11.	**Hand thickness** This is the distance between the dorsal and palmar surfaces of the hand	LEFT mm RIGHT mm
12.	**Hand length** Length is determined by measuring the distance from the distal wrist crease to the tip of the longest digit on the palmar aspect.	LEFT mm RIGHT mm
13.	**Tibial Height** Tibial height is measured from the bony landmark of the tibial tuberosity to the floor.	LEFT mm RIGHT mm

The participant’s weight was recorded on scales whilst their height was measured with a stadiometer. Measurements of knee, ankle, elbow, and wrist and hand thickness were measured with electronic Vernier calliper. Inter anterior superior iliac spine (ASIS), leg length, shoulder offset, hand length and tibial height were measured with a tape measure and the tibial torsion angle with a goniometer.

3.3 Marker placement for data capture

This section describes in detail where the Plug-in Gait markers should be placed on the subject (table 3.2 and figure 3.2). Standard operating procedure for lower limb marker placement is as per the Plug-in Gait model requirements with the addition of a medial epicondyle knee marker (KME). The additional LKME marker is to allow for a virtual knee alignment device (KAD) to be included in the dynamic trial captures. Additional markers (six in total for left and right; PEX, TEX and BEX) were also placed on the pelvis and thorax segments to compensate for potential marker occlusion during data capture. The assessor was evaluated for competency in lower limb marker placement prior to the FMS data collection stage (Chapter 4). Within Chapter 4 sources of error arising from marker placement variability and the methods for assessing reliability are discussed. Where only left side markers are listed, the positioning is identical for the right side.

Table 3.2 A Marker positions for the Plug-in Gait Model

Head Markers - A head band was used for marker attachment

Label	Anatomical location	Placement
LFHD	Left head front	Approximately over the left temple
RFHD	Right head front	Approximately over the Right temple
LBHD	Left head back	Back of the head, roughly in a horizontal plane of the front head markers
RBHD	Right head back	Back of the head, roughly in a horizontal plane of the front head markers

Torso Markers

Label	Anatomical location	Placement
C7	7th Cervical vertebrae	Over the spinous process of the 7th cervical vertebrae
T10	10th Thoracic vertebrae	Over the spinous process of the 10th thoracic vertebrae
CLAV	Clavicle	Jugular Notch where the clavicles meet the sternum
STRN	Sternum	Xiphoid process of the sternum
RBAK	Right Back	Placed in the middle of the right scapula. The marker has no symmetrical marker on the left side. The asymmetry helps the auto labelling routine determine right from left on the subject.
LTEX	Front of thorax	Anterior surface of the thorax, inferior down the line with the nipple, placed superior to the last palpable rib
LBEX	Back of thorax	Posterior surface of the thorax, inferior down the line with the inferior angle of the scapula, placed superior to the last palpable rib

Table 3.2.B Marker positions for the Plug-in Gait Model

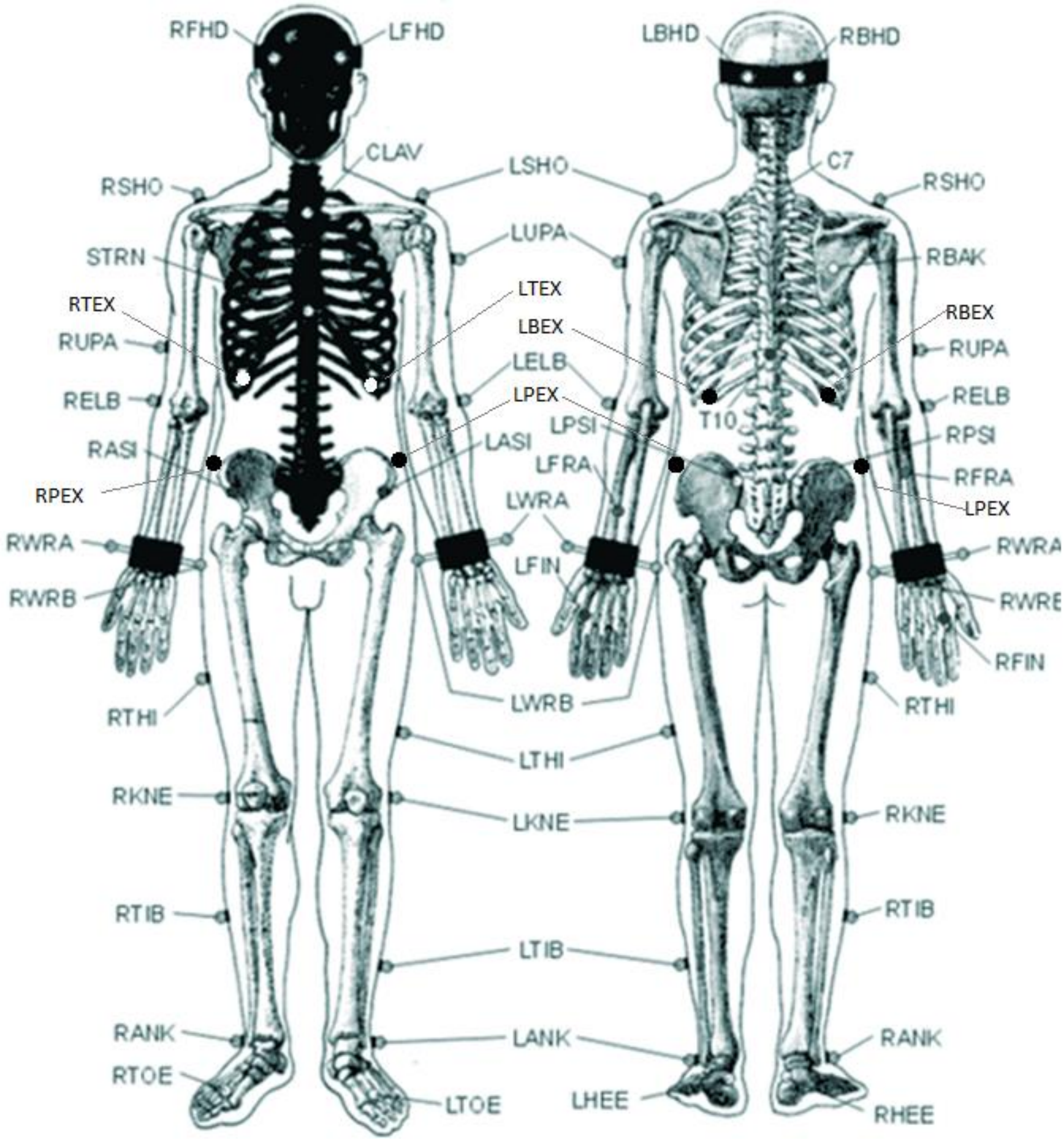
Upper Limb Markers

Label	Anatomical location	Placement
LSHO	Left Shoulder	Over the acromio-clavicular joint
LUPA	Left upper arm	On the upper arm between the elbow and shoulder markers. Asymmetrical to RUFA
LELB	Left elbow lateral epicondyle	Medial epicondyle of the humerus approximating elbow joint axis
LFRA	Left forearm	On the lower arm between the elbow and wrist markers. Asymmetrical to RFRA
LWRA	Left wrist radial side	Lateral aspect of wrist distal to radial styloid
LWRB	Left wrist ulna side	Medial aspect of the wrist distal to ulna styloid
LFIN	Left finger	Dorsum of the hand inferior to the head of the second metacarpal

Lower Limb Markers

Label	Anatomical location	Placement
LASI	Anterior superior iliac spine (ASIS)	Placed directly over the left ASIS. Repeat for other ASIS
LPSI	Posterior superior iliac spine (PSIS)	Place directly over the Left PSIS Repeat for the other PSIS
LPEX	Iliac crest	Placed inferior to the iliac crest in line with the mid axillary line.
LTHI	Thigh	Placed over the lower lateral one third surface of the thigh, below the swing of the arm. Asymmetrical to RTHI
LKNE	Knee - lateral epicondyle	Placed over the lateral epicondyle of the knee
LKME	Knee – medial epicondyle	Placed over the medial epicondyle of the knee
LTIB	Shank	Placed over the lower lateral one third surface of the shank
LANK	Ankle	Place the marker on the most prominent point of the lateral malleolus
LTOE	Forefoot	Place the marker on the dorsum of the foot directly over the head of the second metatarsal.
LHEE	Calcaneus	Using the metal gauge, check the height of fore foot marker above the ground. Palpate the calcaneum and place a marker in the centre of the posterior aspect of the calcaneum, at the same height above the ground (or at the same height above the plantar surface of the heel if the heel doesn't touch the ground) as the forefoot marker.

Figure 3.2 Graphical representation of marker placement for Plug-in Gait



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Walking series capture

Once the static capture had been completed, a series of transverse walks of the walkway was carried out by the participant to record their gait pattern. The lower limb model is well established for gait analysis in clinical practice. As a result, the values associated with normative gait analysis are more clearly defined and understood. Therefore, kinematic outputs observed during the walking series were used as a reference to ensure marker placement was accurate and allow for any necessary post processing adjustments to be made. (Justification for only selecting the lower limb values is described in section 4.1). For all walking trials the knee varus/valgus angle in the swing phase of the gait cycle was used as a quality control measure, as is commonly used in clinical gait analysis and described by Schwartz et al (2004). If a peak value of more than 15 degrees, or a range larger than 20 degrees of knee valgus was identified, the KAD was rotated by five degree increments (see Appendix IX) to ensure the correct orientation of the knee joint centre.

3.3.1 Plug-in Gait model

Segment definition and kinematic analysis were carried out according to the conventional Plug-in Gait model for both the upper and lower body (Appendix VIII). For any processes that differed from the conventional Plug-in Gait model, a justification and description of the processes has been provided below.

3.3.1.1 Upper body Kinematics

Prior to data collection, it was intended that the upper body component of the Plug-in Gait model would be used for upper body kinematics. However, due to problems arising from marker co-linearity which affected the segment geometry, other methods for calculating the required shoulder and elbow angle outputs were used. The same methods were used to address the occurrence of gimbal lock[4] which was present in some cases due to the positional and movement requirements of the FMS tests. These methods have been described below. The Plug-in Gait model was not used for kinematic outputs; however the shoulder and wrist joint centres were used for some parts of the analysis as they were not subject to the problems discussed above and can be seen in Appendix VIII.

[4] A loss of rotational degrees of freedom due to a singularity i.e. two axis becoming parallel and the matrix solutions become unobtainable (Grassia 1998; Murray 1999)

3.3.1.1.1 Shoulder angle outputs

For the thorax, a different local co-ordinate system and cardan angle sequence was used when calculating shoulder angles. This was done in order to overcome gimbal lock as described previously. The local co-ordinate system for the thorax was calculated with the C7, CLAV, STRN and T10 markers. The primary local Y-axis was defined from the midpoint of STRN and T10 to the midpoint of CLAV and C7. A temporary local Z-axis was established, defined as the midpoint of CLAV and STRN to the midpoint of C7 and T10. The cross product of the Y axis and temporary Z axis was used to define the local X axis. The cross product of the X and Y planes was used to correct the temporary Z axis.

The humerus was defined using the shoulder joint centre (HUP) (previously identified in the Plug-in Gait model) to the lateral elbow marker (ELB). The dot product of the humerus to the Y-plane of the thorax was used to calculate the angle of elevation. The plane of elevation was calculated from initially finding the cross product of the Y-axis of the thorax and the humerus, and then the dot product of these two. As a result of this method, the angle of rotation could not be calculated due to an insufficient number of markers. Additionally, due the demands of the FMS tests participants approached positions which may have caused the occurrence of gimbal lock in the new model. Therefore only the angle of elevation was used for validating the rules of the FMS. As a consequence of this, we were unable to obtain kinematic values for the orientation of the humeral segment relative to the thorax (thoracohumeral joint) for the planes of abduction and rotation. This did not affect our ability to validate rules for FMS subtests involving upper limb movement, as they only required evaluation of shoulder elevation angles.

3.3.1.1.2 Elbow angle outputs

In order to calculate the elbow angle, the angle between two vectors were used. One vector was defined from the wrist joint centre (WJC) to the elbow marker (ELB), representative of the distal forearm. The other vector was defined from the lateral elbow marker (ELB) to the shoulder joint centre marker (HUP), representing the proximal humerus segment. The inverse cosine of the dot product of the two defined vectors was used to calculate the angle. For this method, the maximum estimated angle error was calculated to be 11 degrees (Appendix X). This was taken into consideration when using this measurement in the validation of the FMS rules.

4 RELIABILITY TESTING FOR MARKER PLACEMENT

4.1 Introduction

Prior to data collection, the inter and intra-rater reliability of the researcher for lower body marker placement was evaluated to ensure the researcher was proficient. This was carried out so that when interpreting the results, the impact of marker placement error could be determined. The lower limb model is well established for gait analysis in clinical practice. As a result, the values associated with normative gait analysis are more clearly defined and understood.

The upper limb model has not been as well integrated into clinical practice and there is no repeatable reference task for the upper limb as an equivalent to walking. Due to the lack of a fixed reference to measure, separation of marker placement variation from task variation would not be possible for either inter or intra-rater reliability testing. The limited use of the upper limb model in clinical practice additionally resulted in the lack of an available person who was proficient (routinely used the upper limb model and marker set) for the researcher to be compared against. The inter and intra-rater reliability of the researcher for marker placement of the upper limb model was therefore not evaluated given the lack of ability to distinguish marker placement variation from task variation or the availability of a suitable comparator.

Appropriate marker placement is important in minimising the effect of marker placement error on any kinematic outputs (Schwartz et al 2004). Methods for anthropometric measurement and marker placement have been described previously (Sections 3.2 and 3.3 respectively). Marker placement reliability was assessed for the lower limb part of the Plug-in Gait model, namely; LASI, RASI, LPSI, RPSI, LTHI, RTHI, LKNEE, LKME RKNEE, RKME (for placement of KAD or virtual reconstruction of KAD), LTIB, RTIB, LANK, RANK, LTOE, RTOE, LHEE and RHEE markers.

4.2 Common methodology for inter and intra rater reliability studies

The same subject was used for both the inter and intra-rater reliability testing. Therefore the same anthropometric measures required for the model were also used in all the studies (Appendix XI). The participant attended in appropriate clothing (shorts). Gait analysis data was used prior to the FMS data collection, and for the inter and intra-rater reliability studies, as the normative values for these variables are fairly well established. This method for establishing marker placement error is also routinely used within current clinical practice.

The variables evaluated were:

- Pelvic tilt, pelvic obliquity and pelvic rotation
- Hip flexion/extension, hip abduction/adduction and hip rotation
- Knee flexion/extension, knee abduction/adduction and knee rotation
- Ankle plantarflexion/dorsiflexion, foot progress angles and ankle rotation

4.2.1 Establishing acceptable limits of error

As is in current clinical practice, a root mean square (RMS) error of five degrees was used as the threshold for determining an acceptable level of error in the kinematic outputs for both the inter and intra rater reliability testing. If the RMS error value exceeded the threshold of five degrees:

i) The variable was investigated to see if the reasons for error could be explained

ii) The relevance of the identified variable to FMS variables being assessed was evaluated.

The knee abduction/adduction angle output of the model was also used as an ad hoc quality assurance tool (Schwartz et al 2004). If the abduction/adduction angle value exceeded more than 10 degrees the position of the knee alignment device/ virtual knee alignment device was rotated by five degree increments to adjust for this error.

4.3 Inter-rater reliability study

4.3.1 Methodology

The researcher was tested against an experienced physiotherapist from The Orthotic Research and Locomotor Assessment Unit (ORLAU), based at The Robert Jones and Agnes Hunt (RJAH) Orthopaedic Hospital National Health Service Foundation Trust in Oswestry. The inter-rater reliability testing was conducted at the ORLAU gait laboratory. Markers (14mm) were tracked at 100 Hz with twelve VICON MX-F40 motion analysis cameras. A Woltring filter as per the Plug-in Gait model was used with a mean square error value of 20. VICON Nexus 1.8.5 was used for marker reconstruction, labelling and application of the model. Data were analysed using VICON Polygon 4.1.2.

The measurements were taken independently and a minimum of five walk trials were conducted for the gait analysis. After completion of the minimum number of five dynamic walking trials or more, the markers were removed. The researcher then repeated the same procedure as that completed by the ORLAU physiotherapist. A total of 20 trials were used for the analysis, 12 available from the experienced ORLAU physiotherapist and eight available from the researcher. The RMS errors of the walking trials were then compared between the researcher and ORLAU physiotherapist.

4.3.2 Results

The walking trials average kinematic data were plotted, comparing the experienced ORLAU physiotherapist against the researcher, for the left and right lower limbs (figures 4.1 and 4.2 respectively). Following completion of the inter-rater reliability study, the data was analysed to identify variables which exceeded the predetermined limits of error (table 4.1). Of the variable assessed right hip rotation (8.3°), right knee rotation (5.7°), right ankle rotation (8.4°) and left ankle plantar flexion/dorsiflexion (5.1°) were identified as having been outside the predetermined threshold. These variables were therefore investigated to see if the reasons for error and relevance to the FMS could be explained section (4.3.3). Apart from the aforementioned variables, all the remaining variables did not exceed the predetermined threshold. The subject's walking speeds were similar for trials between the ORLAU physiotherapist and the researcher (1.41 m/s and 1.45 m/s respectively). These have been presented in table 4.2. Individual gait graphs for the experienced ORLAU physiotherapist and researcher, for all trials are located in Appendix XII and Appendix XIII respectively.

Figure 4.1 Walking trials average for left lower limb. Experienced ORLAU physiotherapist plotted against researcher

KEY

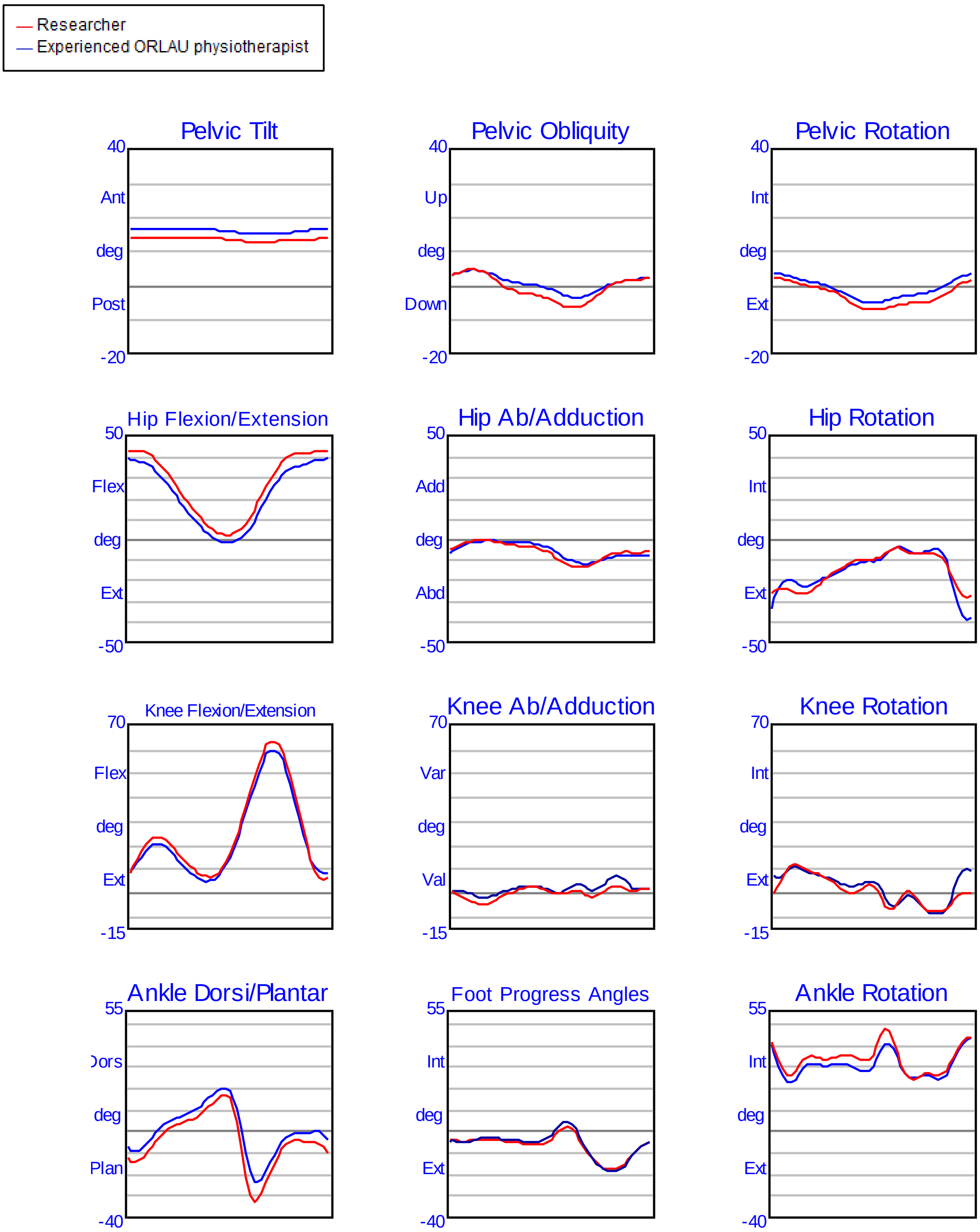


Figure 4.2 Walking trials average for right lower limb. Experienced ORLAU physiotherapist plotted against researcher

KEY

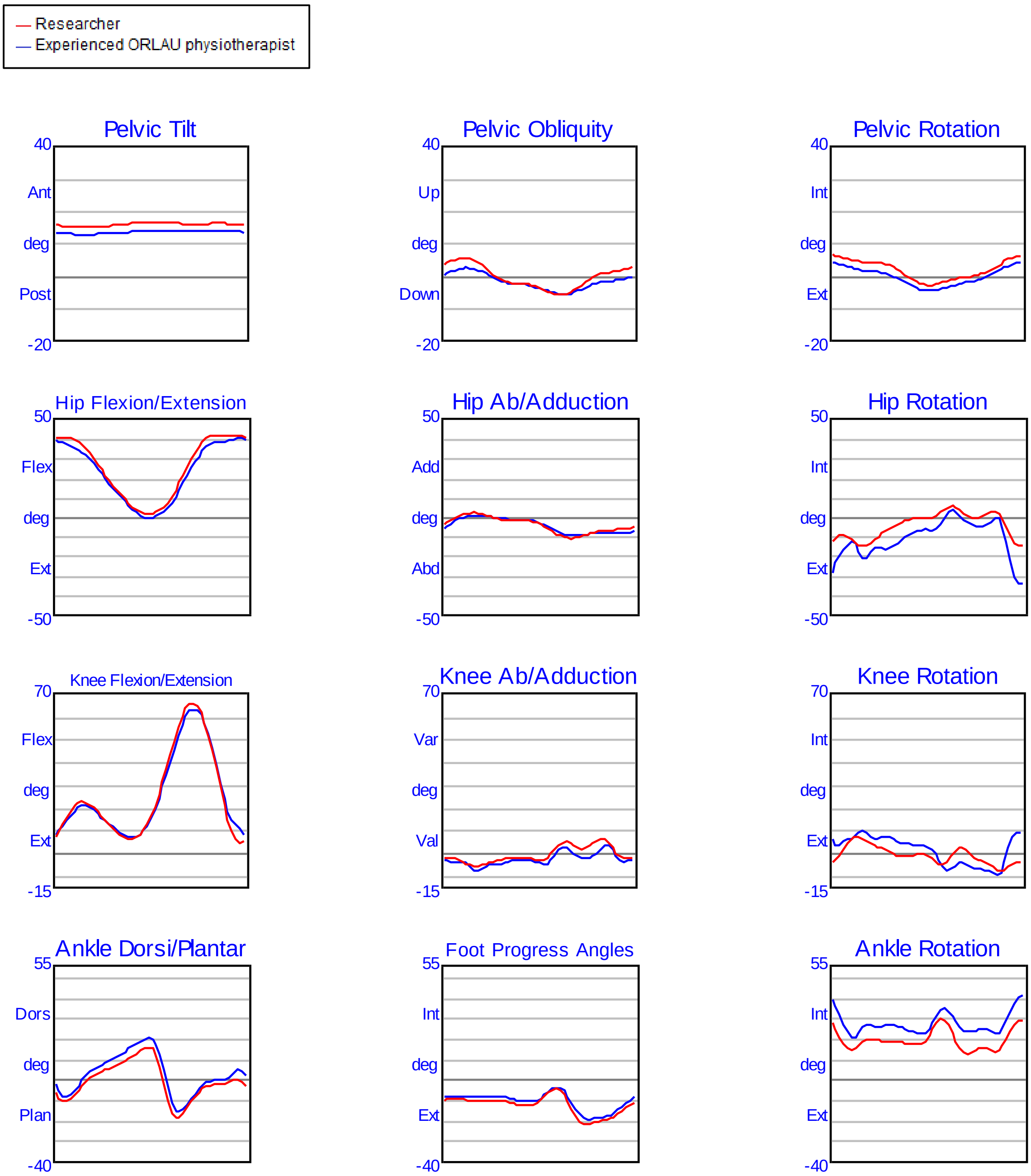


Table 4.1 Root Mean Square error for marker placement error in the inter-rater reliability study

Kinematic variable	RMS error (degrees) to 1dp	
Pelvis	**Left**	**Right**
Pelvic tilt	**2.5°**	**2.5°**
Pelvic obliquity	**1.9°**	**2.0°**
Pelvic rotation	**2.0°**	**2.2°**
Hip		
Hip flexion/extension	**5.0°**	**2.9°**
Hip abduction/adduction	**1.6°**	**1.1°**
Hip rotation	**3.7°**	**8.3°**
Knee		
Knee flexion/extension	**2.6°**	**2.3°**
Knee abduction/adduction	**2.2°**	**2.4°**
Knee rotation	**3.4°**	**5.7°**
Ankle/Foot		
Ankle plantarflexion/dorsiflexion	**5.1°**	**4.0°**
Foot progress angles	**1.1°**	**2.0°**
Ankle rotation	**3.4°**	**8.4°**

Table 4.2 Walking speeds for ORLAU physiotherapist and researcher

Assessor	Left	Right
Walking Speed (ORLAU Physio.)	1.41 ± 0.039 m/s	1.41 ± 0.033 m/s
Walking Speed (Researcher)	1.44 ± 0.058 m/s	1.45 ± 0.057 m/s

4.3.3 Discussion

Of the variables assessed, the largest sources of RMS error occurred within the transverse plane on the right lower limb for hip, knee and ankle rotation. As the Plug-in Gait biomechanical model is hierarchical, any errors that occur proximally are likely to be propagated distally. Errors of the hip and knee are also influenced by the location of the hip and knee joint centres. These joint centres are influenced by marker placement, anthropometric measures and position of the KAD. As the same anthropometric measures were used for all studies, the sources of error identified in this study are likely to have arisen as a result of proximal marker placement error and differences in KAD alignment. This would explain the right lower limb rotational errors within the hip, knee and ankle joint. The effect of proximal marker placement error on the distal aspects of the model is demonstrated by the similar results for the right hip rotation (8.3°) and right ankle rotation (8.4°) variables.

Knee rotation error within this study can also be attributed to proximal errors, joint centre locations, and KAD alignment, as these are known to contribute to knee errors (Schwartz et al 2004). Due to the hierarchical nature of the model, errors within the knee also affect the ankle, as the rotation off set of the knee is used in conjunction with the bi-malleolar axis measurement to determine the amount by which ankle axis is rotated. This error is further compounded by differences observed in the subject posture between the static capture for calibration and the dynamic captures for analysis. Marker movement as a result of different soft tissue artefact / skin movement contributes to this error.

Another factor to consider as an explanation for differences in the kinematic outputs would be walking speed, as variations in walking speed is known to affect this variable (Schwartz et al 2008). However, in this inter-rater reliability study walking speeds were found to be similar between the ORLAU physiotherapist and researcher and thus may not be considered as a contributory factor in the kinematic differences (table 4.2). The errors in the transverse plane that exceeded the threshold in this interrater reliability study are unlikely to have a significant effect on the validation process of the FMS tests and scoring criteria. As described in the FMS validation chapter (Chapter 5), no absolute values of rotation or joint kinematics in the transverse plane will be used for validating the rules of the FMS. When reporting the kinematic variability of the FMS, only the ranges of the rational values identified will be considered.

For the left ankle plantar flexion/dorsiflexion variable (5.1°), the RMS error exceeded the predetermined threshold. The left ankle plantar flexion/dorsiflexion error (5.1°) error was similar to the error of the left hip flexion/extension variable (5.0°) which did not exceed the predetermined threshold. The effect of proximal marker placement error in view of the hierarchical nature of the model may explain this error. Errors associated with this variable are also unlikely to have a significant effect on the validation process of the FMS tests and scoring criteria. No absolute values of ankle flexion/extension kinematics will be used for validating the rules of the FMS. When reporting the kinematic variability of the FMS, only the ranges of the ankle flexion/extension values identified will be considered.

4.3.4 Conclusion

Results from the inter-rater reliability study support that the researcher is proficient in marker placement required as a precursor for data capture. Errors that exceeded the threshold were identified for the transverse plane knee and ankle variables. However, their effect on the FMS validation process is non-significant as no absolute values of rotation or other joint kinematics in the transverse plane will be used for validating the rules of the FMS. The researcher was also found to have exceeded the threshold for error in the sagittal plane for the left ankle in the inter-rater reliability study. Errors associated with this variable are also unlikely to have a significant effect on the validation as no absolute values of ankle flexion/extension kinematics will be used for validating the rules of the FMS. As some kinematic variables will be used to classify participants and compare them against the scale of the FMS, understanding the ranges of error associated with the researcher for marker placement will help in interpretation of these kinematic results for validation purposes. Therefore it can be assumed that when interpreting kinematic results of the sagittal and coronal plane variables in the FMS validation process, these will be a reliable measurement of the movements being undertaken by the participant. Furthermore any inter and intra-subject kinematic differences may more confidently be attributed to actual differences in the participant and not marker placement error.

4.4 Intra-rater reliability study

4.4.1 Methodology

The researcher was then tested against himself for consistency. The intra-rater reliability testing was conducted at the movement analysis laboratory (Turing Laboratory) located at Keele University. Markers (14mm) were tracked at 100 Hz with eight VICON MX-T20 motion analysis cameras. A Woltring filter as per the Plug-in Gait model was used with a mean square error value of 20. The data from three separate sessions (consisting of the average data from five dynamic walking trials in each session) was used for the analysis. After each session was completed the markers were removed and the researcher then repeated the marker placement and data capture for the associated dynamic walking trials.

4.4.2 Results

The walking trials average kinematic data were plotted, comparing walking sessions one, two and three, for the left and right lower limbs (figures 4.3 and 4.4 respectively). Of the variables assessed, the largest sources of error occurred within the transverse plane for the left hip rotation and right ankle rotation (table 4.3). These occurred for left hip rotation (session three - 6.5°), right ankle rotation (session two - 8.8°), right ankle rotation session three – 6.7°). These variables were identified as having exceeded the predetermined threshold and were therefore investigated to see if the reasons for error and relevance to the FMS could be explained (section 4.4.3). Apart from the aforementioned variables, all the remaining variables did not exceed the predetermined threshold. The subject's walking speeds for walking sessions one, two and three were similar (1.28 m/s, 1.31 m/s and 1.41 m/s respectively). These results have been presented in (table 4.4).

Figure 4.3 Averages of walking sessions one, two and three. Plotted for left lower limb gait variables

KEY

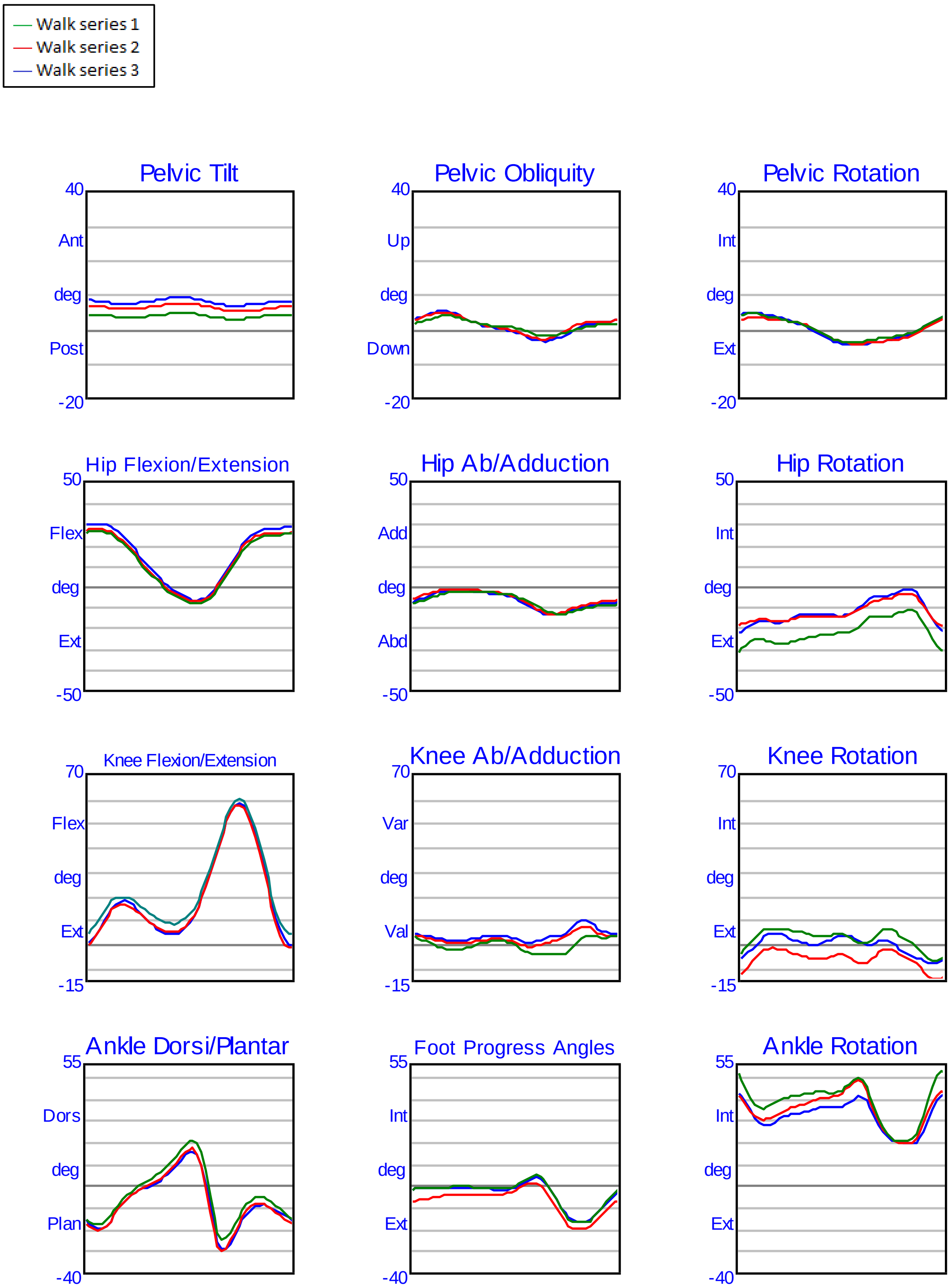


Figure 4.4 Averages of walking sessions one, two and three. Plotted for right lower limb gait variables

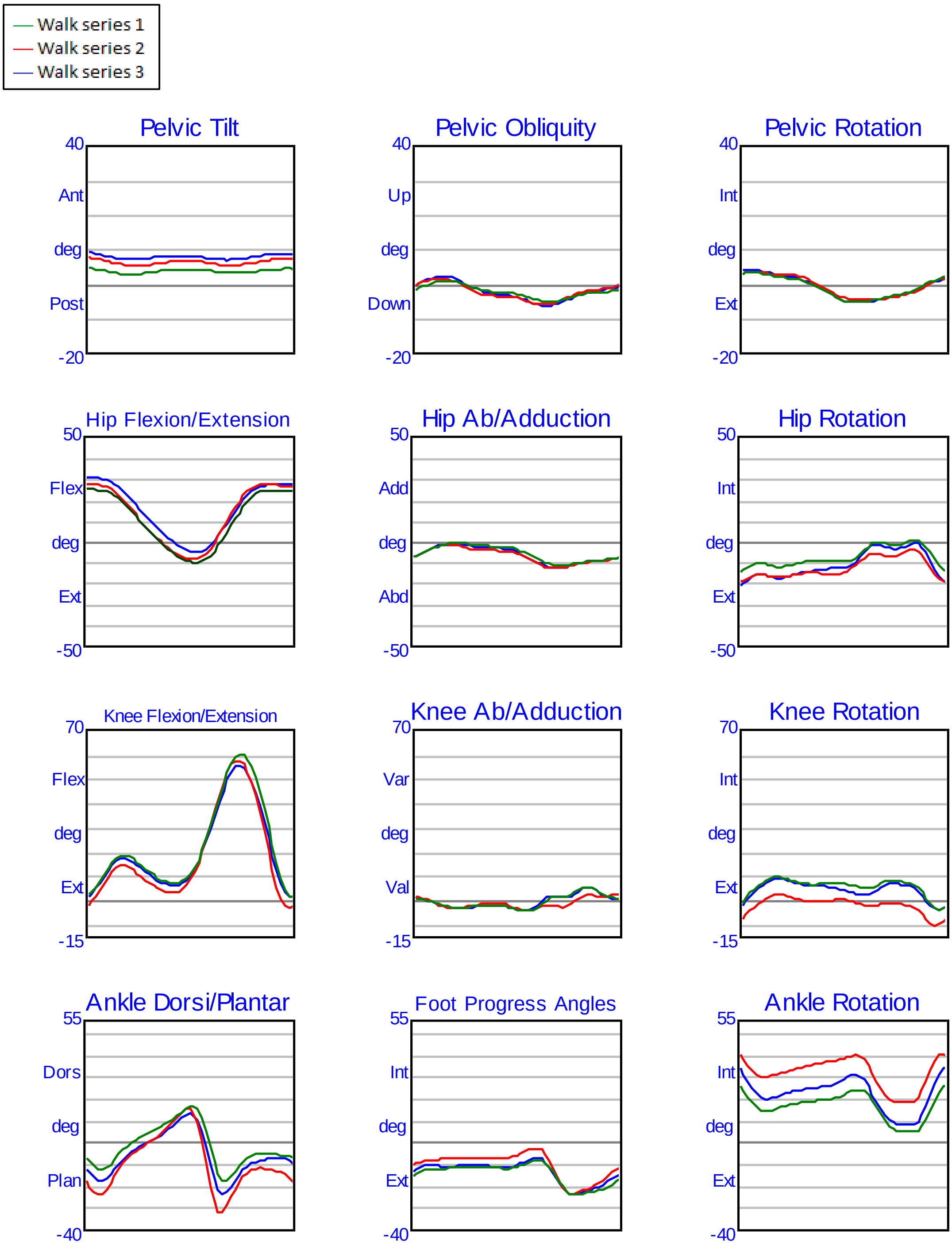


Table 4.3 Root Mean Square error values for all three intra rater reliability walking sessions

Root mean square error (degrees)			
Pelvis	**Session**	**Left**	**Right**
Pelvic Tilt	1	1.9°	1.8°
	2	0.3°	0.2°
	3	2.2°	2.4°
Pelvic Obliquity	1	0.4°	0.3°
	2	0.3°	0.4°
	3	0.6°	0.6°
Pelvic Rotation	1	0.4°	0.3°
	2	0.5°	0.4°
	3	0.4°	0.3°
Hip			
Hip Flexion/Extension	1	1.6°	2.5°
	2	0.4°	1.5°
	3	3.8°	1.3°
Hip Abduction/Adduction	1	0.3°	0.1°
	2	0.8°	0.8°
	3	0.8°	0.8°
Hip Rotation	1	3.4°	1.2°
	2	3.1°	2.4°
	3	**6.5°**	3.1°
Knee			
Knee Flexion/Extension	1	1.0°	1.1°
	2	1.4°	2.8°
	3	2.3°	2.3°
Knee Abduction/Adduction	1	3.0°	0.5°
	2	0.7°	1.3°
	3	2.6°	0.6°
Knee Rotation	1	1.6°	1.4°
	2	4.7°	5.0°
	3	3.9°	2.7°
Ankle/Foot			
Ankle Plantarflexion/Dorsiflexion	1	1.3°	1.0°
	2	1.3°	4.7°
	3	2.4°	4.2°
Foot Progress angles	1	1.1°	0.7°
	2	2.3°	2.6°
	3	1.4°	1.6°
Ankle Rotation	1	3.5°	1.2°
	2	1.4°	**8.8°**
	3	3.9°	**6.7°**

Table 4.4 Average walking speeds for sessions one, two, three of the intra rater reliability study

Walk series	Left	Right
Walking speed - Session 1	1.28 ± 0.069 m/s	1.30 ± 0.063 m/s
Walking speed - Session 2	1.31 ± 0.033 m/s	1.30 ± 0.063 m/s
Walking speed - Session 3	1.40 ± 0.051 m/s	1.41 ± 0.046 m/s

4.4.3 Discussion

These errors are reflective of those identified inter-rater reliability study and are likely to be resultant from marker placement errors which are propagated due to the construct of the model as described previously. Similarly, errors in the transverse plane that exceeded the threshold in this intra-rater reliability study are unlikely to have a significant effect on the validation process of the FMS tests and scoring criteria. As described in the FMS validation chapter (Chapter 5), no absolute values of rotation or other joint kinematics in the transverse plane will be used for validating the rules of the FMS.

The effect of variable walking speed on the kinematic variables was investigated for the intra rater reliability study. The walking speeds between sessions for the intra rater reliability study were similar (table 4.4). The variability between sessions is small and within the ranges (1.05 to 1.43 m/s) considered to be typical for normal gait speed in healthy adults (Oberg et al 1993). As previously mentioned, reasons for which the transverse plane variables (left hip rotation and right ankle rotation) exceeded the error threshold can be explained. It can therefore be concluded that the variability in walking speeds would not account for the observed differences.

In the intra-rater reliability study, fewer variables were identified as having exceeded the threshold when compared against the inter-rater reliability study (three versus four variables respectively). Additionally, the magnitudes of the errors were smaller for the intra-rater reliability when compared to the inter-rater reliability study. Results from the intra-rater reliability study demonstrate a higher level of reliability and provide justification for the use of a single assessor in the FMS validation processes.

4.4.4 Conclusion

Results from the intra-rater reliability study support that the researcher is proficient in marker placement required as a precursor for data capture. Errors that exceeded the threshold were identified for the transverse plane knee and ankle variables. However, their effect on the FMS validation process is non-significant as no absolute values of rotation or other joint kinematics in the transverse plane will be used for validating the rules of the FMS. As some kinematic variables will be used to classify participants and compare them against the scale of the FMS, understanding the ranges of error associated with the researcher for marker placement will help in interpretation of these kinematic results for validation purposes.

The researcher is reliable for marker placement and it can therefore it can be assumed that when interpreting kinematic results of the sagittal and coronal plane variables in the FMS validation process, these will be a reliable measurement of the movements being undertaken by the participant. Furthermore any inter and intra-subject kinematic differences may more confidently be attributed to actual differences in the participant and not marker placement error.

5 OPERATIONALISATION OF THE FUNCTIONAL MOVEMENT SCREEN (FMS) EXERCISE TESTS

Rules for the FMS and associated scoring criteria are taken from the FMS level one manual (version four) provided to the researcher on attendance of the FMS training course (Functional Movement systems and Gray Cook 2012). For the processes of validation, the original principles of the FMS has been evaluated given that they underpin the existing FMS framework and have been used for informing the existing literature.

5.1 Introduction

As identified in the literature review, the FMS is a screening tool, introduced in 1998 with the original purpose of rating and ranking movement patterns in high school athletes (Functional Movement Systems and Gray Cook 2012). It has since been used as an assessment tool for athletes of varying ability and within multiple sporting disciplines such as soccer (McCall et al 2015) and American football (Kiesel 2007). It has also been used to assess professionals in dangerous occupations such as those in military service (O'Connor et al 2011). The final score from the FMS has been used for determining injury risk and informing injury prevention programs (Kiesel 2007). Previous research has identified that people who score 14 or less, have an 11 fold increase of sustaining an injury that will result in them missing three or more weeks of participation (Kiesel 2007). (Reasons for selection the FMS have been discussed in Chapters 1 and 2).

The FMS Exercise tests, Clearing tests and scoring processes

The FMS is comprised of seven exercise tests namely the Deep Squat, Hurdle Step, Inline Lunge, Shoulder Mobility, Active Straight-Leg Raise, Trunk Stability Push-Up and Rotary Stability tests. These have been presented in figure 5.1. In order to carry out the FMS, testing equipment is required as presented in figure 5.2.

Figure 5.1 Exercise tests of the FMS

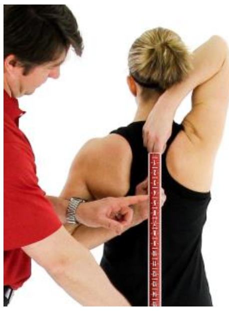
<table>
<tr><th colspan="4">Exercise tests</th></tr>
<tr><th>Deep Squat</th><th>Hurdle Step</th><th>Inline Lunge</th><th>Shoulder Mobility</th></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><th>Active Straight Leg Raise</th><th>Trunk Stability Push-Up</th><th colspan="2">Rotary Stability</th></tr>
<tr><td></td><td></td><td colspan="2"></td></tr>
</table>

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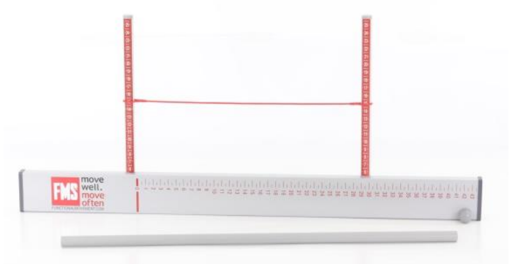
Figure 5.2 Equipment needed to carry out the FMS test

<table>
<tr><th>“FMS Test Kit”</th><th>“FMS Test Kit”</th></tr>
<tr><td>1. A four foot dowel rod
2. Two smaller dowel rods
3. A small capped piece
4. An elastic band</td><td>
</td></tr>
</table>

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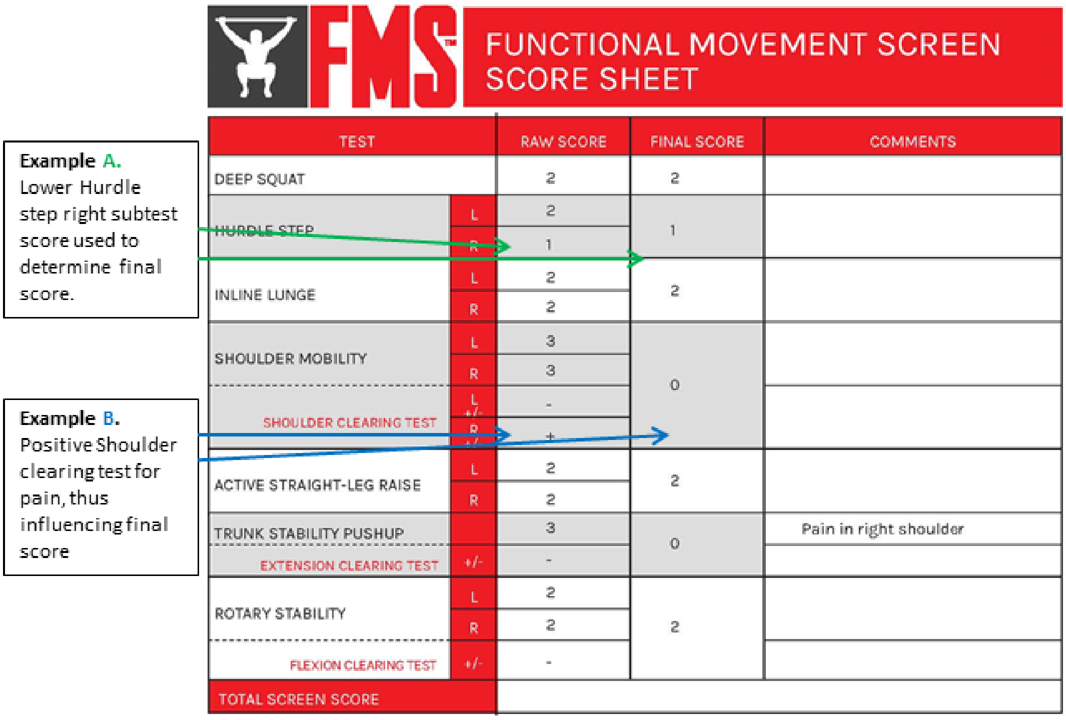
Each subtest test requires participants to perform movements according to standardised verbal instructions, unique to that subtest, for starting position and completing the movement. The score reflects the performance of the movement according to the criteria for that subtest. The criteria for each score is comprised of rules, for example in the Deep Squat test, the criteria for achieving the maximum score of three involves a rule in which the participant is required to keep their knee aligned over their foot. The assessor is required to observe if the participant is able to comply with the rule, alongside the other rules which make up the scoring criteria, and award a score based on their observation. The seven exercise tests are scored on what is reported as an ordinal scale ranging from zero to three, in which a score of:

- 0 is awarded if pain is present and reported at any point during the exercise test
- 1 is awarded if the participant is unable to perform the movement pattern
- 2 is awarded if the participant performs the pattern with compensation or imperfection
- 3 is awarded if the participant performs the pattern as directed (including meeting a list of prescribed performance criteria)

(Lloyd et al 2014)

Therefore, in order to score the highest possible score of a 3, all of the scoring criteria must be met by the participant. The actual number of exercise tests completed when performing the FMS ranges between 13 to 15 tests. This is based on the individual's performance of initial subtest requirements and tests which require evaluation for left and right. For each subtest, the participant is allowed three attempts in order to achieve the highest possible score. As per the FMS instructions to the assessor "*If the initial movement falls within the criteria for a score of three, there is no need to complete the remaining attempts*". This means that if the participant scores the highest possible score before the third attempt, that score is recorded and the testing stops. For all subtests scores (raw scores) and associated variations, the lowest score is used as the final score as per Example A figure 5.3

Figure 5.3 Adapted FMS score sheet demonstrating scoring processes



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Additionally, some of the exercise tests are informed by clearing tests, which are performed after the exercise tests (figure 5.4). The three clearing tests are the shoulder clearing test, spinal flexion clearing test and spinal extension clearing test. Each clearing test is associated with a specific exercise test i.e. following completion of the shoulder mobility exercise test the shoulder clearing test is then carried out. The clearing tests of spinal extension and flexion are associated with the Trunk Stability Push-Up and Rotary Stability exercise tests respectively. The three clearing tests have a dichotomous outcome of pain or no pain and are scored on a nominal scale. Despite the dichotomous outcomes of the clearing tests, they can influence the final score. For example, a participant scoring three for both left and right on the Shoulder Mobility exercise test, who then has pain on the shoulder clearing test would have a final score of zero as per example B figure 5.3 (Functional Movement Systems and Gray Cook 2012).

Figure 5.4 Clearing tests of the FMS

Clearing Tests		
Shoulder clearing test	Spinal extension clearing test	Spinal flexion clearing test
		
Associatted exercise test: Shoulder Mobility	Associatted exercise test: Trunk Stability Push-Up	Associatted Exercise test: Rotary Stability

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Validation of the FMS Rules

In order to validate the rules of the exercise tests, the test movements and thresholds that make up the scoring criteria had to be quantified. For example, in the Deep Squat test (5.1.1) as per the FMS handbook (Functional Movement Systems and Gray Cook 2012), there are five rules/ scoring criteria that the assessor must consider. However, when validating the test (quantifying the movement and rules) there are in reality 11 variables which the assessor must consider when scoring the participant in order to capture all the requirements of the descriptor. The variable identification process allows for the real-time assessor awarded score to be compared retrospectively against the objective measures taken by the 3D motion capture system as a part of the validation process. For the purpose of this study only the seven exercise tests were validated against the photogrammetric system. This was carried out as they are scored on an ordinal scale in which the assessor is required to award a score based on their observation and interpretation of the whole movement. The FMS screening was carried out by an experienced certified FMS assessor, a professional, who has used the FMS in clinical practice, professional football, and undergone training and accreditation through Functional Movement Systems in the use of the FMS (Appendix XIV).

Prior to commencing the test, participants completed a warm up familiarising themselves with all the exercise tests. This was completed a minimum of two times and up until they felt they had sufficiently practised the test. The FMS testing procedure was then carried out, following completion of the measurements and marker placement, with the participants barefooted. The testing protocol and instructions were the same as those stipulated from the FMS handbook except the following adaptations:

1. Participants were required to complete all three attempts for each test and on each side where appropriate.
2. Participants were required to complete the overhead squat (all three attempts) without the heel raise initially and again with the heel raise.
3. As per the FMS instructions, the highest score achieved was documented for that movement task. This was unless a lower score was achieved on the opposite side in which case that was taken as the final score.
4. The left side was tested first on each test.

For this study the official "FMS Test Kit" was not used. The testing equipment used in this study met the handbook requirements as stated above. A box measuring 50mm x100mm was used in place of the *"2x6"* box described in the scoring criteria (a box measuring 2 inches x 6 inches (50.8mm x 152.4mm). The height of the box used in this study was similar to the official "FMS Test Kit" (50mm compared to 50.8mm). Therefore it would not affect the tests in which it was used; Deep Squat, Inline Lunge and Active Straight-Leg Raise tests. The width of the box is used in the in line lunge test to provide a base for standing and positioning of the feet. For this test the width of the box was greater than the width of any of the participant's feet and therefore would not have affected the test. In the Rotary Stability test, the width of the box is used for placement of the upper and lower limbs at the start of the test. However for the validation process, the anatomical markers of the participants were used and any levels of tolerance set were larger than the difference in box width. Therefore for this study, the equipment used met the standard described in the handbook and any difference in size between the "FMS Test Kit" and the one used in this study would have minimal impact on the validation processes.

The order of the FMS tests carried out was:

1) **Deep Squat** *(Exercise test)*
    a. No heel raise
    b. With heel raise
2) **Hurdle Step** *(Exercise test)*
    a. Left
    b. Right
3) **Inline Lunge** *(Exercise test)*
    a. Left
    b. Right
4) **Shoulder Mobility** *(Exercise test)*
    a. Left
    b. Right
5) **Shoulder Mobility** *(Clearing test)*
    a. Left
    b. Right
6) **Active Straight-Leg Raise** *(Exercise test)*
    a. Left
    b. Right
7) **Trunk Stability Push-Up** *(Exercise test)*
8) **Spinal extension** *(Clearing test)*
9) **Rotary Stability** *(Exercise test)*
    a. Unilateral repetition
        i. Left
        ii. Right
    b. Diagonal repetition
        i. Left
        ii. Right
10) **Spinal flexion** *(Clearing test)*

Convention system used (reminder for reader)

For a full description of the lab orientation and convention system see section 3.1.1. Movement occurring along the following axes corresponded to these movements.

- Movement along the X axis - medial/lateral.
- Movement along the Y axis - anterior/posterior.
- Movement along the Z axis - superior/inferior.

5.1.1 Deep Squat (heel raise and no heel raise)

This subtest has two subtest variations

1. **Deep Squat no heel raise –** In the deep squat test, the first three attempts are carried out with no heel raise.
2. **Deep Squat with heel raise -** If the participant was unable to meet all of the criteria needed to score a three in the Deep Squat with no heel raise subtest, the starting position was modified by placing a 50 mm x 100 mm box under the heels as per the FMS instructions.

Apart from this variation in the Deep Squat with heel raise subtest, the starting position, verbal instructions and scoring criteria are the same as described below. The starting position description and verbal instructions are taken from the FMS handbook and have been italicised for all subtests.

Starting Position

Instep of the feet (medial malleoli) in vertical alignment with the outside of the shoulders.

Feet in sagittal plane with no lateral outturn of the toes. Participant rests dowel on top of the head to adjust the hand position, resulting in the elbows at a 90 degree angle. Participant presses the dowel overhead with the shoulders flexed and abducted and the elbows fully extended.

Verbal instructions

Please let me know if there is any pain while performing the following movement.

- *Stand tall with your feet approximately shoulder width apart toes pointing forward.*
- *Grasp the dowel in both hands and place it horizontally on top of your head so your shoulders and elbows are at 90 degrees.*
- *Press the dowel so that it is directly above your head.*
- *While maintaining an upright torso and keeping your heels and the dowel in position, descend as deep as possible.*
- *Hold the descend position for a count of one, then return to the starting position.*
- *Do you understand the instructions?*

Figure 5.5 Scoring Criteria for the Deep Squat test (no heel raise and heel raise)

3

Upper torso is parallel with tibia or towards vertical | Femur below horizontal
Knees aligned over feet | Dowel aligned over feet

2

Upper torso is parallel with tibia or towards vertical | Femur below horizontal
Knees aligned over feet | Dowel aligned over feet | Heels are elevated

1

Tibia and upper torso are not parallel | Femur is not below horizontal
Knees are not aligned over feet | Dowel is not aligned over feet

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Validation of the Deep Squat scoring criteria

Based on the description of the test, instructions given to the participant and scoring criteria, it was identified that the FMS requires the assessor to consider 11 variables for the FMS Deep Squat test (table 5.1)

Table 5.1 Operationalisation of the FMS Deep Squat test rules

Deep Squat		
FMS rules	**Number of variables for consideration in real-time by the assessor**	**Flag №**
Upper torso is parallel with tibia or towards vertical	1. Thorax inclination angle must be less than the tibial inclination angle	1[1]
Femur below horizontal	2. Left femur angle must be greater than 90 degrees horizontal to the coronal plane at peak knee flexion 3. Right femur angle must be greater than 90 degrees horizontal to the coronal plane at peak knee flexion	2[1] 3[1]
Knees aligned over feet	4. Left knee joint centre does not exceed medial and lateral borders of the foot in the coronal plane. 5. Right knee joint centre does not exceed medial and lateral borders of the foot in the coronal plane.	4[1] 5[1]
Dowel aligned over feet	6.Left dowel position (forwards) does not exceed anterior foot border in the sagittal plane 7.Left dowel position (backwards) does not exceed heel position in the sagittal plane 8.Right dowel position (forwards) does not exceed anterior foot border in the sagittal plane 9.Right dowel position (backwards) does not exceed heel position in the sagittal plane	6[1] 7[1] 8[1] 9[1]
Keeping your heels in position	10.Left heel displacement must not exceed 5mm vertically 11.Right heel displacement must not exceed 5mm vertically	10[1] 11[1]

In order to operationalise the rules of the FMS, quantified thresholds for objective measures of performance needed to be determined. The justification and methodology for selection of threshold values have been presented as a chapter in the appendices (Appendix XV)

In order to ensure all 11 variables were assessed, 11 flag conditions were used to quantify and evaluate the 11 variables identified. A flag is a condition parameter i.e. a dichotomous variable of two values in which, 1 = condition not met, 0 = condition met.

Therefore when scoring, the Deep Squat test (with and without heel raise) requires the assessor to consider 11 variables throughout the movement. The score awarded at the time of testing was compared with the quantitative measures taken using the VICON and automated thresholds used in analysing the movements. Therefore if a participant was awarded a score of three on the FMS scale, when compared to the quantitative measures, all of the 11 flag conditions should have been met on the Deep Squat with no heel raise subtest. If a participant was awarded a score of two on the FMS scale, when compared to the quantitative measures, not all of the 11 criteria should have been met on the Deep Squat with no heel raise subtest. If a score of one was awarded on the FMS scale, a minimum of one of the scoring criteria variables should not have been met with the Deep Squat with heel raise subtest.

The scoring criteria and thresholds of the FMS Deep Squat test were quantified using the methods described below. In the flag condition below, 1 indicates this as the first flag condition; the superscript ^{1} indicates this as the first FMS subtest, which in this case, is the FMS Deep Squat. This is therefore the first flag condition of the first FMS subtest. This has been applied to all of the operationalised rules of the FMS.

Flag condition(s) : **1^{1}**

Variable number(s) : **1**

FMS rule : **Upper torso is parallel with tibia or toward vertical**

For each attempt:

i. The peak knee flexion angle was identified for left and right.
ii. The left and right peak knee flexion angles were compared. The side with a larger peak knee flexion angle was used alongside the time at which peak knee flexion was achieved.
iii. The peak left and right tibial inclination angles were compared. The side with a larger tibial inclination angle and value was used for the comparison against the thorax inclination angle at the previously identified time point.
iv. At the time point, identified in the previous step, the thorax inclination angle was compared with the larger of the tibial inclination angles. If the thorax inclination angle was less than or equal to the tibial inclination angle, the upper torso was considered to have been parallel with the tibia or towards vertical. Thus meeting the condition.

Flag condition(s) **: 2[1], 3[1]**

Variable number(s) **: 2, 3**

FMS rule **: Femur is below horizontal**

For each attempt and for both left and right:

i. The angle of the femur relative to the horizontal axis was calculated throughout the trial.

ii. If the maximum angle of the femur relative to the horizontal axis was greater than 90 degrees, the femur was considered to be below horizontal, thus meeting the condition.

Flag condition(s) **: 4[1], 5[1]**

Variable number(s) **: 4, 5**

FMS rule **: Knees aligned over feet**

For each attempt and for both left and right

i. Two vertical planes were created to define the projected boundaries of the foot.

ii. The medial border passed through two points, 50mm medial to the heel and toe markers (labelled as TOE and HEE in the Plug-in Gait model)

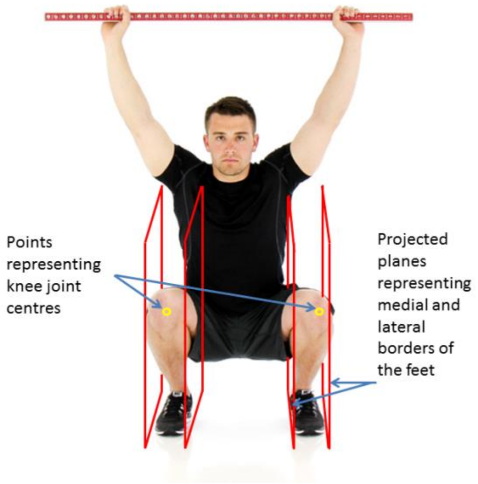
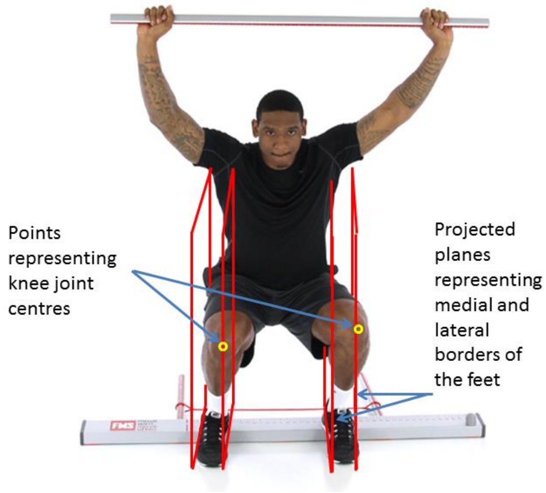
iii. The lateral plane was parallel to this but passing through the lateral ankle marker (labelled as ANK in the Plug-in Gait model).

iv. Both planes contained the lab vertical Z-axis.

v. The distance of the knee joint centre (labelled as FEO in the Plug-in Gait model) relative to the planes defining the medial and lateral borders of the foot was calculated throughout the test.

vi. If the knee joint centre went outside of the planes defining the medial and lateral border of the foot. The knee was considered to have not been aligned over the foot, thus not meeting the condition (figure 5.6).

Figure 5.6 Examples of the knee joint centres relative to the projected planes (defining the medial and lateral borders of the feet), meeting and not meeting the condition

<table>
<tr>
<td>Knee joint centre remains within projected planes defining the borders of the foot, thus meeting the condition</td>
<td>Knee joint centre not remaining within projected planes defining the borders of the foot, thus not meeting the condition</td>
</tr>
<tr>
<td>
</td>
<td>
</td>
</tr>
</table>

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Flag condition(s) **: 6^{1}, 7^{1}, 8^{1}, 9^{1}**

Variable number(s) **: 6, 7, 8, 9**

FMS rule **: Dowel aligned over feet**

For each attempt and for both left and right

i. The finger markers (labelled as FIN in the Plug-in Gait model) were used to measure the position of the dowel. The anterior and posterior displacement was determined by the global Y co-ordinates of the finger markers.
ii. The global Y co-ordinates of the toe markers were identified (labelled as TOE in the Plug-in Gait model) and used to determine the anterior border of the feet. The anterior border made up by the RTOE and LTOE was then translated anteriorly another 40mm to reflect the position of the toes.
iii. This acted as the anterior limit of where the bar had to remain in order to meet the criteria of staying aligned over the feet.
iv. The Y co-ordinates of the heel markers (labelled as HEE in the Plug-in Gait model) were identified for the RHEE and LHEE.
v. The Y co-ordinates of the HEE markers were used to determine the posterior border of the feet. This acted as the posterior limit of where the bar had to remain in order to meet the criteria of staying aligned over the feet.

Flag condition(s) **: 10^{1}, 11^{1}**

Variable number(s) **: 10, 11**

FMS rule **: "Keeping your heels… in position"**

For each attempt and for both left and right:

i. The height of the heel marker (labelled as HEE in the Plug-in Gait model) was identified at the start of the attempt. (Z co-ordinates of the marker in the global frame)
ii. The height of the heel marker relative to its starting position was calculated throughout the trial.
iii. If the heel marker position increased by 5mm or more from its starting height, the heel was considered to have exceeded the elevation threshold, thus not meeting the condition.

5.1.2 Hurdle Step

Starting position

Participants' tibial height is measured from the bony landmark of the tibial tuberosity to the floor.

The participant will stand with the outside of the right foot against the base of the hurdle, in line with one of the hurdle uprights. Adjust the hurdle to the relevant height. Participant standing directly behind the centre of the hurdle base, feet touching at both heels and toes and with the toes aligned and touching the base of the hurdle.

Verbal instructions

Please let me know if there is any pain while performing the following movement.

- *Stand tall with your feet together and toes touching the test kit.*
- *Grasp the dowel with both hands and place it behind your neck and across the shoulders.*
- *While maintaining an upright torso, raise the leg and step over the hurdle, making sure to raise the foot towards the shin and maintaining foot alignment with the ankle, knee and hip.*
- *Touch the floor with the heel and return to the starting position while maintaining foot alignment with the ankle, knee, and hip.*
- *Do you understand the instructions?*

This was completed for both the left and right legs. The score is recorded as the leg that is used to step over the hurdle (moving leg).

Figure 5.7 Scoring Criteria for the Hurdle Step test

3

Hips, knees and ankles remain aligned in the sagittal plane
Minimal to no movement is noted in lumbar spine | Dowel and hurdle remain parallel

2

Alignment is lost between hips, knees and ankles | Movement is noted in lumbar spine
Dowel and hurdle do not remain parallel

1

Contact between foot and hurdle occurs | Loss of balance is noted

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Validation of the Hurdle Step scoring criteria

Based on the description of the test, instructions given to the participant and scoring criteria, it was identified that the FMS requires the assessor to consider 16 variables for the FMS Hurdle Step test rules (table 5.2).

Table 5.2 Operationalisation of the FMS Hurdle Step test rules

Hurdle step		
FMS rules	**Number of variables for consideration in real-time by the assessor**	**Flag №**
Hips, knees and ankles remain aligned in the sagittal plane	1. Moving limb – Hip joint – pure flexion /extension at the joint with no rotation or abduction/adduction allowed 2. Moving limb - Knee joint - pure flexion /extension at the joint 3. Moving limb – Ankle joint/foot position – pure plantar flexion/dorsiflexion with no inversion/eversion allowed	1^2
	4. Stabilising limb - Hip joint – pure flexion /extension at the joint with no rotation or abduction/adduction allowed 5. Stabilising limb - Knee joint - pure flexion /extension at the joint 6. Stabilising limb - Ankle joint/foot position – pure plantar flexion/dorsiflexion with no inversion/eversion allowed	2^2
Minimal to no movement noted in the lumbar spine	7. Lumbar spine flexion/extension angle must not exceed 10 degrees 8. Lumbar spine rotation angle not exceed 10 degrees 9. Lumbar spine side flexion angle not exceed 10 degrees	3^2 4^2 5^2
*Based on review of the pictorial scoring criteria	10. Thorax inclination angle not exceed 10 degrees 11. Thorax rotation angle not exceed 10 degrees 12. Thorax side flexion angle not exceed 10 degrees	6^2 7^2 8^2
Dowel and Hurdle remain parallel	13. Dowel position remains parallel to the horizontal axis (Left and right hand position) not exceed 10 degrees difference	9^2
Loss of Balance	14. Loss of balance (episode where a participant is required to make contact with the floor to stop themselves falling over)	10^2
Contact between foot and hurdle occurs	15. Foot height higher than measured tibial height (to the test target) 16. Foot height higher than measured tibial height (from the test target)	11^2 12^2

To correctly be awarded the highest score of three in the Hurdle Step screening test, the participant is required to successfully meet all 12 flag conditions in at least one attempt. For the scoring category of two, not all 12 flag conditions should be met in any attempt, for the participant to be correctly assigned. In order to correctly be assigned to the category of one, the participant must meet the criteria associated with a score of one i.e. *contact between the foot and hurdle, and a loss of balance* (flag conditions 10^2, 11^2 or 12^2). Therefore, any participant within scoring categories two or three should not have consistently failed the identified criteria associated to the scoring category of one.

Flag condition(s) **: 1^2, 2^2**

Variable number(s) **: 1, 2, 3, 4, 5, 6**

FMS rule **: Hips, knees and ankles remain aligned in the sagittal plane**

For this rule, the same method as that used in the "**Knees aligned over feet"** rule of the Deep Squat test was implemented. This was done for each attempt, and for both the moving and static limbs. If the limbs were not "aligned in the sagittal plane" it was identified that the knee joint centre would not be positioned over the foot. This would be resultant from abduction/adduction or rotational movements occurring proximally in the hip joint or a change in the position of the foot distally. Both of these would have an effect on the position of the knee joint centre in relation to the defined planes of tolerance. This method was used to validate scoring criteria one to six.

Flag condition(s) **: 3^2, 4^2, 5^2, 6^2, 7^2, 8^2**

Variable number(s) **: 7, 8, 9, 10, 11, 12**

FMS rule **: Minimal to no movement noted in the lumbar spine**

For each attempt:

i. The angle of the lumbar spine was identified at the start of the attempt for the sagittal, coronal and transverse planes. Movement occurring in these planes represented flexion, side flexion and rotation respectively.
ii. The angle relative to its starting position was calculated throughout the trial in all three planes.
iii. If the angle exceeded 10 degrees or more from its starting angle in any of the planes, it was considered that the movement threshold was exceeded. Thus not meeting the condition.

The same method and process was repeated for the thorax angles with relation to the lab co-ordinate system. Movement of the thorax was selected as a scoring determinant in the quantified variables as despite not being stated in the written criteria, on review of the pictorial scoring criteria (figure 5.7), it can be argued that the criteria demonstrates thorax movement as a violation of the rules.

Flag condition(s) **: 9**[2]

Variable number(s) **: 13**

FMS rule **: Dowel and Hurdle remain parallel**

For each attempt:

i. The finger markers (labelled as FIN in the Plug-in Gait model) were used to measure the position of the dowel.

ii. A third virtual marker was created. This was done using the X and Y co-ordinates of the right finger marker (labelled as RFIN in the Plug-in Gait model) and the Z co-ordinates of the left finger marker (LFIN)

iv. The angle between the markers was calculated. If the angle was greater than 10 degrees or more, it was considered that the dowel was not parallel to the hurdle and that the movement threshold was exceeded, thus not meeting the condition.

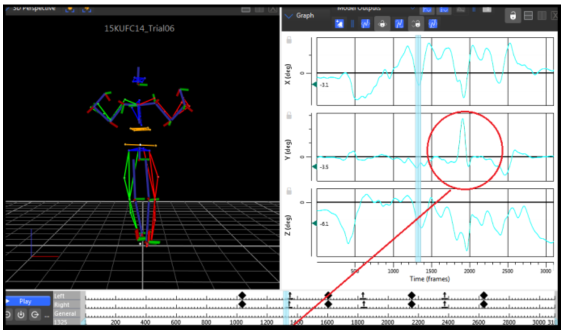
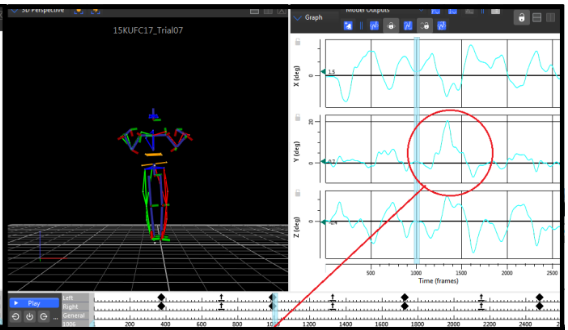
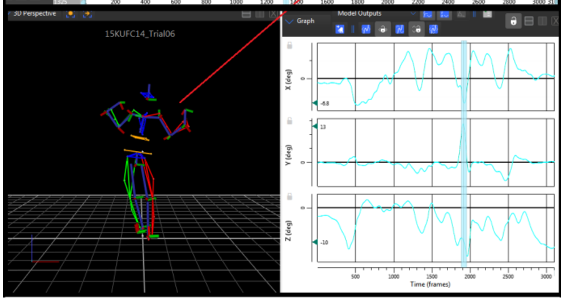
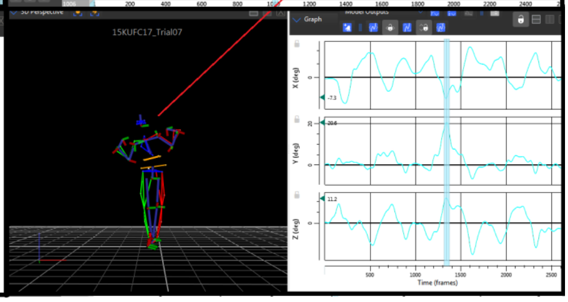
Flag condition(s) **: 10**[2]

Variable number(s) **: 14**

FMS rule **: Loss of Balance**

This rule was evaluated by a retrospective visual assessment carried out by the assessor. A loss of balance was defined as an episode in which the participant was required to use their moving limb to stop them from falling over. This was usually identified alongside an increase in the lateral tilt of the thorax segment (figure 5.8).

Figure 5.8 Episodes demonstrating loss of balance (LOB)

	Participant 15KUFC14	Participant 15KUFC17
Prior to LOB		
LOB		

Flag condition(s) **: 11[2], 12[2]**

Variable number(s) **: 15, 16**

FMS rule **: Contact between foot and hurdle occurs**

For each attempt and for left and right:

i. The height of the heel marker (labelled as HEE in the Plug-in Gait model) was identified by the Z co-ordinates of the marker in the global axis.

ii. The height of the heel marker calculated throughout the trial.

iii. The heel elevation threshold was determined by the measured height of the participant's tibial tuberosity.

iv. If the maximum heel marker height was less than the elevation threshold, it was considered that the participant was unable to clear the height of the hurdle, thus not meeting the condition.

5.1.3 Inline Lunge

Starting position

The participants' tibial height was measured from the bony landmark of the tibial tuberosity to the floor. *The participant placed the toe of their back foot at the start line on the kit. Using the tibial measurement, the heel of the front foot is placed at the distance indicated by the tibial length. The dowel is placed behind the back touching the head thoracic spine and sacrum. The participants hand opposite the front foot should be grasping the dowel at the cervical spine. The alternate hand grasped the dowel at the lumbar spine.*

Verbal Instructions

Please let me know if there is any pain while performing the following movement.

- *Step onto the 2x6 in this study (50 mm x 100 mm box) with a flat right foot and your toe on the zero mark.*
- *The front heel should be placed according to your tibial measurement*
- *Both toes must be pointing forward with flat feet.*
- *Place the dowel along the spine so it touches the back of your head, your upper back and the middle of the buttocks.*
- *While grasping the dowel, your right hand should be against the back of your neck and the left hand should be against your lower back.*
- *Maintaining an upright posture so the dowel stays in contact with your head, upper back and top of the buttocks descend into a lunge position so the right knee touches the 2x6 behind your left heel.*
- *Return to starting position.*
- *Do you understand the instructions?*

The front leg identifies the side being scored. The testing process was carried out with the left leg leading.

Figure 5.9 Scoring Criteria for the Inline Lunge test

3

Dowel contact maintained | Dowel remains vertical | No torso movement noted
Dowel and feet remain in sagittal plane | Knee touches board behind heel of front foot

2

Dowel contact not maintained | Dowel does remain vertical
Movement noted in torso | Dowel and feet remain do not remain in sagittal plane
Knee does not teach board behind heel of front foot

1

Loss of balance is noted | Inability to complete movement pattern

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Validation of the Inline Lunge

Based on the description of the test, instructions given to the participant and scoring criteria, it was identified that the FMS requires the assessor to consider 14 variables for the FMS Inline Lunge test rules (table 5.3).

Table 5.3 Operationalisation of the FMS Inline Lunge test rules

Inline Lunge		
FMS rules	**Number of variables for consideration in real-time by the assessor**	**Flag №**
Dowel contact maintained - head, thorax and sacrum Dowel remains vertical	1. Dowel contact maintained with head 2. Dowel contact maintained with thorax 3. Dowel contact maintained with pelvis 4. Dowel remains vertical	1^3 $2^3 + 3^3$
No torso movement noted	5. Thorax inclination angle 6. Thorax rotation angle 7. Thorax side flexion angle 8. Dowel remains aligned with laboratory sagittal plane (repetition of 4.)	4^3 5^3 6^3 (3^3)
Dowel and feet remain in sagittal plane	9. Front foot position remains unchanged from its starting position. Starting position in which it is aligned with the sagittal plane of the laboratory 10. Back foot remains unchanged from its starting position in which it is aligned with the sagittal plane of the laboratory	$7^3 + 8^3$ $9^3 + 10^3$
Knee touches board behind heel of front foot	11. 12. Knee touches board behind heel of front foot 11. Rear leg knee joint centre below front leg ankle joint centre 12. Rear leg knee touches front heel	11^3 12^3
"Feet flat"	13. Front foot remains flat	13^3
"Loss of balance noted"	14. Loss of balance noted	14^3

For this test, the participant is required to meet 14 flag conditions required for the highest score of three. For the scoring category of two, not all 14 flag conditions should be met in any attempt. In order to correctly be assigned to the category of one, the participant must meet the criteria associated with a score of one i.e. *loss of balance and inability to complete movement pattern* (14^3). There are no parameters which determine "*inability to complete movement pattern"* and so it cannot used as a classifier.

Within this test it was identified that the rules as articulated by the FMS had:

- Repetition between rules
- More than one component associated with a single rule
- A lack of clearly defined requirements

An example of repetition between rules was identified between the rules of:

a) **"Dowel remains vertical"** and **"Dowel and feet remain in sagittal plane"**
b) **"Dowel contact maintained"** and **"No torso movement"**

For case a) if the dowel were to lose alignment with the sagittal plane, it could be considered that the dowel was no longer vertical.

For case b) it was identified that if torso movement were to occur (thorax inclination), this would likely result in a loss of contact with the dowel and one of the required segments (head or sacrum). Additionally it could be considered that the dowel was no longer vertical. As a result of the overlap between rules, more than one of the FMS rules could be addressed by one of the validation steps in some cases.

An example of a rule with more than one component and lacking clearly defined requirements was:

11. **Knee touches board behind heel of front foot**

This rule is comprised of two main parts

1. Knee touches board <u>behind heel of front foot</u> - The ability of the participant to maintain the position of the rear leg in relation to the front foot.
2. <u>Knee touches board</u> behind heel of front foot - The ability of the participant to lower the knee of the rear leg enough to touch the board.

From the scoring criteria and pictorial representation (figure 5.9), it is not clear if

a) Rear leg position should be maintained throughout the whole attempt, or
b) If it is only necessary for the point at which the rear knee touches the board behind the leading foot.

In instances where multiple components were identified within a single rule, each component was evaluated seperately. For rules that lacked clarity around the requirements, each feasible interpretation was evaluated. Fourteen flag conditions were used to account for the 13 variables identified. The scoring criteria and thresholds of the FMS Inline Lunge test were quantified using the methods described below.

Flag condition(s) **: 1**[3]

Variable number(s) **: 1, 2, 3, 4**

FMS rule **: Dowel contact maintained - head, thorax and sacrum**

For this one rule, the test requires the assessor to observe three separate segments and their relationship to the dowel. For the validation of this rule, the three segments were analysed individually or as a part of another rule due to the previously described overlap between rules.

For each attempt:

i. The starting angle of the cervical spine was identified at the start of the attempt for the sagittal plane.
ii. The angle relative to its starting position was calculated throughout the trial in all three planes.
iii. If the angle exceeded 10 degrees or more from its starting angle in any of the planes, it was considered that the movement threshold was exceeded. Thus not meeting the condition.

If the neck flexion angle identified above, exceeded the 10 degree movement threshold it was considered that

- The head had lost contact with the bar and therefore not meeting the condition or
- If contact with the dowel had been maintained at the head a loss of contact elsewhere at the sacrum or thorax would have occurred.
- Torso movement was evaluated in the **"No torso movement"** rule

Flag condition(s) **: 2[3], 3[3]**

Variable number(s) **: 2, 3, 4**

FMS rule **: Dowel remains vertical**

For each attempt:

i. The finger markers (labelled as FIN in the Plug-in Gait model) were used to measure the position of the dowel.
ii. The angle of the dowel relative to the vertical axis was calculated throughout the trial.
iii. If the angle was greater than 20 degrees or more, it was considered that the dowel was not vertical.

The angle threshold was increased from 10 degrees (used in previous validation steps) to 20 degrees to account for the offset that would naturally occur as a result of the finger marker placement.

Due to the requirements of the test, some people may have been unable to get the dowel into a vertical position. Therefore, in addition to the previous validation step, it was investigated if the dowel position changed more than 10 degrees from the start of the test.

For each attempt:

i. The finger markers (labelled as FIN in the Plug-in Gait model) were used to measure the position of the dowel.
ii. The angle of the dowel relative to the floor was calculated at the start of the trial.
iii. The angle of the dowel relative to the floor was calculated throughout the trial.
iv. If the angle of the dowel was greater than 10 degrees from its original starting position, it was considered that the dowel was not vertical, thus not meeting the condition.

Flag condition(s) **: 4^3, 5^3, 6^3**

Variable number(s) **: 5, 6, 7**

FMS rule **: No torso movement noted**

For each attempt:

i. The starting angle of the thorax segment was identified at the start of the attempt for the sagittal, coronal and transverse planes. Movement occurring in these planes represented inclination, side flexion and rotation respectively.
ii. The angle relative to its starting position was calculated throughout the trial in all three planes.
iii. If the angle exceeded 10 degrees or more from its starting angle in any of the planes, it was considered that the movement threshold was exceeded. Thus not meeting the condition.

Flag condition(s) **: 7^3, 8^3, 9^3, 10^3**

Variable number(s) **: 9, 10**

FMS rule **: Dowel and feet remain in sagittal plane**

Dowel in sagittal plane

This aspect of the rule was validated in the above step of "**Dowel remains vertical" (Flag condition 2 + 3, variable 4)**. If the dowel failed to remain vertical it was considered to no longer be aligned in the sagittal plane.

Feet in sagittal plane

Validation of this rule will be explained below as it forms part of the next rule. As a result the method used to validate this rule will be similar for the flowing rule.

Flag condition(s) : **11[3], 12[3]**

Variable number(s) : **11, 12**

FMS rule : **Knee touches board behind heel of front foot**

This rule is comprised of two main parts:

11. Knee touches board behind heel of front foot - The ability of the participant to maintain the position of the rear leg in relation to the front foot.
12. Knee touches board behind heel of front foot - The ability of the participant to lower the knee of the rear leg enough to touch the board.

Knee touches board behind heel of front foot

For this aspect of the rule and the "**Feet in sagittal plane"** rule, a similar method as that used in the "**Knees aligned over feet"** rule of the Deep Squat test was implemented, apart from the following changes. The leading foot defined the planes of tolerance, for both the front leg and rear leg knee joint centre.

From the scoring criteria and pictorial representation (figure 5.9), it is not clear if

a) The position of the rear leg relative to the front foot should be maintained throughout the whole attempt, or
b) If it is only necessary for the point at which the rear knee touches the board behind the leading foot

Therefore both instances were evaluated.

For each attempt - instance a) a similar method as that used in the "**Knees aligned over feet"** rule of the Deep Squat test was implemented as described above.

For the rule **"feet in sagittal plane ",** it was identified that if the position of the feet changed the knee would not be aligned over the feet. Likewise any abduction/adduction or rotational movement occurring proximally in the hip joint would effect on the position of the knee joint centre in relation to the defined planes of tolerance.

For each attempt - instance b) a similar method as that used in instance a) and the "**Knees aligned over feet"** rule of the Deep Squat test was implemented apart from the following changes.

i. The projected planes of tolerance were established as previously described.
ii. The minimum distance between the leading foot heel marker (labelled as HEE in the Plug-in Gait model) and the rear leg knee joint centre (FEO) was calculated for each attempt. The time point at which the minimum distance occurred was identified.
iii. At this time point, the distance of the knee joint centre for both the leading and rear legs (labelled as FEO in the Plug-in Gait model) relative to the planes defining the medial and lateral borders of the foot was calculated.
iv. If either knee joint centre went outside of the planes defining the medial and lateral border of the foot. The knee was considered to have not been aligned over the foot, thus not meeting the condition.
v. Additionally if the distance between the heel and knee joint centre marker was greater than the predetermined level of tolerance of 100mm. The knee was considered not to have been within touching distance of the heel, therefore not meeting the criteria.

<u>Knee touches board</u> behind heel of front foot

For each attempt

i. The height of the leading leg ankle joint centre was identified at the start of the attempt. This was determined by the global frame Z co-ordinates of the virtual ankle joint centre marker (labelled as TIO in the Plug-in Gait model).
ii. The minimum height of the knee joint centre was calculated. This was determined by the global frame Z co-ordinates of the virtual knee joint centre marker (labelled as FEO in the Plug-in Gait model).
iii. If the minimum knee joint centre height at the lowest point was less than the initial ankle joint centre, the rear leg was considered to have touched the board, thus meeting the condition.

Flag condition(s) **: 13**[3]

Variable number(s) **: 13**

FMS rule **: "Feet flat"**

For each attempt:

i. The height of the leading leg heel marker (labelled as HEE in the Plug-in gait model) was identified at the start of the attempt. (Z co-ordinates of the marker in the global frame)

ii. The height of the heel marker relative to its starting position was calculated throughout the trial.

iii. If the heel marker position increased by more than 5mm from its starting height, the heel was considered to have exceeded the elevation threshold, resulting in the foot not being flat and thus not meeting the condition.

Flag condition(s) **: 14**[3]

Variable number(s) **: 14**

FMS rule **: "Loss of balance noted"**

For this rule, the same definition and method as that used in the Hurdle Step test "Loss of balance" rule was used.

5.1.4 Shoulder Mobility

Starting position

Participants hand length is determined by measuring the distance from the distal wrist crease to the tip of the longest digit. Participants were required to stand with their feet together. The participant was then then be asked to make a fist with each hand, thumbs inside the fingers.

Verbal instructions

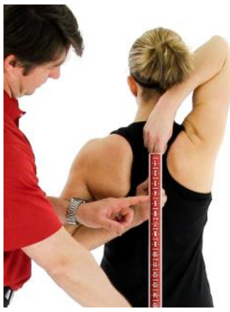
Please let me know if there is any pain while performing the following movement.

- *Stand tall with your feet together and arms hanging comfortably.*
- *Make a fist so your fingers are around your thumbs.*
- *In one motion, place the right fist over the head and down your back as far as possible while simultaneously taking your left fist up your back as far as possible.*
- *Do not "creep" your hands closer after the initial placement.*
- *Do you understand the instructions?*

The top shoulder identifies the side being scored i.e. hand behind head.

Figure 5.10 Scoring Criteria for the Shoulder Mobility test

3



Fists are within one hand length

2

Fists are within one and a half hand lengths

1

Fists are not within one and a half hand lengths

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Validation of the Shoulder Mobility test

Based on the description of the test, instructions given to the participant and scoring criteria, it was identified that the FMS requires the assessor to consider three variables for the Shoulder Mobility test rules (table 5.4).

Table 5.4 Operationalisation of the FMS Shoulder Mobility test rules

Shoulder Mobility		
FMS rules	**Number of variables for consideration in real-time by the assessor**	**Flag №**
In one motion / Do not “creep” your hands closer after the initial placement	1. Top shoulder – i.e. hand behind head – continuous movement	1^4
	2. Bottom shoulder – i.e. hand behind back – continuous movement	2^4
Minimal distance between the participants two hands	3. The minimal distance between the participants two hands	Scoring Variable check

For this test, the participant is required to meet three variables for the highest score of three. Two flag conditions were used to account for two variables. For the third variable, a score was generated with the photogrammetric system, based on the FMS criteria (minimal distance between hands) so that it could and compared with the real-time assessor score.

Flag condition(s) **: 1^4, 2^4**

Variable number(s) **: 1, 2**

FMS rule **: In one motion / Do not “creep” your hands closer after the initial placement**

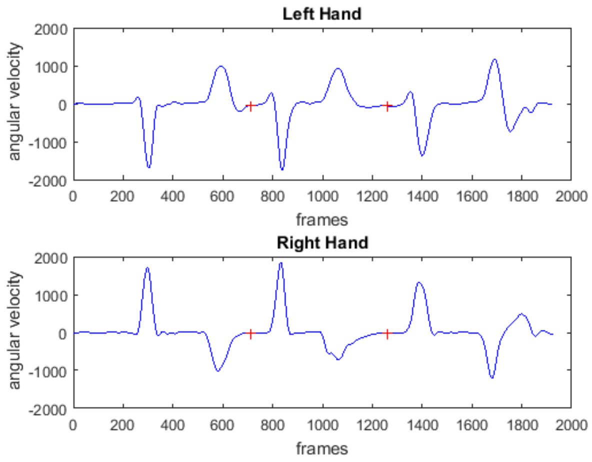
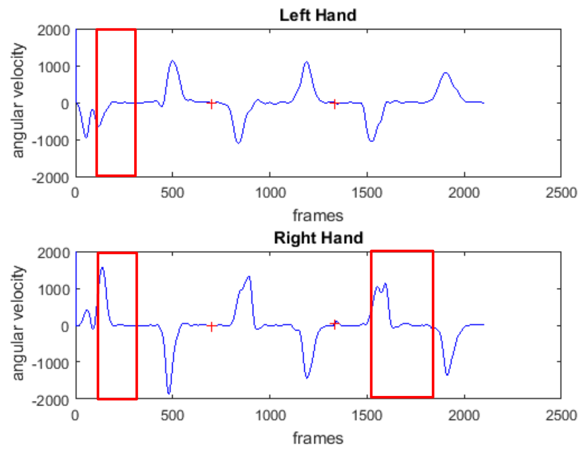
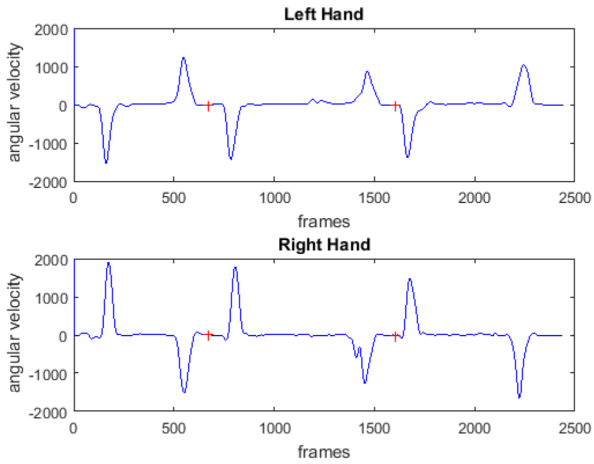
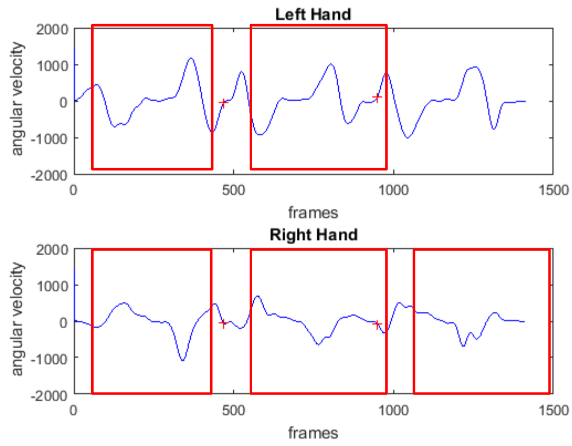
For each attempt and for left and right:

i. In order to assess of the movement was continuous, the velocity profile of the finger markers (labelled as FIN in the Plug-in Gait model) was plotted for each hand.

ii. These were then visually assessed to see if the participant’s hand moved in one motion for the attempt.

iii. If the assessor was unable to identify a single peak within the first part of the movement, or several peaks were evident, there was considered to be a break in the trajectory of the marker indicating that the movement was not continuous, thus not meeting the condition (figure 5.11)

Figure 5.11 Finger marker velocity graphs- Examples of continuous and discontinuous attempts

One continuous movement	Discontinuous movement - "double bump"
PARTICIPANT 15KUFC10  + end of attempt/ start of next attempt All three attempts successful for both hands	PARTICIPANT 15KUFC22  + end of attempt/ start of next attempt Attempt 1 for left and right unsuccessful Attempt 3 for right hand unsuccessful
PARTICIPANT 15KUFC08  + end of attempt/ start of next attempt All three attempts successful for both hands	PARTICIPANT 15KUFC05  + end of attempt/start of next attempt Attempt 1 and 2 unsuccessful for both hands Attempt 3 successful for left hand only

Flag condition(s) **: (scoring variable check)**

Variable number(s) **: 3**

FMS rule **: Minimal distance between hands**

As the outcome of this rule is not pass or fail, it was not treated as a flag outcome. This rule was used to retrospectively compare the real-time assessor score against the score that would be attributed if the VICON had been used for scoring.

For each attempt:

i. The minimal distance between the left and right finger markers was calculated (labelled as LFIN and RFIN in the Plug-in Gait model respectively).

ii. This distance was compared with the participant's hand length and a score was awarded based on the FMS criteria.

iii. This enabled the real-time score, awarded by the assessor, to be compared with the score awarded by the motion capture system i.e. the measurement of the assessor was compared with the quantified measurement.

iv. As per the FMS a score of

    a. Three was awarded if the minimal distance between hands was less than the participants hand length

    b. Two was awarded if the minimal distance between hands was greater than the participants hand length but less than one and a half hand lengths

    c. One was awarded if the minimal distance between hands was greater than or equal to one and a half hand lengths

5.1.4.1 Shoulder clearing test

Starting position

Participant stands with feet together.

Verbal instructions

Please let me know if there is any pain while performing the following movement.

- *Stand tall with your feet together and arms hanging comfortably.*
- *Place your left palm on your right shoulder.*
- *While maintaining palm placement, raise your left elbow as high as possible*
- *Do you feel any pain?*

The test is repeated on the right shoulder. The shoulder clearing test is not scored, however if pain is produced, a positive (+) is recorded on the score sheet, and a score of zero is given to the entire Shoulder Mobility test.

Figure 5.12 Scoring of the Shoulder clearing test

	**Clearing Test** Perform this clearing test bilaterally. If the individual does receive a positive score, document both scores for future reference. If there is pain associated with this movement, give a score of zero and perform a thorough evaluation of the shoulder or refer out.

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Validation of the Shoulder Mobility test

The clearing tests (shoulder, spinal flexion and spinal extension) were carried out as per the FMS protocol. No validation with the motion capture system took place as this would not provide any additional information to the outcomes of the clearing tests. The exercise tests have an ordinal scale in which the score is dependent on the assessor's interpretation of the movement. However the clearing tests have a dichotomous outcome (nominal scale) which is dependent on the participant.

5.1.5 Active Straight-Leg Raise

Starting Position

Participant lies supine with the arms by the sides, palms up and head flat on the floor.

The FMS box is placed under the knees. Both feet should be in a neutral position, the soles of the feet perpendicular to the floor.

Verbal instructions

Please let me know if there is any pain while performing the following movement.

- *Lay flat with the back of your knees against the 2x6 and your toes pointing up.*
- *Place both arms next to your body with the palms facing up.*
- *Begin with feet together in a neutral position*
- *With the scoring leg remaining straight and the back of the opposite knee maintaining contact with the 2x6,raise your scoring leg as high as possible.*
- *Do you understand the instructions?*

The moving limb identifies the side being scored. The test is repeated on the alternate side.

Figure 5.13 Scoring criteria for the Active Straight-Leg Raise

3

Vertical line of the malleolus resides between mid-thigh and ASIS
The non-moving limb remains in a neutral position

2

Vertical line of the malleolus resides between mid-thigh and joint line
The non-moving limb remains in a neutral position

1

Vertical line of the malleolus resides below the joint line
The non-moving limb remains in a neutral position

Validation of the Active Straight-Leg Raise

Based on the description of the test, instructions given to the participant and scoring criteria, it was identified that the FMS requires the assessor to consider 11 variables for the FMS Active Straight-Leg Raise test rules (table 5.5).

Table 5.5 Operationalisation of the FMS Active Straight-Leg Raise test rules

Active Straight-Leg Raise		
FMS rules	**Number of variables for consideration in real-time by the assessor**	**Flag №**
Maintaining the original starting position of the ankle and knee (moving limb and static limbs)	1. Moving limb knee flexion angle 2. Moving limb ankle plantarflexion angle	1^5 2^5
The non-moving limb remains in neutral position	3. Static limb hip flexion angle 4. Static limb hip abduction/adduction angle 5. Static limb hip rotation angle 6. Static limb knee flexion angle 7. Static limb ankle plantarflexion angle	3^5 4^5 5^5 6^5 7^5
Both feet should be in a neutral position, the soles of the feet perpendicular to the floor / Begin with the feet together in a neutral position	8. Moving limb foot position relative to the horizontal axis 9. Static limb foot position relative to the horizontal axis	8^5 9^5
Head remains flat on the floor	10. Head remains flat on the floor	10^5
Ankle position	11. Ankle position relevant to defined anatomical thresholds	Scoring variable

For this test, the participant is required to meet 11 variables for the highest score of three. Ten flag conditions were used to account for 10 variables related to the rules. For the 11th variable, a score was generated with the VICON, based on the FMS criteria (ankle position relevant to defined anatomical thresholds) so that it could and compared with the real-time assessor score. To be correctly assigned to the scoring category of three, the participant should have all 10 criteria successfully met and the score generated by the photogrammetric system should be equal to the real-time awarded score. It is not possible to identify if participants have been categorised correctly between scoring categories one and two due to the rule "*The non-moving limb remains in a neutral position"* (Flag conditions 3^5 to 7^5). This rule is present in all three categories and is therefore non-discriminatory. Whilst the participant's ability to meet all the required criteria may be used to check if they were correctly assigned to the scoring category of three, this is not possible for scoring categories one and two. It is only possible, for these cases, to check if the real-time assessor score is the same, or less than, the score awarded by the photogrammetric system based on ankle position.

Flag condition(s) **: 1^{5}, 2^{5}, 6^{5}, 7^{5}**

Variable number(s) **: 1, 2, 6, 7**

FMS rule **: Maintaining the original starting position of the ankle and knee (moving limb and static limbs)**

Knee (1^{5}, 6^{5})

For each attempt:

i. The angle of the knee was identified at the start of the attempt for the sagittal plane. Movement occurring in this plane represented knee flexion/extension.
ii. The flexion/extension angle relative to its starting position was calculated throughout the trial.
iii. If the angle exceeded 10 degrees from its starting angle, it was considered that the movement threshold was exceeded. Thus not meeting the condition.

The same process was used for the knee joint of the static/ non-moving limb in validation of the rule, the **non-moving limb remains in neutral position.**

Ankle (2^{5}, 7^{5})

For each attempt:

i. The angle of the ankle was identified at the start of the attempt for the sagittal plane. Movement occurring in this plane represented ankle plantarflexion/dorsiflexion.
ii. The plantarflexion/dorsiflexion angle relative to its starting position was calculated throughout the trial.
iii. If the angle exceeded 10 degrees from its starting angle, it was considered that the movement threshold was exceeded. Thus not meeting the condition.

The same process was used for the ankle joint of the static/ non-moving limb in validation of the rule, the **non-moving limb remains in neutral position.**

The non-moving limb remains in neutral position (Flag condition and variable numbers 3^5-7^5)

The starting positions of the hip, knee and ankle in the non-moving/static limb were used for validation of this rule. For the knee and ankle components, the same methods as those used in the moving limb were implemented.

Flag condition(s) : **3^5, 4^5, 5^5**

Variable number(s) : **3, 4, 5**

FMS rule : **The non-moving limb remains in neutral position (Hip)**

For each attempt:

i. The angle of the hip was identified at the start of the attempt for the sagittal, coronal and transverse planes. Movement occurring in these planes represented hip flexion/extension, adduction/abduction and external/internal rotation respectively.
ii. The angle relative to its starting position was calculated throughout the trial in all three planes.
iii. If the angle exceeded 10 degrees or more from its starting angle in any of the planes, it was considered that the movement threshold was exceeded. Thus not meeting the condition.

Flag condition(s) : **8^5, 9^5**

Variable number(s) : **8, 9**

FMS rule : **Both feet should be in a neutral position, the soles of the feet perpendicular to the floor / Begin with the feet together in a neutral position**

For this rule there is a discrepancy between:

i. The instruction to the assessor as stated in the test description, and
ii. The verbal instruction to the participant from the assessor.

The description "both feet should be in a neutral position, the soles of the feet perpendicular to the floor" indicates a specified position for the feet. However the verbal instruction to the participant "begin with the feet together in a neutral position" does not clearly stipulate the threshold for what is considered a neutral position and is therefore open to interpretation by the participant. Due to the lack of a clearly defined position from the verbal instructions, the instruction to the assessor from the description was evaluated.

For each attempt:

i. The ankle joint centre and toe markers were used to measure the position of the foot (labelled as TIO and TOE in the Plug-in Gait model respectively).
ii. The minimum angle of the foot relative to the floor in the sagittal plane, at the start of the attempt (defined as the first 100 frames or 1 second) was calculated.
iii. If the angle minimum angle was greater than 10 degrees, it was considered that the foot was not perpendicular to the floor at any point during the beginning of the test, thus not meeting the condition.

Flag condition(s) : 10[5]

Variable number(s) : 10

FMS rule : Head remains flat on the floor

This rule was evaluated by a retrospective visual assessment carried out by the assessor. If the participant lifted their head off the floor their head was no longer considered to remain flat on the floor thus not meeting the condition.

Flag condition(s) : **(scoring variable check)**

Variable number(s) : **11**

FMS rule : **Ankle position relevant to predefined anatomical thresholds**

As the outcome of this rule is not pass or fail, it was not treated as a flag outcome. This rule was used to retrospectively compare the real-time assessor score against the score that would be attributed if the VICON had been used for scoring.

For each attempt:

i. The moving limb markers identifying the ASIS and knee joint centre were identified at the start of the attempt (labelled ASI and KNE in the Plug-in Gait model respectively).
ii. At this time point, a virtual marker was created at the midpoint of the ASIS and knee joint centre markers (MID_THI).
iii. The global frame Y-coordinates of the mid-thigh and knee joint centre markers at the start of the attempt was used as the scoring thresholds.
iv. The position of the ankle marker (ANK) throughout the trial, relative to the mid-thigh and knee joint centre markers at the start of the attempt was measured.
v. This enabled the real-time score, awarded by the assessor, to be compared with the score awarded by the motion capture system as per the FMS scoring criteria.
vi. As per the FMS, a score of
    a. Three was awarded if the ankle marker resided between the virtual mid-thigh and ASIS markers
    b. Two was awarded if the if the ankle marker resided between the virtual mid-thigh and knee joint markers
    c. One was awarded if the if the ankle marker did not reside between the virtual mid-thigh and knee joint markers

5.1.6 Trunk Stability Push-Up

Starting position

Participant assumes prone position with the arms extended overhead. Males starting position is with thumbs placed at the top of the forehead. The knees are fully extended, the ankles are neutral and the soles of the feet are perpendicular to the floor.

Verbal Instructions

Please let me know if there is any pain while performing the following movement.

- *Lie face down with your arms extended overhead and your hands shoulder width apart (distal aspect of the thumbs in line with the AC joint).*
- *Pull your thumbs down in line with the forehead.*
- *With your legs together, pull your toes towards the shins and lift your knees and elbows off the ground.*
- *While maintaining a rigid torso, push your body as one unit into a push-up position.*
- *Do you understand the instructions?*

If the participant fails to complete the push up with hands in this position to score a 3, the thumbs are then aligned with the chin and the test sequence completed in an attempt to score a 2.

Figure 5.14 Scoring criteria for the Trunk Stability Push-Up

3

Men perform a repetition with thumbs aligned with the top of the head
Women perform with thumbs aligned with the chin
The body lift as a unit with no lag in the spine

2

Men perform a repetition with thumbs aligned with the chin
Women perform with thumbs aligned with the chin
The body lift as a unit with no lag in the spine

1

Men are unable to perform a repetition with thumbs aligned with the chin
Women are unable to perform with thumbs aligned with the chin

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Validation of the Trunk Stability Push-Up rules

Based on the description of the test, instructions given to the participant and scoring criteria, it was identified that the FMS requires the assessor to consider ten variables for the FMS Trunk Stability Push-Up rules (table 5.6).

Table 5.6 Operationalisation of the FMS Trunk Stability Push-Up test rules

Trunk Stability Push-Up		
FMS rules	**Number of variables for consideration in real-time by the assessor**	**Flag №**
Thumbs in line with forehead/ Hand position	1. Left hand position remains unchanged throughout attempts 2. Right hand position remains unchanged throughout attempts	1[6] 2[6]
The body lifts as a unit with no lag in the spine/ there should be no sway in the spine during the test	3. Thorax and pelvis start movement at the same time and move at a similar speed 4. No lumbar extension	3[6] 4[6]
Knees are fully extended	5. Left knee starts in extended position 6. Right knee starts in extended position	5[6] 6[6]
Ankles are neutral and the soles of the feet perpendicular to the floor / pull your toes towards your shins	7. Left foot position relative to the horizontal axis 8. Right foot position relative to the horizontal axis	7[6] 8[6]
Push up position	9. Left elbow extended at end of movement 10. Right elbow extended at end of movement	9[6] 10[6]

For this test, the participant is required to meet 11 variables for the highest score of three. Ten flag conditions were used to account for 10 variables related to the rules. In order to be correctly assigned to the scoring category of a 3 the participant is required to meet all 10 flag conditions. Therefore a participant would have been erroneously assigned to the scoring category of a three if one of the flag conditions had not been met when during the attempts where the thumbs are aligned with the top of the head. In order to be correctly assigned to the scoring category of a 2 the thumb position is changed to be in line with the chin and all 10 flag conditions should be met. In order to be correctly assigned to the scoring category of a 1 participant should not have met at least one of the 10 flag conditions when their thumbs are aligned with the chin.

Flag condition(s) : **1[6], 2[6]**

Variable number(s) : **1, 2**

FMS rule : **Thumbs in line with forehead/ Hand position**

For this test, the starting position (thumbs in line with the forehead) was standardised as per the FMS protocol. At the time of testing the position was checked by the assessor. However, as no markers were placed on the thumbs, it was not possible to retrospectively check thumb position relative to the forehead. Furthermore the marker set used for the head did not provide clear demarcations of the forehead. For validation, it was however possible to observe the position of the hands (finger markers) to see if they moved during the testing.

For each attempt and for both left and right:

i. The Y coordinates of the finger markers in the global frame was identified for each hand at the start of the attempt (labelled as FIN in the Plug-in Gait model).
ii. The Y coordinates of the finger markers in the global frame were then calculated throughout each attempt
iii. If the fingers moved more that 5mm from their starting position in the global Y axis (indicating anterior/posterior displacement) the thumbs were considered to have “lost alignment” (changed their position with reference to the forehead), thus not meeting the condition.

Flag condition(s) : **3[6], 4[6]**

Variable number(s) : **3, 4**

FMS rule : **The body lifts as a unit with no lag in the spine/ there should be no sway in the spine during the test**

It was identified that there are two components to this rule.

1. The thorax and pelvis segments should commence movement at the same time and absolute speed with relation to the lab.
2. There should be no extension in the lumbar spine throughout the movement.

<u>The body lifts as a unit</u> with no lag in the spine (3)

For each attempt:

i. The global frame Z coordinates of the C7 and posterior superior iliac spine (PSIS) markers located on the thorax and pelvic segment respectively, were identified.
ii. The speed of the markers was calculated throughout the attempt.
iii. It was reasoned that, as the task requires pushing with the upper limbs, it is likely that movement will occur in the proximal thorax segment first. Therefore the movement of the pelvis relative to the thorax was evaluated.
iv. The peak velocity was identified for the C7 marker.
v. For C7, the time at which ten percent of peak velocity was reached was used to identify the start of the movement.
vi. An additional two points were identified and plotted, 25 frames before and after the start of the movement (50 frames in total, equivalent to 0.5 seconds). These time points were used to set the levels of tolerance.
vii. The velocity profiles of the segments were plotted along with the additional.
viii. These were then visually reviewed by the assessor to determine if the body lifted as one unit, i.e. if the movement of the two segments was synchronous.
ix. The body was considered to have lifted as one unit if:

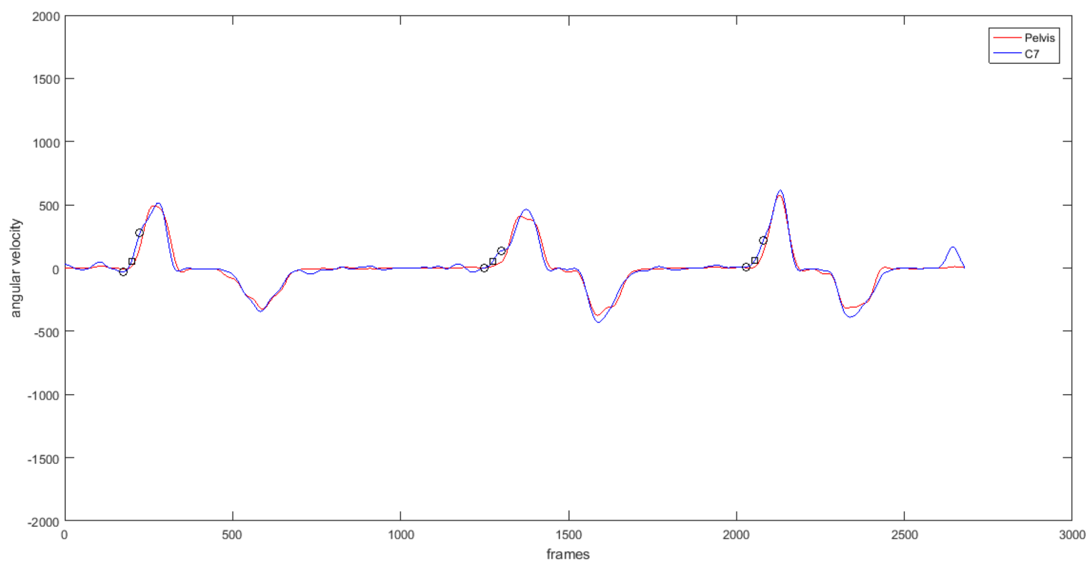
a. The pelvis segment was observed to have started moving within the 25 frames before or after the start of the thorax segment, and

b. The velocity profiles of both segments was similar i.e. the assessor was able to identify a single peak within the first part of the movement. If several peaks were evident there was considered to be a break in the trajectory of the marker indicating that the movement was not continuous, thus not meeting the condition as per the figures below (figure 5.15 and 5.16).

Figure 5.15 The velocity profiles of pelvis and thorax segments for flag condition 3[6]

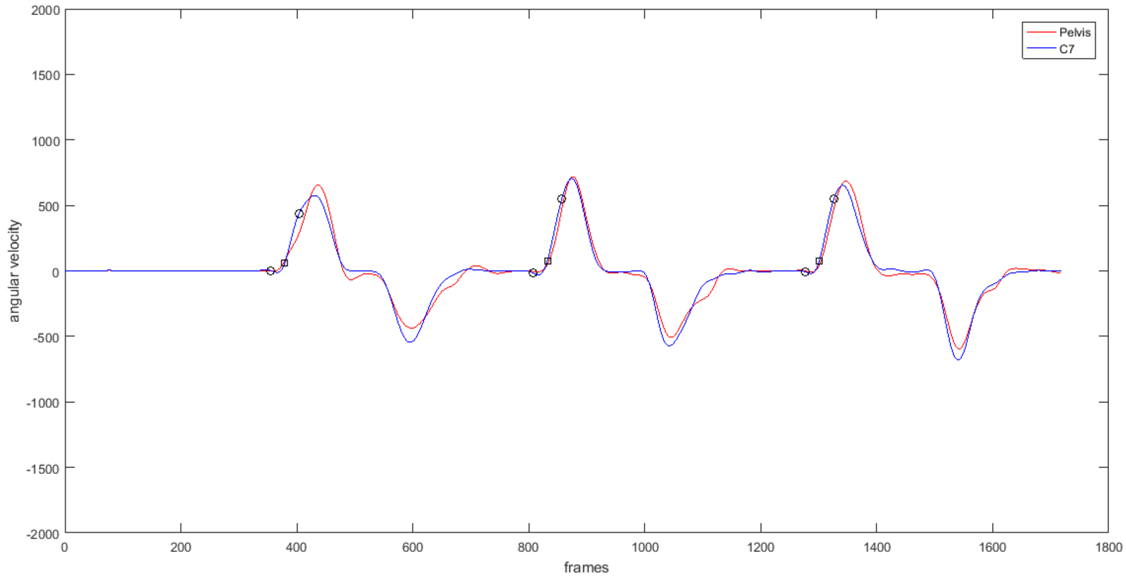
Body lifts as one unit with no lag in spine

PARTICIPANT 15KUFC06



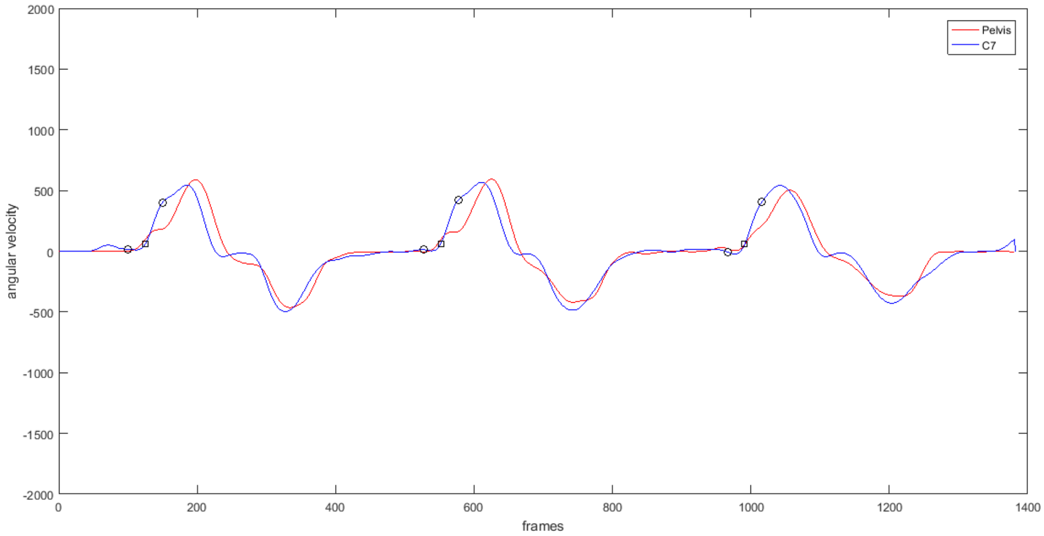
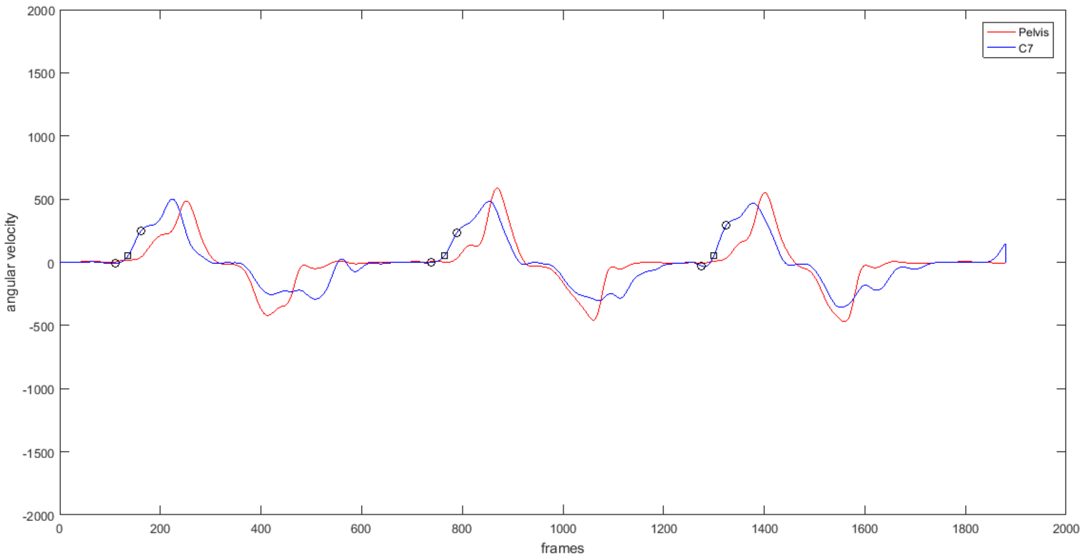
□ = start of movement (C7 marker)
○ = point indicating 25 frames before or after the start of the movement

PARTICIPANT 15KUFC21



□ = start of movement (C7 marker)
○ = point indicating 25 frames before or after the start of the movement

Figure 5.16 The velocity profiles of pelvis and thorax segments for flag condition 3[6]

Failure to lift body as one unit with lag in spine
PARTICIPANT 15KUFC07  □ = start of movement (C7 marker) ○ = point indicating 25 frames before/after the start of the movement
PARTICIPANT 15KUFC11  □ = start of movement (C7 marker) ○ = point indicating 25 frames before or after the start of the movement

The body lifts as a unit with <u>no lag in the spine</u> (4)

For each attempt:

i. The angle of the lumbar spine was identified at the start of the attempt for the sagittal plane. Movement occurring in this plane represents flexion/extension.

ii. The angle relative to its starting position was calculated throughout the trial.

iii. If the angle exceeded 10 degrees in the direction of extension from its starting angle, it was considered that lag was present in the spine, thus not meeting the condition.

Flag condition(s) : 5[6], 6[6]

Variable number(s) : 5, 6

FMS rule : Knees are fully extended

For each attempt and for both left and right:

i. The angle of the knee was identified at the start of the attempt for the sagittal plane. Movement occurring in this plane represented knee flexion/extension.

ii. The minimum flexion/extension angle was calculated from the start of the attempt to the 100th frame.

iii. If the minimum angle exceeded 10 degrees, it was considered that the knee was not fully extended for any point during the beginning of the test, thus not meeting the condition.

Flag condition(s) : 7[6], 8[6]

Variable number(s) : 7, 8

FMS rule : Ankles are neutral and the soles of the feet perpendicular to the floor / pull your toes towards your shins

As was evident in the Active Straight-Leg Raise test, there is a discrepancy between

i. The instructions to the assessor from the test description, and

ii. The verbal instruction to the participant from the assessor.

The description “ankles are neutral and the soles of the feet perpendicular to the floor” indicates a specified position for the feet. However the verbal instruction to the participant “ pull your toes towards your shins” does not clearly stipulate a threshold for how far the person is to pull their toes forward and is therefore open to interpretation by the participant. Due to the lack of a clearly defined position from the verbal instructions, the rule as to assessor from the description was evaluated.

For each attempt:

i. The ankle joint centre and toe markers (labelled as TIO and TOE in the Plug-in Gait model respectively) were used to measure the position of the foot.
ii. The minimum angle of the foot relative to the floor, in the sagittal plane, at the start of the attempt (defined as the first 100 frames or 1 second) was calculated.
iii. If the angle minimum angle was greater than 10 degrees, it was considered that the foot was not perpendicular to the floor for the beginning of the test, thus not meeting the condition.

Flag condition(s) : 9[6], 10[6]

Variable number(s) : 9, 10

FMS rule : Push up position

If the participant was able to achieve full elbow extension on both sides, it was considered that they successfully completed a press up.

For each attempt:

i. The minimum flexion/extension elbow angle was identified.
ii. If the minimum angle achieved was less than 30 degrees it was considered that the participant achieved sufficient elbow extension to complete the push up, thus meeting the criteria.

5.1.6.1 Spinal extension clearing test

Starting position

Participant prone on the floor.

Verbal instructions

- *While lying on your stomach, place your hands palms down, under your shoulders.*
- *With no lower body movement, press your chest off the surface as much as possible by straightening your elbows.*
- *Do you feel pain?*

The test may be completed up to three times. The spinal extension clearing test is not scored, however if pain is produced, a positive (+) is recorded on the score sheet, and a score of zero is given to the entire push up test.

Figure 5.17 Scoring of the Spinal extension clearing test

	**Spinal Extension Clearing Test** Spinal extension is cleared by performing a press-up in the push up position. If there is pain associated with this motion, give a zero and perform a more thorough evaluation or refer out. If the individual does receive a positive score, document both scores for future reference.

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Validation of the Spinal extension clearing test

The spinal extension clearing tests was carried out as per the FMS protocol. No validation with the motion capture system took place for reasons previously discussed in the Shoulder clearing test.

5.1.7 Rotary Stability

This subtest has two subtest variations in addition to a left and right component.

1. **Rotary Stability (unilateral repetition) –** In the unilateral variation, the first three attempts of the movement require ipsilateral upper and lower limb movement. The limbs are required to remain over the board throughout the attempt.
2. **Rotary Stability (diagonal repetition) -** If the participant was unable to meet all of the criteria needed to score a three in the Rotary Stability (unilateral repetition) subtest, the test was modified by having the participant complete a diagonal repetition as per the FMS instructions. For this test the limbs are only required to touch over the board. Apart from these variations, verbal instructions and scoring criteria are similar as described below.

Starting position

Participants were asked to get into the quadruped position with the 50 mm x 100 mm board between the hands and knees. The 50 mm x 100 mm board should be parallel to the spine, and the shoulders and hips should be 90 degrees relative to the torso, with the ankles neutral and soles of the feet perpendicular to the floor. Before the movement begins the hands should be open, with the thumbs, knees and feet all touching the board.

Verbal instructions

Please let me know if there is any pain while performing the following movement.

- *Get on your hands and knees over the board so your hands are under your shoulders and your knees are under your hips*
- *The thumbs, knees and toes must contact the sides of the board, and the toes must be pulled toward the shins.*
- *At the same time, reach your left hand forward and left leg backward, like you are flying.*
- *Then without touching down, touch your left elbow to your knee directly over the board.*
- *Return to the extended position.*
- *Return to the start position.*

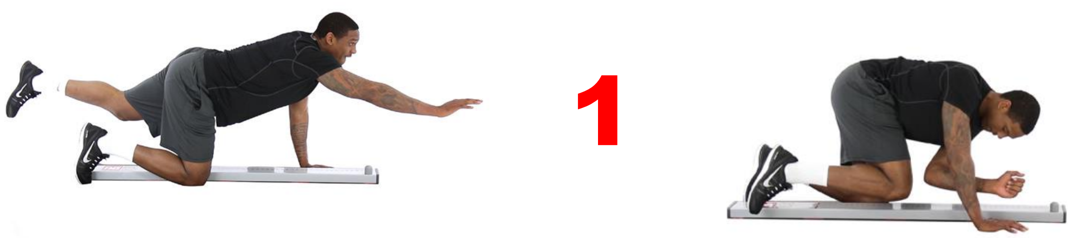
- *Do you understand the instructions?*

The moving upper limb indicates the side being tested. The test is repeated on the alternate side. If the participant is unable to perform a unilateral repetition, the participant will be instructed to repeat with a diagonal pattern.

Figure 5.18 Scoring criteria for the Rotary Stability test (unilateral and diagonal repetitions)

Performs a correct unilateral repetition | Unilateral limbs remain over the board

Performs a correct diagonal repetition | The diagonal knee and elbow meet over the board



Inability to perform a diagonal repetition

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Validation of the Rotary Stability (unilateral repetition) rules

Based on the description of the test, instructions given to the participant and scoring criteria, it was identified that the FMS requires the assessor to consider 23 variables for the FMS Rotary Stability (unilateral repetition) test rules (table 5.7.)

Table 5.7 Operationalisation of the FMS Rotary Stability (unilateral repetition) test rules

Rotary Stability (unilateral repetition)		
FMS rules	**Number of variables for consideration in real-time by the assessor**	**Flag №**
The thumbs, knees and toes must contact the sides of the board	1. Stabilising limb - Thumb - maintains contact with board 2. Stabilising limb - Knee - maintains contact with board 3. Stabilising limb – Toe - maintains contact with board	1^7 2^7 3^7
Ankles neutral and soles of the feet perpendicular to the floor (toes pulled towards the shins)	4. Stabilising limb - ankle angle remains unchanged throughout attempts 5. Stabilising limb - foot position perpendicular to the horizontal axis at start of attempts 6. Moving limb - foot position perpendicular to the horizontal axis at start of attempts	4^7 5^7 6^7
Hands are under your shoulders and your knees are under your hips (shoulders and hips should be 90 degrees relative to the torso)	7. Stabilising limb - shoulder angle – 90 degrees relative to the torso at start of attempts 8. Moving limb - shoulder angle – 90 degrees relative to the torso at start of attempts	7^7 8^7
	9. Stabilising limb - Hip angle – 90 degrees relative to the torso at start of attempts 10. Moving limb - Hip angle – 90 degrees relative to the torso at start of attempts	9^7 10^7
"At the same time, reach your hand forward and leg backward"	11. Ipsilateral upper and lower limb movement starts simultaneously	11^7
"While remaining in line over the board"	12. Moving arm stays in line over board 13. Moving leg stays in line over board	12^7 13^7
"Like you are flying"	14. Moving limb – shoulder joint – achieves "full" elevation at end of movement 15. Moving limb – elbow joint – achieves "full" extension at end of movement 16. Moving limb – hip joint – achieves "full" extension at end of movement 17. Moving limb – knee joint – achieves "full" extension at end of movement	14^7 15^7 16^7 17^7
Touch elbow to knee	18. Moving limbs - elbow and knee touch over the board (flexion of hip, knee, elbow and extension of the shoulder)	18^7
Without touching down	19. No contact of moving limbs with floor	19^7
"Like you are flying"	20. 21. 22. 23. Repeat 14. 15. 16. 17. respectively	20^7, 21^7 22^7, 23^7

Validation of the Rotary Stability (diagonal repetition) rules

Based on the description of the test, instructions given to the participant and scoring criteria, 23 variables were identified and quantified for the FMS Rotary Stability diagonal repetition test rules.

All of the rules of the diagonal repetition were similar to that of the unilateral repetition except that

i. the movement is diagonal and

ii. two of the rules are not required, namely rules numbered

12. Moving arm stays in line over board, and
13. Moving leg stays in line over board

The FMS states for the diagonal variation, the arm and leg need not be aligned over the board; however, the elbow and knee do need to **touch over it**. This rule therefore has multiple components namely:

1. The elbow and knee are required to make contact, and at the point of contact
    a. The elbow is required to be over the board
    b. The knee is required to be over the board

Based on the description of the test, instructions given to the participant and scoring criteria, it was identified that the FMS requires the assessor to consider 23 variables for the FMS Rotary Stability (diagonal repetition) test rules (table 5.8.)

Table 5.8 Operationalisation of the FMS Rotary Stability (diagonal repetition) test rules

Rotary Stability (diagonal repetition)		
FMS rules	**Number of variables for consideration in real-time by the assessor**	**Flag №**
The thumbs, knees and toes must contact the sides of the board	1. Stabilising limb - Thumb - maintains contact with board 2. Stabilising limb - Knee - maintains contact with board 3. Stabilising limb – Toe - maintains contact with board	1^8 2^8 3^8
Ankles neutral and soles of the feet perpendicular to the floor (toes pulled towards the shins)	4. Stabilising limb - ankle angle remains unchanged throughout attempts 5. Stabilising limb - foot position perpendicular to the horizontal axis at start of attempts 6. Moving limb - foot position perpendicular to the horizontal axis at start of attempts	4^8 5^8 6^8
Hands are under your shoulders and your knees are under your hips (shoulders and hips should be 90 degrees relative to the torso)	7. Stabilising limb - shoulder angle – 90 degrees relative to the torso at start of attempts 8. Moving limb - shoulder angle – 90 degrees relative to the torso at start of attempts	7^8 8^8
	9. Stabilising limb - Hip angle – 90 degrees relative to the torso at start of attempts 10. Moving limb - Hip angle – 90 degrees relative to the torso at start of attempts	9^8 10^8
“At the same time, reach your hand forward and leg backward	11. Contralateral upper and lower limb movement starts simultaneously	11^8
“the arm and leg need not be aligned over the board; however, the elbow and knee do need to touch over it”	12. Elbow and knee touch over the board (flexion of hip, knee, elbow and extension of the shoulder) 13. Moving limbs – knee over board (in order to touch elbow) 14. Moving limbs - elbow over board (in order to touch knee)	12^8 13^8 14^8
“Like you are flying”	15. Moving limb – hip joint – achieves “full” extension at end of movement 16. Moving limb – knee joint – achieves “full” extension at end of movement 17. Moving limb – shoulder joint – achieves “full” elevation at end of movement 18. Moving limb – elbow joint – achieves “full” extension at end of movement	15^8 16^8 17^8 18^8
Without touching down	19. No contact of moving limbs with floor	19^8
Like you are flying”	20. 21. 22. 23. Repeat 15. 16. 17.18. respectively	20^8, 21^8, 22^8, 23^8

To correctly be awarded the highest score of three in the Rotary Stability (unilateral repetition) subtest, the participant is required to successfully meet all 23 variables in at least one attempt. For the Rotary Stability (diagonal repetition) subtest, the participant is also required to meet all 23 variables associated with that subtest so that a correct score of two is awarded. Therefore, for the correct score of one, the participant should not have met all of the 23 criteria in any of the three attempts.

Flag condition(s) **: 1[7], 2[7], 3[7]**

Variable number(s) **: 1, 2, 3**

FMS rule **: The thumbs, knees and toes must contact the sides of the board**

As with the Trunk Stability Push-Up no markers were placed on the thumbs. It was however possible to observe the position of the hands (finger markers) to see if they moved during the testing. The same method was used for the fingers, knee and feet.

For each attempt and for both left and right:

i. The global frame X coordinates of the finger, knee joint centre and toe markers were at the start of the attempt (labelled as FIN, FEO and TOE in the Plug-in Gait model)

ii. The global frame X coordinates of the markers were calculated throughout each attempt

iii. If the markers moved more that 5mm from their starting position in the global X axis, (indicating medial/lateral displacement) the fingers, knees or feet were considered to have lost contact with the board, thus not meeting the condition.

Flag condition(s) **: 4[7], 5[7], 6[7]**

Variable number(s) **: 4, 5, 6**

FMS rule **: Ankles neutral and soles of the feet perpendicular to the floor (toes pulled towards the shins)**

It was identified that this rule is comprised of two components:

1. <u>**Ankles neutral**</u> **and soles of the feet perpendicular to the floor** – relating to the ankle angle.
2. **Ankles neutral and** <u>**soles of the feet perpendicular to the floor**</u> – relating to the position of the foot relative to the floor

As previously discussed with this rule, which is also present in the Active Straight-Leg Raise and Trunk Stability Push-Up tests, there is a discrepancy between the instructions to the assessor and the instructions to the participant. However, unlike the Active Straight-Leg Raise and Trunk Stability Push-Up tests, both the ankle and foot position are stipulated in the description provided to the assessor and will therefore be evaluated.

Ankles neutral and soles of the feet perpendicular to the floor (4[7])

For the ankle angle, the rule describes it as a requirement for both ankles. However the ankle angle of the moving limb would change as a result of the required movement, therefore this rule is not feasible for the moving limb. Therefore only the stabilising/ non-moving limb was analysed. As a result of the relationship between the foot position and the ankle angle, the moving limb could be evaluated in the second component of the rule. If the moving limb starting position of the foot was not perpendicular to the floor, it is unlikely that the ankle angle will be in a neutral position.

For each attempt:

i. The starting angle of the non-moving/stabilising ankle was identified at the start of the attempt for the sagittal plane. Movement occurring in this plane represented ankle plantarflexion/dorsiflexion.
ii. The plantarflexion/dorsiflexion angle relative to its starting position was calculated throughout the trial.
iii. If the angle exceeded 10 degrees from its starting angle, it was considered that the movement threshold was exceeded. Thus not meeting the condition.

Ankles neutral and soles of the feet perpendicular to the floor (5[7], 6[7])

For each attempt:

i. The ankle joint centre and toe markers (labelled as TIO and TOE in the Plug-in Gait model respectively) were used to measure the position of the foot.
ii. The minimum angle of the foot relative to the floor from the start of the attempt to +100 frames was calculated (equivalent to 1 second).
iii. If the angle minimum angle was greater than 10 degrees, it was considered that the foot was not perpendicular to the floor for the beginning of the test, thus not meeting the condition.

Flag condition(s) : 7[7], 8[7], 9[7], 10[7]

Variable number(s) : 7, 8, 9, 10

FMS rule : **Hands are under your shoulders and your knees are under your hips (shoulders and hips should be 90 degrees relative to the torso)**

For each attempt and for both left and right:

i. The angle of the hip and shoulder, relative to the thorax, was identified at the start of the attempt for the sagittal plane. Movement occurring in this plane represented flexion/extension.
ii. As the test requires shoulders and hips to be 90 degrees relative to the torso, the tolerance was set between 80 to 100 degrees.
iii. If the angle occurring at the hip or shoulder was less than 100 degrees but greater than or equal to 80 degrees, it was considered that the condition was met.

Flag condition(s) : **11**[7]

Variable number(s) : **11**

FMS rule : **"At the same time, reach your hand forward and leg backward"**

For this rule, the ability of the participant to synchronously initiate ipsilateral movement of their upper and lower limb was evaluated. (For the diagonal repetitions the same method was used on the contralateral limbs).

i. The starting angle of the ipsilateral shoulder and hip in the sagittal plane was identified, representing flexion/extension.
ii. A movement exceeding 5 degrees in either the shoulder or hip joint was considered the start of a movement.
iii. The time at which this occurred was identified independently for both the shoulder and hip joints.
iv. If the difference between the start of movement in the shoulder and the start of movement in the hip was greater than 50 frames (equivalent to 0.5 seconds). It was considered that the movement was asynchronous, thus not meeting the condition.

Flag condition(s) **: 12[7], 13[7]**

Variable number(s) **: 12, 13**

FMS rule **: "While remaining in line over the board"**

For each attempt:

i. The lateral elbow and knee joint centre markers (labelled as ELB and FEO in the Plug-in Gait model) were used to identify the positions of the upper and lower limbs respectively.

ii. The global frame X coordinates of the lateral elbow and knee joint centre markers were used to determine threshold criteria at the start of the attempt. They were used to indicate the borders of the 100mm x 150mm board.

iii. If the global X co-ordinates of the upper or lower limb markers exceeded the thresholds established at the start of the attempt, it was considered that the limbs no longer remained in line over the board, thus not meeting the criteria.

Flag condition(s) : **14[7], 15[7], 16[7], 17[7]**

Variable number(s) : **14, 15, 16, 17**

FMS rule : **“Like you are flying”**

For this rule, the participant is required to achieve the following movements at the associated joints

1. Shoulder elevation
   i. The maximum elevation angle of the moving ipsilateral shoulder was calculated.
   ii. If the maximum elevation angle was greater than 150 degrees it was considered that the participant sufficiently elevated their shoulder, thus meeting the condition.
2. Elbow extension
   i. The minimum angle of the moving ipsilateral elbow was calculated in the sagittal plane representing flexion/extension.
   ii. If the minimum elbow angle was less than 30 degrees it was considered that the participant sufficiently extended their elbow, thus meeting the condition.
3. Hip extension
   i. The minimum angle of the moving ipsilateral hip was calculated in the sagittal plane representing flexion/extension
   ii. If the minimum hip angle was less than 30 degrees it was considered that the participant sufficiently extended their hip, thus meeting the condition.
4. Knee flexion
   i. The minimum angle of the moving ipsilateral knee was calculated in the sagittal plane representing flexion/extension.
   ii. If the minimum knee angle was less than 30 degrees it was considered that the participant sufficiently extended their hip, thus meeting the condition.

Flag condition(s) : **18**[7]

Variable number(s) : **18**

FMS rule : **Touch elbow to knee**

For each attempt:

i. The minimum distance between the global frame X –coordinates of ipsilateral lateral elbow and knee joint centre markers was calculated (labelled as ELB and FEO in the Plug-in Gait model). Indicating anterior/posterior movement

ii. If the distance between the markers was greater than 190 mm it was considered that the participant was unsuccessful in touching their elbow to their knee, thus not meeting the condition.

iii. A threshold of 190mm was selected on the basis that within the sample, the summed maximum knee and elbow widths equalled 240mm. Therefore as an estimate, the joint centre or joint line markers would be located half way from these offsets, equating to 120mm. A further 70 mm was added to this to account for some tolerance with marker placement and an inability to use the elbow joint centre for reasons described previously in the Plug-in Gait methodology section 3.3.1.

Flag condition(s) **: 19[7]**

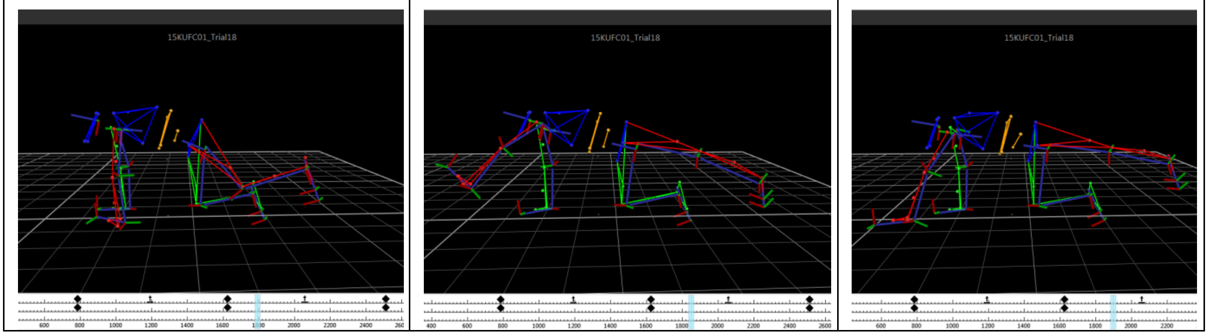
Variable number(s) **: 19**

FMS rule **: Without touching down**

This rule was evaluated by a retrospective visual assessment, carried out by the assessor**.** If the participant made contact with the floor at any point during the attempt it was considered that the participant had touched down, thus not meeting the condition (figure 5.19).

Figure 5.19 Flag condition 19[7] – Participant touching ground

A. Starting movement	B. Attempt of movement	C. Failed attempt (touched down)



Flag condition(s) **: 20[7], 21[7], 22[7], 23[7]**

Variable number(s) **: 20, 21, 22, 23**

FMS rule **: Return to extend position**

The requirements of this rule are the same as those in the rule **"Like you are flying"**. As the rule requirements are the same, the same methods were used to validate this rule.

Flag condition(s) **: 14[7], 15[7], 16[7], 17[7]**

Validation of the Rotary Stability (diagonal repetition) rules

For the Rotary Stability diagonal repetition, flag conditions and variables are the same as those for the unilateral repetition from numbers 1 to 11 and 19. Flag conditions 15 to 18 in the diagonal repetition are the same as flag conditions 14 to 17 in the unilateral repetition. Therefore flag conditions 20 – 23 in the diagonal repetition will reflect flag conditions 15 to 18.

The only variation in flag conditions and variables in the two subtest variations is flag conditions 12 – 14 for the diagonal repetition. This is resultant from the rule "the arm and leg need not be aligned over the board; however, the elbow and knee do need to touch over it."

Flag condition(s) : **12[8], 13[8], 14[8]**

Variable number(s) : **12, 13, 14**

FMS rule : **"the arm and leg need not be aligned over the board; however, the elbow and knee do need to touch over it"**

During this diagonal variation, the arm and leg need not be aligned over the board; however, the elbow and knee do **need to touch** over it. **(12)**

For each attempt:

i. The minimum distance between the global frame, X and Y coordinates of the lateral elbow and knee joint centre markers were calculated.
ii. As the movement is diagonal there is an anterior/ posterior and medial/lateral component, hence the selection of the global frame, X and Y coordinates.
iii. If the distance between the markers was greater than 190 mm in either the X or Y planes it was considered that the participant was unsuccessful in touching their elbow to their knee, thus not meeting the condition.

During this diagonal variation, the arm and leg need not be aligned over the board; however, the elbow and knee do need to **touch over it. (13, 14)**

For each attempt:

i. The lateral elbow and knee joint centre markers (labelled as ELB and FEO in the Plug-in Gait model) were used to identify the positions of the upper and lower limbs respectively.

ii. The global frame, X coordinates of the lateral elbow and knee joint centre markers were used to determine threshold criteria at the start of the attempt. They were used to indicate the borders of the 100mm x 150mm board.

iii. The minimum distance between the lateral elbow and knee joint centre markers was calculated and the time point at which this occurred was identified.

iv. At this time point, the global frame X and Y coordinates of the lateral elbow and knee joint centre markers were compared with their staring positions.

v. If at this time point, they were identified as being less than their stating positions, it was considered that they were aligned over the board at the point they should have been touching, thus meeting the condition.

5.1.7.1 Spinal flexion clearing test

Starting position

Patient in quadruped position.

Verbal instructions

- *Get on all fours, and rock your hips towards your heels*
- *Lower your chest to your knees, and reach your hands in front of your body as far as possible*
- *Do you feel any pain?*

The test may be completed up to three times. The spinal flexion clearing test is not scored, however if pain is produced, a positive (+) is recorded on the score sheet, and a score of zero is given to the entire Rotary Stability test.

Figure 5.20 Scoring of the Spinal flexion clearing test

	**Spinal Flexion Clearing Test** Spinal flexion can be cleared by first assuming a quadruped position, then rocking back and touching the buttocks to the heels and chest to thighs. The hands should remain in front of the body, reaching out as far as possible. If there is pain associated with this motion, give a zero and perform a more thorough evaluation or refer out. If the individual receives a positive score, document both scores for future reference.

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Validation of the Spinal flexion clearing test

The spinal flexion clearing tests was carried out as per the FMS protocol. No validation with the motion capture system took place for reasons previously discussed in the Shoulder clearing test.

6 VALIDITY OF THE FMS AS A MEASUREMENT AND ASSESSMENT TOOL

6.1 Introduction

The developers of the FMS attribute its usefulness to its simplicity and practicality (Functional Movement Systems and Gray Cook 2012). The FMS is advocated as a *"simple grading system of motor appraisal."* Whilst it may initially appear as a simple clinical test and scale, the impossibility of the system as a result of its complexity is apparent on further evaluation of the FMS framework, exercise sub-tests and associated scoring criteria. Assessors are required to consider multiple constructs related to scoring criteria in addition to simultaneously observing multiple body segments during complex 3D movements. During this, the assessor has a limited number of attempts in which to view the movements and is limited to a 2D field of view during any one attempt. This provides challenges in the real-time evaluation of the participant's performance during the FMS. The identified sources of complexity and their effect on the validity of the FMS will be evaluated further in this chapter. Additionally the underlying assumptions of the FMS, alongside its reported measurement and assessment capabilities, will be evaluated. For the purpose of this chapter, definitions for measurement and assessment are taken from Kondraske (1990):

> **"Measurement** is defined as - a process in which an absolute standard (such as a ruler) is used to quantify a single dimension or aspect of an observed object or event or the result of such a process (e.g. length in number of centimetres)"

> **"Assessment** is defined as - the process of determining the worth or value of a measurement, or collective set of measurements, in a specific context to the result of such a process. This usually involves a subjective judgement or a quantitative comparison of one measure to another."

Validity is defined as the ability of a scale or system to accurately measure what it is expected to measure (Payton 1994). Therefore, in order for the FMS to be considered valid, it must be able to produce accurate measurements for its reported capabilities. The reported measurement capabilities of the FMS are that it may be used as a:

a) Method for assessing muscle strength, range of motion, asymmetry, balance and kinaesthetic awareness
b) Scale for rating and ranking movement patterns
c) Indicator of injury risk through identification of a final score

(Cook et al 2006a, Cook et al 2006b, Cook et al 2010, Functional Movement Systems and Gray Cook 2012, Kiesel et al 2007)

Despite the FMS being originally intended for rating and ranking movement patterns in high school athletes (Functional Movement Systems and Gray Cook 2012), it has since been used as a measure of injury risk in various sporting disciplines and occupations. Although questions have been raised about the efficacy of pre-season measures and screening processes for predicting injury (Bahr 2016), the FMS remains a commonly used screening tool during the pre-season period (McCall et al 2015). Therefore, the points discussed previously will be considered when evaluating the underlying assumptions of the FMS, alongside its reported measurement and assessment capabilities, within this chapter.

6.2 Results for the criterion validity of the FMS subtests

Twenty four male footballers competing in the British University and College Sports leagues, volunteered to participate in the study. Further information regarding participant recruitment and characteristics are reported in Chapter 7. Simultaneous capture of FMS performance with the photogrammetric system allowed for the criterion validity and hierarchy within the FMS system to be assessed. The FMS test requires participants to perform movements, for which a score is awarded based on how many criteria they meet for that subtest. The photogrammetric system therefore allowed the performance of the participant to be measured. It also allows for a comparison to be made between the real-time assessor score and the criteria quantified by the photogrammetric system. For example, in order to achieve the highest possible score of three in that subtest, when compared with the photogrammetric system all of the scoring variables (flag conditions) must have been met, as quantified in Chapter 5. In order for the FMS scale to be considered valid, the real-time awarded score should match the score that would have been awarded by the photogrammetric system (based on the number of variables met). This section presents the results of the real-time assessor score compared with the criteria quantified by the photogrammetric system.

Two methods were selected to demonstrate the criterion validity results of the FMS.

- The first method demonstrates the number of successful flag conditions met for each attempt against the awarded score (For each subtest, each participant is ranked in descending order according to real-time assessor awarded score).
- The second selected method was a colour coded heat map

Both methods have been presented in a single table for each subtest, to allow for comparison of the real-time assessor score against the photogrammetric system. Annotated instructions to help interpret the results of the table have been provided in table 6.1.

Without a suitable method for summarising the data, subsequent interpretation would be difficult. For example, the Deep Squat no heel raise sub test would have 33 columns associated with it (11 flag conditions multiplied by three attempts for each subtest). For all tests within the Deep Squat subtest, there would be 99 columns. This results from the subtests variations (e.g. the Deep Squat heel raise and no heel raise tests) or a left and right component. The final score is informed by the lower of these two scores. As a result, the subtest that informs the final score will be different between people. It should be considered that there are three sets of awarded scores for most tests (Deep Squat, Hurdle Step, Inline Lunge, Shoulder Mobility, Active Straight-Leg Raise, and Trunk Stability Push-Up).

- Subtest variation 1 (sub score) -> subtest variation 2 (sub score) -> subtest variation 3 (Final score)

For the Rotary Stability test, there are five sets of awarded scores as a result of thre being a left and right component and a subtest variation. Within this study, only one awarded score set was used for the Trunk Stability Push-Up as no participants were required to complete the subtest variation during real-time assessment. This method of data analysis reduced the number of columns from 816 to 272. Given the large volume of data (multiple columns within the dataset, arising from multiple subtests, flag conditions and attempts), it was therefore necessary to present the data in a format that allowed it to be interpreted without discarding relevant information. Within the relevant sections, heat maps will be presented for each of the subtests. For all subtest, the table’s containing criteria met and heat maps have been presented first, followed by a summary of the result.

Table 6.1 Annotated instructions to help with interpretation of results

4.

Therefore when evaluating the real-time assessor score against the photogrammetric system.

In order to score a three:

- All the flag conditions should be successfully met for at least one attempt.
- We would expect that for a participant who was awarded a real-time score of a three, there would be no red boxes. A red box would indicate that they consistently failed one flag condition over three attempts.
- Based on this, it is evident in this example below that the participant (15KUFC10) has been allocated to the incorrect scoring category.

Deep Squat - No heel raise - 11 flag conditions															
ID	FMS subscore	Criteria met			Flag conditions										
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11
15KUFC10	3	3/11	4/11	3/11											
15KUFC01	2	3/11	3/11	2/11											

To score a two:

- The participant should not have successfully met all the criteria for any attempt (except for Deep Squat Heel raise and Rotary stability Diagonal repetition subtests)
- We would expect that for a participant who was correctly awarded a real-time score of a two, at least one red box. A red box indicates they consistently failed one flag condition over three attempts.

To score a one:

- The participant should not have successfully met all the criteria for any attempt. Additionally they should have met the flag condition associated with the scoring category of a one, at least once.
- For the FMS scale to be considered a measure, it should be able to categorise people into mutually exclusive categories.
- In order for categories to be mutually exclusive, the constructs which determine any one category should be unique to that category.
    - For example, for all participants who scored a two, it would be expected that they all fail to meet the same or similar flag conditions.
- This would be reflected in the heat map, whereby those who scored a two would be distinguishable from those scoring a three or one.
- Additionally, if the FMS scale allows for people to be ranked in a logical order, this would be demonstrated in the heat map.
    - For example when ranked in descending order according to real-time assessor awarded score, participants with higher real-time assessor scores are expected to consistently meet more criteria than those with lesser scores.
    - Therefore more green and yellow boxes would be expected at the upper limits of the heat maps, with more orange and red boxes towards the lower limits. This should also be true for descending number of injuries if the reported injury capabilities of the FMS are true.

6.2.1 Results for validation of the FMS Deep Squat (heel raise and no heel raise screening test scoring criteria)

The FMS Deep Squat test has two variations, one without an adjustment (no heel raise) and one with an adjustment (heel raise). As per the FMS protocol, the lower of the two scores is used to determine the final score. For this subtest, a table of results for the Deep Squat no heel raise subtest variation has presented first (table 6.2) followed by a text summary of the results. The same format has been used for the following subtests of the Deep Squat heel raise subtest and final score results (table 6.3 and table 6.4 respectively).

Table 6.2 Results for validation of the FMS Deep Squat no heel raise screening test scoring criteria

Deep Squat - No heel raise - 11 flag conditions															
ID	FMS subscore	**Criteria met**			**Flag conditions**										
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11
15KUFC10	**3**	3/11	4/11	3/11											
15KUFC01	**2**	3/11	3/11	2/11											
15KUFC06	**2**	2/11	3/11	3/11											
15KUFC07	**2**	6/11	4/11	3/11											
15KUFC08	**2**	6/11	6/11	6/11											
15KUFC09	**2**	2/11	3/11	3/11											
15KUFC11	**2**	7/11	6/11	6/11											
15KUFC13	**2**	4/11	3/11	4/11											
15KUFC14	**2**	5/11	5/11	6/11											
15KUFC15	**2**	5/11	4/11	5/11											
15KUFC17	**2**	4/11	4/11	4/11											
15KUFC18	**2**	6/11	6/11	7/11											
15KUFC19	**2**	3/11	3/11	4/11											
15KUFC21	**2**	2/11	2/11	3/11											
15KUFC22	**2**	5/11	5/11	4/11											
15KUFC23	**2**	4/11	4/11	6/11											
15KUFC02	**1**	3/11	3/11	6/11											
15KUFC03	**1**	6/11	5/11	4/11											
15KUFC04	**1**	6/11	5/11	5/11											
15KUFC05	**1**	3/11	3/11	3/11											
15KUFC12	**1**	3/11	3/11	3/11											
15KUFC16	**1**	4/11	4/11	4/11											
15KUFC24	**1**	5/11	4/11	3/11											
15KUFC25	**1**	4/11	4/11	4/11											

Legend
0 successful attempts
1 successful attempt
2 successful attempts
3 successful attempts

Text summary of results for validation of the FMS Deep Squat <u>no</u> heel raise screening test scoring criteria

For this subtest, one participant was awarded a real-time assessor score of three (15KUFC10). On review of the three attempts, they failed to meet 11 flag conditions in any attempt. In this instance, a score of three should not have been awarded. The participant has been classified incorrectly. The remaining participants were correctly not awarded a real-time assessor score of three. No participants consistently met all 11 flag conditions. There were no patterns to be observed with respect to criteria met or not met.

To check if those participants not awarded a three were assigned to the correct scoring category; see results for validation of the FMS Deep Squat heel raise screening test final.

Table 6.3 Results for validation of the FMS Deep Squat heel raise screening test scoring criteria

Deep Squat - Heel raise - 11 flag conditions															
ID	FMS subscore	**Criteria met**			**Flag conditions**										
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11
15KUFC10	3	6/11	7/11	8/11											
15KUFC01	2	5/11	6/11	5/11											
15KUFC06	2	7/11	10/11	10/11											
15KUFC07	2	6/11	8/11	8/11											
15KUFC08	2	7/11	6/11	6/11											
15KUFC09	2	9/11	7/11	8/11											
15KUFC11	2	7/11	6/11	7/11											
15KUFC13	2	5/11	6/11	6/11											
15KUFC14	2	4/11	3/11	3/11											
15KUFC15	2	11/11	10/11	11/11											
15KUFC17	2	7/11	6/11	6/11											
15KUFC18	2	7/11	9/11	9/11											
15KUFC19	2	6/11	7/11	7/11											
15KUFC21	2	6/11	9/11	8/11											
15KUFC22	2	7/11	10/11	7/11											
15KUFC23	2	6/11	8/11	6/11											
15KUFC02	1	5/11	5/11	5/11											
15KUFC03	1	5/11	5/11	5/11											
15KUFC04	1	5/11	6/11	7/11											
15KUFC05	1	4/11	3/11	5/11											
15KUFC12	1	7/11	5/11	4/11											
15KUFC16	1	3/11	3/11	5/11											
15KUFC24	1	4/11	5/11	4/11											
15KUFC25	1	6/11	6/11	6/11											

Legend	
	0 successful attempts
	1 successful attempt
	2 successful attempts
	3 successful attempts

Text summary of results for validation of the FMS Deep Squat heel raise screening test scoring criteria

For this subtest, 15 participants were assigned a real-time score of two and eight participants were awarded a score of one. In those who scored two, only one participant (15KUFC15) is identified as being assigned to the correct category (meeting all 11 flag conditions in at least one attempt). Fourteen of the 15 participants awarded a score of two were incorrectly categorised and should be within the scoring category of one. For participants assigned to the real-time scoring category of one, none of the eight participants met all 11 flag conditions in any attempt. They have therefore been assigned to the correct scoring category. Flag conditions (7) and (9), left and right dowel position backwards relative to the posterior border of the foot, were consistently met by all participants over the three attempts. Flag condition (1), thorax inclination angle relative to tibial inclination angle, was consistently met over three attempts by 23 out of the 24 participants (only 15KUFC25 did not meet this flag condition on any attempts). There were no flag conditions consistently not met over the three attempts by all participants.

Table 6.4 Results for validation of the FMS Deep Squat screening test scoring criteria (Final)

Deep Squat - Final Score- 11 Flag conditions																
ID	FMS score	Criteria met			Flag conditions											
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11
15KUFC10	3	3/11	4/11	3/11											
15KUFC01	2	5/11	6/11	5/11											
15KUFC06	2	7/11	10/11	10/11											
15KUFC07	2	6/11	8/11	8/11											
15KUFC08	2	7/11	6/11	6/11											
15KUFC09	2	9/11	7/11	8/11											
15KUFC11	2	7/11	6/11	7/11											
15KUFC13	2	5/11	6/11	6/11											
15KUFC14	2	4/11	3/11	3/11											
15KUFC15	2	11/11	10/11	11/11											
15KUFC17	2	7/11	6/11	6/11											
15KUFC18	2	7/11	9/11	9/11											
15KUFC19	2	6/11	7/11	7/11											
15KUFC21	2	6/11	9/11	8/11											
15KUFC22	2	7/11	10/11	7/11											
15KUFC23	2	6/11	8/11	6/11											
15KUFC02	1	5/11	5/11	5/11											
15KUFC03	1	5/11	5/11	5/11											
15KUFC04	1	5/11	6/11	7/11											
15KUFC05	1	4/11	3/11	5/11											
15KUFC12	1	7/11	5/11	4/11											
15KUFC16	1	3/11	3/11	5/11											
15KUFC24	1	4/11	5/11	4/11											
15KUFC25	1	6/11	6/11	6/11											

Legend
0 successful attempts
1 successful attempt
2 successful attempts
3 successful attempts

Text summary of results for validation of the FMS Deep Squat screening test scoring criteria (Final)

For the final scores, nine out of the 24 participants were assigned to the correct scoring category; 15 participants were assigned to the incorrect scoring category. No participants were correctly assigned to the scoring category of three. One participant (15KUFC15) was correctly assigned to the scoring category of two and eight participants were correctly assigned to the scoring category of one. Flag conditions (7) and (9), left and right dowel position backwards relative to the posterior border of the foot, were consistently met by all participants over the three attempts. Flag condition (1), thorax inclination angle relative to tibial inclination angle, was consistently met over three attempts by 23 out of the 24 participants (all except 15KUFC25). There were no patterns to be observed with respect to criteria met or not met.

6.2.2 Results for validation of the FMS Hurdle Step screening test scoring criteria

The FMS Hurdle Step test is completed for both the left and right sides. As per the FMS protocol, the lower of the two scores is used to determine the final score. For this subtest, a table of results for the FMS Hurdle Step left subtest has presented first (table 6.5) followed by a text summary of the results. The same format has been used for the following subtests of the FMS Hurdle Step right subtest and final score results (table 6.6 and table 6.7 respectively).

Table 6.5 Results for validation of the FMS Hurdle Step screening test scoring criteria (Left)

Hurdle Step - Left - 12 Flag conditions																
ID	FMS subscore	**Criteria met**			**Flag conditions**											
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12
15KUFC01	3	6/12	5/12	7/12												
15KUFC06	3	8/12	8/12	8/12												
15KUFC07	3	8/12	8/12	7/12												
15KUFC10	3	9/12	9/12	9/12												
15KUFC11	3	7/12	7/12	7/12												
15KUFC14	3	8/12	4/12	7/12												
15KUFC21	3	7/12	7/12	6/12												
15KUFC23	3	7/12	8/12	8/12												
15KUFC03	2	8/12	7/12	5/12												
15KUFC04	2	7/12	6/12	5/12												
15KUFC05	2	6/12	6/12	7/12												
15KUFC08	2	4/12	5/12	4/12												
15KUFC09	2	7/12	8/12	8/12												
15KUFC12	2	8/12	7/12	8/12												
15KUFC13	2	6/12	8/12	8/12												
15KUFC15	2	6/12	7/12	5/12												
15KUFC16	2	7/12	8/12	7/12												
15KUFC17	2	6/12	3/12	5/12												
15KUFC18	2	4/12	5/12	5/12												
15KUFC19	2	5/12	7/12	6/12												
15KUFC22	2	7/12	8/12	7/12												
15KUFC24	2	5/12	6/12	6/12												
15KUFC25	2	6/12	6/12	5/12												
15KUFC02	1	5/12	5/12	5/12												

Legend	
	0 successful attempts
	1 successful attempt
	2 successful attempts
	3 successful attempts

Text summary of results for validation of the FMS Hurdle Step screening test scoring criteria (Left)

For this subtest eight participants were awarded a real-time score of three, 15 participants were awarded a score of a two and one participant was awarded a score of one. None of those awarded a real-time score of three met all 12 flag conditions in any attempt and have therefore not been correctly assigned. Fifteen participants have correctly been assigned to the scoring criteria of two for this subtest. No participants in scoring categories two and three consistently failed the flag conditions associated with the scoring category of one. The participant who was assigned to the category of one (15KUFC02) did not fail any criteria associated with this category in any attempt and has therefore been assigned incorrectly (flag conditions (10), (11) and (12)).

Flag conditions (11) and (12), foot height higher than measured tibial height (to the test target and from test target), were consistently met by all participants over the three attempts. All participants failed to consistently meet flag conditions (1), (3) and (5) over the three attempts. Flag condition (1) checked that only pure flexion (plantar flexion)/extension (dorsiflexion) occurred at the moving limb hip, knee and ankle joints. Flag condition (3) and (5) were used to check that no lumbar spine flexion and side flexion occurred respectively. Flag condition (10) was used to evaluate if loss of balance occurred. Flag conditions (11) and (12) were used to check if contact was made between the participant's foot and hurdle.

Table 6.6 Results for validation of the FMS Hurdle Step screening test scoring criteria (Right)

Hurdle Step - Right - 12 Flag conditions																
ID	FMS subscore	Criteria met			Flag conditions											
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12
15KUFC07	3	7/12	7/12	6/12												
15KUFC09	3	7/12	8/12	8/12												
15KUFC11	3	6/12	8/12	8/12												
15KUFC12	3	9/12	9/12	9/12												
15KUFC18	3	6/12	7/12	6/12												
15KUFC24	3	7/12	8/12	8/12												
15KUFC25	3	7/12	6/12	6/12												
15KUFC01	2	5/12	5/12	6/12												
15KUFC02	2	5/12	3/12	5/12												
15KUFC03	2	7/12	8/12	8/12												
15KUFC04	2	6/12	5/12	7/12												
15KUFC05	2	6/12	5/12	6/12												
15KUFC06	2	7/12	9/12	8/12												
15KUFC08	2	6/12	6/12	6/12												
15KUFC10	2	8/12	8/12	8/12												
15KUFC13	2	6/12	8/12	8/12												
15KUFC14	2	7/12	8/12	8/12												
15KUFC15	2	6/12	5/12	7/12												
15KUFC16	2	6/12	7/12	7/12												
15KUFC17	2	6/12	6/12	5/12												
15KUFC19	2	6/12	7/12	6/12												
15KUFC21	2	7/12	8/12	7/12												
15KUFC22	2	6/12	8/12	6/12												
15KUFC23	2	7/12	8/12	8/12												

Legend
0 successful attempts
1 successful attempt
2 successful attempts
3 successful attempts

Text summary of results for validation of the FMS Hurdle Step screening test scoring criteria (Right)

For this subtest seven participants were awarded a real-time score of three and 17 participants were awarded a score of two. None of those awarded a real-time score of three met all 12 flag conditions in any attempt and have therefore not been correctly assigned. Seventeen participants have correctly been assigned to the scoring criteria of two for this subtest. No participants in scoring categories two and three consistently failed the criteria associated with the scoring category of a one (flag conditions 10, 11, 12).

Flag conditions (9), (11) and (12) were consistently met by all participants over the three attempts. Flag condition (9) checked that the dowel remained parallel to the horizontal axis for all attempts and flag conditions (11 + 12) checked the foot height was higher than measured tibial height to the test target and from test target. All participants failed to consistently meet flag conditions (3) and (5) over the three attempts. Flag condition (3) and (5) were used to check that no lumbar spine flexion and side flexion occurred respectively. Flag condition (10) was used to evaluate if loss of balance occurred. Flag conditions (11) and (12) were used to check if contact was made between the participant's foot and hurdle.

Table 6.7 Results for validation of the FMS Hurdle Step screening test scoring criteria (Final)

Hurdle Step - Final - 12 Flag conditions																	
ID	FMS score	Criteria met			Flag conditions												
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12
15KUFC07	3	7/12	7/12	6/12												
15KUFC11	3	7/12	7/12	7/12												
15KUFC01	2	5/12	5/12	6/12												
15KUFC03	2	8/12	7/12	5/12												
15KUFC04	2	7/12	6/12	5/12												
15KUFC05	2	6/12	5/12	6/12												
15KUFC06	2	7/12	9/12	8/12												
15KUFC08	2	4/12	5/12	4/12												
15KUFC09	2	7/12	8/12	8/12												
15KUFC10	2	8/12	8/12	8/12												
15KUFC12	2	8/12	7/12	8/12												
15KUFC13	2	6/12	8/12	8/12												
15KUFC14	2	7/12	8/12	8/12												
15KUFC15	2	6/12	7/12	5/12												
15KUFC16	2	6/12	7/12	7/12												
15KUFC17	2	6/12	3/12	5/12												
15KUFC18	2	4/12	5/12	5/12												
15KUFC19	2	5/12	7/12	6/12												
15KUFC21	2	7/12	8/12	7/12												
15KUFC22	2	6/12	8/12	6/12												
15KUFC23	2	7/12	8/12	8/12												
15KUFC24	2	5/12	6/12	6/12												
15KUFC25	2	6/12	6/12	5/12												
15KUFC02	1	5/12	5/12	5/12												

Legend	
	0 successful attempts
	1 successful attempt
	2 successful attempts
	3 successful attempts

Text summary of results for validation of the FMS Hurdle Step screening test scoring criteria (Final)

For the final real-time scores, 21 out of the 24 participants were assigned to the correct scoring category and three participants were assigned to the incorrect scoring category (15KUFC07, 15KUFC11, 15KUFC02). Two participants were awarded a score of three, 21 participants were awarded a score of two and one participant was awarded a score of one. None of those awarded a real-time score of three (15KUFC07, 15KUFC11) met all 12 flag conditions in any attempt and have therefore not been correctly assigned. Twenty one participants were correctly assigned to the scoring category of two as they did not meet all the required criteria. No participants in scoring categories two and three consistently failed the criteria associated with the scoring category of one (flag conditions 10, 11, 12). The participant who was assigned to the category of one (15KUFC02) did not fail any criteria associated with these categories in any attempt and has therefore been assigned incorrectly.

Flag conditions (11) and (12), foot height higher than measured tibial height (to the test target and from test target), were consistently met by all participants over the three attempts. All participants failed to consistently meet flag conditions (3) and (5) over the three attempts. Flag condition (3) and (5) were used to check that no lumbar spine flexion and side flexion occurred respectively. Flag condition (10) was used to evaluate if loss of balance occurred. Flag conditions (11) and (12) were used to check if contact was made between the participant’s foot and hurdle.

6.2.3 Results for validation of the FMS Inline Lunge screening test scoring criteria

The FMS Inline Lunge test is completed for both the left and right sides. As per the FMS protocol, the lower of the two scores is used to determine the final score. For this subtest, a table of results for the FMS Inline Lunge left subtest has presented first (table 6.8) followed by a text summary of the results. The same format has been used for the following subtests of the FMS Inline Lunge right subtest and final score results (table 6.9 and table 6.10 respectively).

Table 6.8 Results for validation of the FMS Inline Lunge screening test scoring criteria (Left)

Inline lunge - Left - 14 flag conditions																		
ID	FMS subscore	Criteria met			Flag conditions													
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12	13	14
15KUFC10	3	9/14	9/14	9/14														
15KUFC11	3	6/14	8/14	8/14														
15KUFC15	3	6/14	6/14	6/14														
15KUFC01	2	8/14	6/14	5/14														
15KUFC03	2	7/14	6/14	7/14														
15KUFC04	2	8/14	7/14	5/14														
15KUFC05	2	6/14	5/14	7/14														
15KUFC06	2	5/14	5/14	5/14														
15KUFC07	2	8/14	8/14	7/14														
15KUFC08	2	5/14	3/14	2/14														
15KUFC09	2	9/14	8/14	6/14														
15KUFC12	2	8/14	7/14	7/14														
15KUFC13	2	8/14	8/14	8/14														
15KUFC14	2	7/14	7/14	6/14														
15KUFC16	2	7/14	7/14	7/14														
15KUFC17	2	8/14	6/14	8/14														
15KUFC18	2	7/14	8/14	8/14														
15KUFC19	2	7/14	9/14	3/14														
15KUFC21	2	5/14	7/14	5/14														
15KUFC22	2	6/14	2/14	6/14														
15KUFC23	2	9/14	8/14	9/14														
15KUFC24	2	7/14	8/14	7/14														
15KUFC25	2	5/14	6/14	8/14														
15KUFC02	1	4/14	3/14	3/14														

Legend	
	0 successful attempts
	1 successful attempt
	2 successful attempts
	3 successful attempts

Text summary of results for validation of the FMS Inline Lunge screening test scoring (Left)

For this subtest three participants were awarded a real-time score of three, 20 participants were awarded a score of two and one participant was awarded a score of one. None of those awarded a real-time score of three met all 14 criteria in any attempt and have therefore not been correctly assigned (15KUFC10, 15KUFC11, 15KUFC15). Twenty participants have correctly been assigned to the scoring category of two for this subtest. No participants in scoring categories two and three consistently failed the criteria associated with the scoring category of one (flag condition 14). The participant who was assigned to the category of one (15KUFC02) did not fail any criteria associated with this category in any attempt and has therefore been assigned incorrectly.

Flag conditions (2) and (5) were consistently met by all participants over the three attempts. Flag condition (2) was used to check if the dowel position changed more than 10 degrees from its starting position and flag condition (5) was used to ensure no thoracic rotation occurred. Flag condition (14) was used to evaluate if a loss of balance occurred. There were no flag conditions consistently not met over the three attempts by all participants.

Table 6.9 Results for validation of the FMS Inline Lunge screening test scoring criteria (Right)

Inline lunge - Right - 14 flag conditions																			
ID	FMS subscore	Criteria met			Flag conditions														
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12	13	14
15KUFC11	3	10/14	11/14	11/14														
15KUFC17	3	10/14	10/14	8/14														
15KUFC18	3	9/14	10/14	9/14														
15KUFC01	2	7/14	6/14	7/14														
15KUFC03	2	7/14	7/14	7/14														
15KUFC04	2	8/14	7/14	8/14														
15KUFC05	2	4/14	6/14	5/14														
15KUFC06	2	9/14	9/14	9/14														
15KUFC07	2	10/14	9/14	8/14														
15KUFC08	2	8/14	7/14	7/14														
15KUFC09	2	7/14	6/14	7/14														
15KUFC10	2	9/14	9/14	9/14														
15KUFC12	2	8/14	10/14	9/14														
15KUFC13	2	8/14	7/14	7/14														
15KUFC14	2	8/14	9/14	9/14														
15KUFC15	2	8/14	8/14	8/14														
15KUFC16	2	8/14	10/14	8/14														
15KUFC19	2	8/14	8/14	9/14														
15KUFC21	2	9/14	5/14	7/14														
15KUFC22	2	7/14	7/14	9/14														
15KUFC23	2	9/14	8/14	10/14														
15KUFC24	2	9/14	10/14	9/14														
15KUFC25	2	7/14	8/14	7/14														
15KUFC02	1	5/14	5/14	4/14														

Legend	
	0 successful attempts
	1 successful attempt
	2 successful attempts
	3 successful attempts

Text summary of results for validation of the FMS Inline Lunge screening test scoring (Right)

For this subtest three participants were awarded a real-time score of three, 20 participants were awarded a score of two and one participant was awarded a score of one. None of those awarded a real-time score of three (15KUFC11, 15KUFC17, 15KUFC18) met all 14 criteria in any attempt and have therefore not been correctly assigned. Twenty participants have correctly been assigned to the scoring category of two for this subtest. No participants in scoring categories two and three consistently failed the criteria associated with the scoring category of one, flag condition (14). The participant who was assigned to the category of one (15KUFC02) did not fail any criteria associated with this category in any attempt and has therefore been assigned incorrectly.

Flag condition (2), used to check the dowel position did not change more than 10 degrees from its starting position, was consistently met by all participants over the three attempts. All participants failed to consistently meet flag conditions (7) (8) and (9) over the three attempts. Flag condition (7 and 8) checked the ability of the participant to maintain the front foot and limb position with the sagittal plane of the laboratory throughout the attempt, and for the point at which the back leg touches the board behind the front foot. Flag condition (9) was used to check of the participant could maintain the back foot and limb position with the sagittal plane of the laboratory throughout the attempt. Flag condition (14) was used to check if loss of balance occurred.

Table 6.10 Results for validation of the FMS Inline Lunge screening test scoring criteria (Final)

Inline lunge - Final - 14 flag conditions																		
ID	FMS score	Criteria met			Flag conditions													
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12	13	14
15KUFC11	3	9/14	9/14	9/14	3	3	3	3	3	3	0	0	0	0	3	3	0	3
15KUFC01	2	8/14	6/14	5/14	3	3	1	2	3	2	0	0	0	0	0	2	0	3
15KUFC03	2	7/14	6/14	7/14	3	3	3	0	3	3	0	0	0	0	1	1	0	3
15KUFC04	2	8/14	7/14	5/14	2	3	3	2	3	3	0	0	0	0	1	0	0	3
15KUFC05	2	4/14	6/14	5/14	2	3	0	1	3	3	0	0	0	0	0	0	0	3
15KUFC06	2	5/14	5/14	5/14	1	3	0	0	3	3	0	0	0	0	2	0	0	3
15KUFC07	2	8/14	8/14	7/14	2	3	3	1	3	3	0	0	0	0	2	3	0	3
15KUFC08	2	5/14	3/14	2/14	1	3	0	0	0	0	0	0	0	0	3	2	0	1
15KUFC09	2	7/14	6/14	7/14	3	3	3	0	3	2	0	0	0	1	2	0	0	3
15KUFC10	2	8/14	7/14	7/14	3	3	3	2	2	3	0	0	0	0	3	0	0	3
15KUFC12	2	8/14	8/14	8/14	3	3	3	3	3	3	0	0	0	0	0	3	0	3
15KUFC13	2	7/14	7/14	6/14	3	3	0	0	3	2	0	0	0	0	3	3	0	3
15KUFC14	2	7/14	7/14	7/14	3	3	3	0	3	3	0	0	0	0	0	3	0	3
15KUFC15	2	8/14	6/14	8/14	3	3	3	3	2	1	0	0	0	1	1	2	0	3
15KUFC16	2	7/14	8/14	8/14	3	3	3	2	3	3	0	0	0	0	0	3	0	3
15KUFC17	2	8/14	8/14	8/14	2	3	3	3	3	3	0	0	0	0	1	3	0	3
15KUFC18	2	8/14	10/14	8/14	3	3	3	2	3	3	0	1	0	2	0	3	0	3
15KUFC19	2	7/14	9/14	3/14	1	3	2	1	2	2	0	0	0	0	3	3	0	2
15KUFC21	2	5/14	7/14	5/14	3	3	0	0	3	1	0	0	0	0	2	2	0	3
15KUFC22	2	6/14	2/14	6/14	2	3	1	0	2	2	0	0	0	0	0	2	0	2
15KUFC23	2	9/14	8/14	9/14	3	3	3	3	3	3	0	0	0	0	3	2	0	3
15KUFC24	2	7/14	8/14	7/14	3	3	3	2	3	3	0	0	0	2	0	0	0	3
15KUFC25	2	5/14	6/14	8/14	0	3	1	0	3	2	0	0	0	2	3	1	1	3
15KUFC02	1	4/14	3/14	3/14	0	3	0	0	3	1	0	0	0	0	0	0	0	3

Legend	
Red	0 successful attempts
Orange	1 successful attempt
Yellow	2 successful attempts
Green	3 successful attempts

Text summary of results for validation of the FMS Inline Lunge screening test scoring (Final)

For the final real-time scores, 22 out of the 24 participants were assigned to the correct scoring category and two participants were assigned to the incorrect scoring category. One participant was awarded a score of three (15KUFC11), 22 participants were awarded a score of two and one participant was awarded a score of one (15KUFC02). The participant awarded a real-time score of three (15KUFC11) did not met all 14 criteria in any attempt and has therefore not been correctly assigned. Twenty-two participants were correctly assigned to the scoring category of two as they did not meet all the required criteria. No participants in scoring categories two and three consistently failed the criteria associated with the scoring category of one, flag conditions (14). The participant who was assigned to the category of one (15KUFC02) did not fail any criteria associated with this category in any attempt and has therefore been assigned incorrectly.

Flag condition (2), used to check the dowel position did not change more than 10 degrees from its starting position, was consistently met by all participants over the three attempts. All participants failed to consistently meet flag conditions (7) and (9) over the three attempts. Flag condition (7) checked the ability of the participant to maintain the front foot and limb position with the sagittal plane of the laboratory throughout the attempt, and flag condition (9) was used to check of the participant could maintain the back foot and limb position with the sagittal plane of the laboratory throughout the attempt. Flag condition (14) was used to check if loss of balance occurred.

6.2.4 Results for validation of the FMS Shoulder Mobility screening test scoring criteria and scoring variable

The FMS Shoulder Mobility test is completed for both the left and right sides. Additionally clearing tests are conducted for the left and right. As per the FMS protocol, the lower of the two scores is used to determine the final score. For this subtest, a table of results for the FMS Shoulder Mobility left subtest has presented first (table 6.11) followed by a text summary of the results. The same format has been used for the following subtests of the FMS Shoulder Mobility right subtest and final score results (table 6.12 and table 6.13 respectively).

Table 6.11 Results for validation of the FMS Shoulder Mobility screening test and scoring variable (Left)

Shoulder Mobility - Left - 2 Flag conditions									
ID	FMS subscore	Criteria met			Score based on minimal hand distance only			Flag conditions	
		Attempt 1	Attempt 2	Attempt 3	Score 1	Score 2	Score 3	1	2
15KUFC07	3	2/2	2/2	0/2	2	2	2		
15KUFC17	3	0/2	0/2	1/2	2	2	2		
15KUFC21	3	2/2	1/2	2/2	2	2	2		
15KUFC24	3	1/2	1/2	0/2	2	2	1		
15KUFC04	2	2/2	2/2	2/2	1	1	1		
15KUFC06	2	0/2	1/2	1/2	1	1	1		
15KUFC08	2	2/2	2/2	2/2	1	1	1		
15KUFC09	2	1/2	2/2	2/2	2	2	2		
15KUFC11	2	2/2	2/2	2/2	2	2	2		
15KUFC13	2	1/2	2/2	1/2	1	1	1		
15KUFC16	2	1/2	2/2	2/2	1	1	1		
15KUFC18	2	1/2	1/2	2/2	1	1	1		
15KUFC23	2	0/2	1/2	1/2	1	1	1		
15KUFC01	1	2/2	2/2	2/2	1	1	1		
15KUFC02	1	0/2	0/2	0/2	1	1	1		
15KUFC05	1	0/2	0/2	0/2	1	1	1		
15KUFC10	1	2/2	2/2	2/2	1	1	1		
15KUFC12	1	1/2	1/2	2/2	1	1	1		
15KUFC14	1	1/2	2/2	1/2	1	1	1		
15KUFC15	1	2/2	2/2	2/2	1	1	1		
15KUFC19	1	0/2	0/2	0/2	1	1	1		
15KUFC22	1	1/2	2/2	2/2	1	1	1		
15KUFC25	1	2/2	2/2	2/2	1	1	1		
15KUFC03	0	0/2	2/2	2/2	1	1	1		

Legend
0 successful attempts
1 successful attempt
2 successful attempts
3 successful attempts

*The boxes highlighted in green indicate attempts where the real-time assessor score was the same as that awarded by the photogrammetric system

Text summary of results for validation of the FMS Shoulder Mobility screening test and scoring variable (Left)

For this subtest, four participants were awarded a real-time score of three; nine participants were awarded a score of two, 10 participants were awarded a score of one and one participant was awarded a score of zero. None of those awarded a real-time score of three successfully met all the required criteria (15KUFC07, 15KUFC17, 15KUFC21, 15KUFC24). Two participants were correctly assigned the score of two as they met the required criteria (15KUFC09, 15KUFC11). The remaining seven participants within the scoring category of two did not meet the required criteria and have therefore not been correctly assigned. All ten participants with a score of one were correctly classified to that scoring category.

There were no patterns to be observed with respect to criteria met or not met.

Table 6.12 Results for validation of the FMS Shoulder Mobility screening test and scoring variable (Right)

Shoulder Mobility - Right - 2 Flag conditions									
ID	FMS subscore	Criteria met			Score based on minimal hand distance only			Flag conditions	
		Attempt 1	Attempt 2	Attempt 3	Score 1	Score 2	Score 3	1	2
15KUFC06	3	0/2	1/2	2/2	1	1	1		
15KUFC07	3	2/2	2/2	2/2	1	1	1		
15KUFC11	3	1/2	2/2	2/2	1	1	1		
15KUFC12	3	2/2	1/2	2/2	1	1	1		
15KUFC16	3	1/2	2/2	2/2	1	1	1		
15KUFC21	3	1/2	1/2	2/2	1	1	1		
15KUFC23	3	2/2	2/2	2/2	1	1	1		
15KUFC04	2	2/2	2/2	2/2	2	2	1		
15KUFC08	2	2/2	2/2	2/2	2	2	2		
15KUFC09	2	2/2	2/2	2/2	2	2	2		
15KUFC13	2	2/2	1/2	2/2	1	1	1		
15KUFC17	2	2/2	2/2	2/2	1	1	1		
15KUFC18	2	0/2	0/2	2/2	1	1	1		
15KUFC24	2	1/2	1/2	0/2	1	1	1		
15KUFC01	1	2/2	2/2	2/2	2	2	2		
15KUFC02	1	1/2	1/2	2/2	2	2	2		
15KUFC03	1	2/2	2/2	2/2	2	2	2		
15KUFC05	1	2/2	2/2	2/2	1	1	1		
15KUFC10	1	2/2	2/2	2/2	1	1	1		
15KUFC14	1	2/2	2/2	2/2	1	1	1		
15KUFC15	1	2/2	2/2	2/2	1	1	1		
15KUFC19	1	1/2	0/2	2/2	1	1	1		
15KUFC22	1	1/2	2/2	0/2	1	1	1		
15KUFC25	1	2/2	1/2	2/2	1	1	1		

Legend	
	0 successful attempts
	1 successful attempt
	2 successful attempts
	3 successful attempts

*The boxes highlighted in green indicate attempts where the real-time assessor score was the same as that awarded by the photogrammetric system

Text summary of results for validation of the FMS Shoulder Mobility screening test and scoring variable (Right)

For this subtest, seven participants were awarded a real-time score of three; seven participants were awarded a score of two, and 10 participants were awarded a score of one. None of those awarded a real-time score of three successfully met all the required criteria. Three participants were correctly assigned the score of two as they met the required criteria (15KUFC04, 15KUFC08, 15KUFC09). The remaining four participants, within the scoring category of two, did not meet the required criteria and have therefore not been correctly assigned. Of the 10 participants assigned to the scoring category of one, seven participants have been correctly assigned whilst the other three participants (15KUFC01, 15KUFC02, 15KUFC03) have not been assigned to the correct scoring category as they meet the criteria for scoring category two (flag conditions (1), (2) and score of two awarded by the photogrammetric system).

There were no patterns to be observed with respect to criteria met or not met.

Table 6.13 Results for validation of the FMS Shoulder mobility screening test and scoring variable (Final)

Shoulder Mobility - Final - 2 Flag conditions									
ID	FMS score	Criteria met			Score based on minimal hand distance only			Flag conditions	
		Attempt 1	Attempt 2	Attempt 3	Score 1	Score 2	Score 3	1	2
15KUFC07	3	2/2	2/2	0/2	2	2	2		
15KUFC21	3	1/2	1/2	2/2	2	3	2		
15KUFC23	3	2/2	2/2	2/2	1	1	1		
15KUFC04	2	2/2	2/2	2/2	1	1	1		
15KUFC06	2	0/2	1/2	1/2	1	1	1		
15KUFC08	2	2/2	2/2	2/2	1	1	1		
15KUFC09	2	1/2	2/2	2/2	2	2	2		
15KUFC11	2	2/2	2/2	2/2	2	2	2		
15KUFC13	2	1/2	2/2	1/2	1	1	1		
15KUFC16	2	1/2	2/2	2/2	1	1	1		
15KUFC17	2	2/2	2/2	2/2	2	1	2		
15KUFC18	2	0/2	0/2	2/2	1	1	1		
15KUFC24	2	1/2	1/2	0/2	2	2	2		
15KUFC01	1	2/2	2/2	2/2	1	1	1		
15KUFC02	1	0/2	0/2	0/2	1	1	1		
15KUFC05	1	0/2	0/2	0/2	1	1	1		
15KUFC10	1	2/2	2/2	2/2	1	1	1		
15KUFC12	1	1/2	1/2	2/2	1	1	1		
15KUFC14	1	1/2	2/2	1/2	1	1	1		
15KUFC15	1	2/2	2/2	2/2	1	1	1		
15KUFC19	1	0/2	0/2	0/2	1	1	1		
15KUFC22	1	1/2	2/2	0/2	1	1	1		
15KUFC25	1	2/2	1/2	2/2	1	1	1		
15KUFC03	0	0/2	2/2	2/2	1	1	1		

Legend	
	0 successful attempts
	1 successful attempt
	2 successful attempts
	3 successful attempts

*The boxes highlighted in green indicate attempts where the real-time assessor score was the same as that awarded by the photogrammetric system

Text summary of results for validation of the FMS Shoulder Mobility screening test and scoring variable (Final)

For the final real-time scores, 13 out of 24 participants were assigned to the correct scoring category and 11 participants were assigned to the incorrect scoring category. No participants were correctly assigned to the scoring category of three. Three participants were correctly assigned to the scoring category of two (15KUFC09, 15KUFC11, 15KUFC15) and eight participants were correctly assigned to the scoring category of one. Of the three participants awarded a real-time score of three; two participants should have been assigned to the scoring category of two (15KUFC07 and 15KUFC21) and one participant should have been assigned to the scoring category of one (15KUFC23). Of the participants awarded a real-time score of two; three participants were assigned to the correct category (15KUFC09, 15KUFC11 and 15KUFC17) and seven participants were incorrectly assigned to the scoring category of two as opposed to one. All 10 participants were correctly assigned to the scoring category of one. As the criteria for scoring a zero pain, reported by the participant, it is not possible to check if they have been assigned to the correct category based on the quantified variables.

There were no patterns to be observed with respect to criteria met or not met.

6.2.5 Results for validation of the FMS Active Straight-Leg Raise screening test scoring criteria and scoring variables

The FMS Active Straight-Leg Raise test is completed for both the left and right sides. As per the FMS protocol, the lower of the two scores is used to determine the final score. For this subtest, a table of results for the FMS Active Straight-Leg Raise left subtest has presented first (table 6.14) followed by a text summary of the results. The same format has been used for the following subtests of the FMS Active Straight-Leg Raise right subtest and final score results (table 6.15 and table 6.16 respectively).

Table 6.14 Results for validation of the FMS Active Straight-Leg Raise screening test scoring criteria and scoring variables (Left)

Active straight leg raise- Left - 10 flag conditions																		
ID	FMS subscore	Criteria met			Score based on ankle position only			Flag Conditions										
		Attempt 1	Attempt 2	Attempt 3	Score 1	Score 2	Score 3	1	2	3	4	5	6	7	8	9	10
15KUFC02_	3	3/10	5/10	5/10	3	3	3										
15KUFC06_	3	3/10	4/10	5/10	3	3	2										
15KUFC08_	3	7/10	7/10	6/10	2	2	2										
15KUFC09_	2	4/10	6/10	7/10	2	2	2										
15KUFC13_	2	6/10	7/10	6/10	2	2	2										
15KUFC01_	1	5/10	7/10	7/10	1	1	1										
15KUFC03_	1	7/10	7/10	7/10	1	1	1										
15KUFC04_	1	4/10	6/10	6/10	2	1	1										
15KUFC05_	1	6/10	7/10	5/10	2	2	2										
15KUFC07_	1	8/10	7/10	8/10	1	1	1										
15KUFC11_	1	5/10	5/10	6/10	2	2	2										
15KUFC12_	1	6/10	8/10	6/10	2	1	1										
15KUFC14_	1	6/10	8/10	7/10	2	2	2										
15KUFC15_	1	5/10	5/10	5/10	2	2	2										
15KUFC16_	1	6/10	6/10	7/10	2	2	1										
15KUFC17_	1	3/10	6/10	5/10	2	2	2										
15KUFC18_	1	7/10	7/10	7/10	2	2	2										
15KUFC19_	1	3/10	5/10	7/10	2	2	2										
15KUFC21_	1	4/10	7/10	7/10	2	2	2										
15KUFC22_	1	6/10	6/10	6/10	2	2	2										
15KUFC23_	1	5/10	6/10	6/10	2	2	2										
15KUFC24_	1	5/10	6/10	6/10	2	2	2										
15KUFC25_	1	6/10	6/10	7/10	2	2	1										
15KUFC10_	1	No data	No data	No data	No data	No data	No data										

Legend
0 successful attempts
1 successful attempt
2 successful attempts
3 successful attempts

*The boxes highlighted in green indicate attempts where the real-time assessor score was the same as that awarded by the photogrammetric system

Text summary of results for validation of the FMS Active Straight-Leg Raise screening test scoring criteria and scoring variables (Left)

For this subtest, three participants were awarded a real-time score of a three; two participants were awarded a score of two, and 18 participants were awarded a score of one. Data were not available for one participant due to problems with marker reconstruction (15KUFC10). No participants were correctly assigned to the scoring category of three as they did not meet the all the required criteria. The score awarded by the photogrammetric system was the same as the real-time assessor score for two out of three participants in the scoring category of three (15KUFC02 and 15KUFC06). The score awarded by the photogrammetric system was the same as the real-time assessor score for both participants in the scoring category of two (15KUFC09 and 15KUFC13). In the scoring category of one, the score awarded by the photogrammetric system was the same as the real-time assessor score for seven participants (15KUFC01, 15KUFC03, 15KUFC04, 15KUFC07, 15KUFC12, 15KUFC16 and 15KUFC25). The remaining 11 participants in scoring category one was awarded a higher score of two by the photogrammetric system. All participants failed to consistently meet flag condition (9) over the three attempts. Flag condition (9) checked the static limb foot position relative to the horizontal axis for the start of the attempt. There were no flag conditions consistently met over the three attempts by all participants.

Table 6.15 Results for validation of the FMS Active Straight-Leg Raise screening test scoring criteria and scoring variables (Right)

Active straight leg raise- Right - 10 flag conditions																		
ID	FMS subscore	Criteria met			Score based on ankle position only			Flag Conditions										
		Attempt 1	Attempt 2	Attempt 3	Score 1	Score 2	Score 3	1	2	3	4	5	6	7	8	9	10
15KUFC02_	3	5/10	5/10	5/10	3	3	3										
15KUFC06_	3	4/10	6/10	6/10	3	2	3										
15KUFC01_	2	5/10	6/10	7/10	2	2	2										
15KUFC08_	2	7/10	7/10	8/10	3	3	3										
15KUFC09_	2	2/10	4/10	4/10	3	3	3										
15KUFC11_	2	2/10	5/10	5/10	2	2	2										
15KUFC13_	2	2/10	4/10	5/10	3	3	3										
15KUFC03_	1	5/10	5/10	6/10	1	1	1										
15KUFC04_	1	3/10	5/10	5/10	2	1	1										
15KUFC05_	1	5/10	6/10	5/10	2	2	2										
15KUFC07_	1	6/10	8/10	7/10	1	1	1										
15KUFC12_	1	4/10	7/10	7/10	2	2	2										
15KUFC14_	1	5/10	6/10	8/10	2	2	2										
15KUFC15_	1	3/10	3/10	4/10	2	2	2										
15KUFC16_	1	5/10	6/10	6/10	2	2	2										
15KUFC17_	1	5/10	6/10	6/10	2	2	2										
15KUFC18_	1	7/10	7/10	8/10	2	2	1										
15KUFC19_	1	3/10	8/10	4/10	3	2	2										
15KUFC21_	1	3/10	4/10	6/10	2	2	2										
15KUFC22_	1	4/10	4/10	5/10	3	2	2										
15KUFC23_	1	3/10	6/10	6/10	2	2	2										
15KUFC24_	1	4/10	5/10	6/10	2	2	2										
15KUFC25_	1	5/10	7/10	7/10	2	2	2										
15KUFC10_	1	No data	No data	No data	No data	No data	No data										

Legend	
	0 successful attempts
	1 successful attempt
	2 successful attempts
	3 successful attempts

*The boxes highlighted in green indicate attempts where the real-time assessor score was the same as that awarded by the photogrammetric system.

Text summary of results for validation of the FMS Active Straight-Leg Raise screening test scoring criteria and scoring variables (Right)

For this subtest, two participants were awarded a real-time score of three; five participants were awarded a score of two, and 17 participants were awarded a score of one. Data were not available for one participant due to problems with marker reconstruction (15KUFC10). No participants were correctly assigned to the scoring category of three as they did not meet the all the required criteria (15KUFC02 and 15KUFC06). The score awarded by the photogrammetric system was the same as the real-time assessor score for both participants in scoring category three. The score awarded by the photogrammetric system was the same as the real-time assessor score for two out of the five participants assigned to the scoring category of two (15KUFC01 and 15KUFC11). The remaining three participants in scoring category two were awarded a higher score of three by the photogrammetric system. In the scoring category of one, the score awarded by the photogrammetric system was the same as the real-time assessor score for four out of 16 participants (15KUFC03, 15KUFC04, 15KUFC07 and 15KUFC18). The remaining 12 participants in scoring category one, were awarded a higher score of two by the photogrammetric system. All participants failed to consistently meet flag condition (9) over the three attempts. Flag condition (9) checked the static limb foot position relative to the horizontal axis for the start of the attempt. There were no flag conditions consistently met over the three attempts by all participants

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Table 6.16 Results for validation of the FMS Active Straight-Leg Raise screening test scoring criteria and scoring variables (Final)

Active straight leg raise- Final - 10 flag conditions																		
ID	FMS score	Criteria met			Score based on ankle position only			Flag Conditions										
		Attempt 1	Attempt 2	Attempt 3	Score 1	Score 2	Score 3	1	2	3	4	5	6	7	8	9	10
15KUFC02	3	3/10	5/10	5/10	3	3	3										
15KUFC06	3	4/10	6/10	6/10	3	3	2										
15KUFC08	2	7/10	7/10	8/10	3	3	3										
15KUFC09	2	2/10	4/10	4/10	3	3	3										
15KUFC13	2	2/10	4/10	5/10	3	3	3										
15KUFC01	1	4/10	6/10	6/10	1	1	1										
15KUFC03	1	5/10	5/10	6/10	1	1	1										
15KUFC04	1	3/10	5/10	5/10	2	1	1										
15KUFC05	1	6/10	7/10	5/10	2	2	2										
15KUFC07	1	6/10	8/10	7/10	1	1	1										
15KUFC11	1	4/10	4/10	5/10	2	2	2										
15KUFC12	1	5/10	7/10	5/10	2	1	1										
15KUFC14	1	5/10	7/10	6/10	2	2	2										
15KUFC15	1	3/10	3/10	4/10	2	2	2										
15KUFC16	1	5/10	5/10	6/10	2	2	1										
15KUFC17	1	2/10	5/10	4/10	2	2	2										
15KUFC18	1	6/10	6/10	6/10	2	2	2										
15KUFC19	1	2/10	4/10	6/10	2	2	2										
15KUFC21	1	3/10	4/10	6/10	2	2	2										
15KUFC22	1	4/10	4/10	5/10	3	2	2										
15KUFC23	1	4/10	5/10	5/10	2	2	2										
15KUFC24	1	4/10	5/10	5/10	2	2	2										
15KUFC25	1	5/10	5/10	6/10	2	2	1										
15KUFC10	1	No data	No data	No data	No data	No data	No data										

Legend
0 successful attempts
1 successful attempt
2 successful attempts
3 successful attempts

*The boxes highlighted in green indicate attempts where the real-time assessor score was the same as that awarded by the photogrammetric system

Text summary of results for validation of the FMS Active Straight-Leg Raise screening test scoring criteria and scoring variables (Final)

For the final scores, two participants were awarded a real-time score of three; three participants were awarded a score of two, and 19 participants were awarded a score of one. Data were not available for one participant due to problems with marker reconstruction (15KUFC10). For the final real-time scores, no participants were correctly assigned to the scoring category of three as they did not meet the all the required criteria. The score awarded by the photogrammetric system was the same as the real-time assessor score for both participants in scoring category three (15KUFC02 and 15KUFC06). For all three participants in scoring category two, the score for awarded by the photogrammetric system did not match the real time assessor score (15KUFC08, 15KUFC09 and 15KUFC13). All scores awarded by the photogrammetric system for the scoring category of two were higher than the real-time assessor awarded score. In the scoring category of one, the score awarded by the photogrammetric system was the same as the real-time assessor score for seven out of 18 participants (15KUFC01, 15KUFC03, 15KUFC04, 15KUFC07, 15KUFC16 and 15KUFC25). For the remaining 11 participants the scores awarded by the photogrammetric system for the scoring category of one were higher than the real-time assessor awarded score. All participants failed to consistently meet flag condition (9) over the three attempts. Flag condition (9) checked the static limb foot position relative to the horizontal axis for the start of the attempt. There were no flag conditions consistently met over the three attempts by all participants

6.2.6 Results for validation of the FMS Trunk Stability Push-up screening test scoring criteria

The FMS Trunk Stability Push-up test is completed in addition to a spinal extension test. For this subtest, a table of results has presented first (Table 6.17) followed by a text summary of the results.

Table 6.17 Results for validation of the FMS Trunk Stability Push-Up screening test scoring criteria

Trunk Stability push up- Final - 10 flag conditions														
ID	FMS score	**Criteria met**			**Flag conditions**									
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10
15KUFC01	3	7/10	7/10	6/10	Yellow	Red	Green	Green	Green	Green	Red	Red	Green	Green
15KUFC02	3	10/10	8/10	7/10	Yellow	Green	Green	Green	Green	Green	Orange	Orange	Green	Green
15KUFC03	3	10/10	8/10	8/10	Green	Green	Green	Green	Green	Green	Orange	Orange	Green	Green
15KUFC04	3	5/10	8/10	5/10	Yellow	Yellow	Green	Yellow	Green	Yellow	Red	Red	Yellow	Yellow
15KUFC05	3	6/10	5/10	7/10	Green	Green	Yellow	Green	Orange	Red	Red	Red	Green	Green
15KUFC06	3	8/10	7/10	8/10	Red	Yellow	Yellow	Green	Green	Green	Orange	Green	Green	Green
15KUFC07	3	6/10	6/10	9/10	Green	Green	Orange	Green	Green	Orange	Orange	Red	Green	Green
15KUFC08	3	7/10	4/10	6/10	Orange	Yellow	Green	Green	Green	Yellow	Red	Red	Red	Green
15KUFC09	3	8/10	10/10	7/10	Green	Yellow	Yellow	Green	Green	Green	Orange	Yellow	Green	Green
15KUFC10	3	9/10	7/10	7/10	Yellow	Green	Green	Green	Yellow	Green	Red	Orange	Green	Green
15KUFC11	3	4/10	8/10	9/10	Yellow	Yellow	Red	Green	Yellow	Green	Orange	Yellow	Green	Green
15KUFC12	3	8/10	7/10	7/10	Green	Green	Green	Green	Green	Orange	Red	Red	Green	Green
15KUFC13	3	8/10	7/10	5/10	Yellow	Yellow	Yellow	Green	Green	Green	Red	Red	Yellow	Green
15KUFC14	3	8/10	8/10	7/10	Green	Yellow	Green	Green	Green	Yellow	Orange	Red	Green	Green
15KUFC15	3	10/10	9/10	9/10	Green	Green	Green	Green	Green	Green	Green	Orange	Green	Green
15KUFC16	3	8/10	8/10	8/10	Green	Green	Green	Green	Green	Green	Red	Red	Green	Green
15KUFC17	3	6/10	5/10	6/10	Orange	Red	Green	Green	Orange	Orange	Yellow	Red	Green	Green
15KUFC18	3	7/10	8/10	7/10	Yellow	Orange	Green	Green	Green	Green	Red	Orange	Green	Green
15KUFC19	3	10/10	6/10	10/10	Yellow	Yellow	Green	Green	Green	Green	Yellow	Yellow	Green	Green
15KUFC21	3	7/10	8/10	6/10	Orange	Yellow	Green	Green	Green	Yellow	Red	Orange	Green	Green
15KUFC22	3	8/10	8/10	8/10	Green	Green	Green	Green	Green	Green	Red	Red	Green	Green
15KUFC23	3	6/10	8/10	7/10	Yellow	Yellow	Green	Green	Green	Green	Red	Red	Green	Yellow
15KUFC24	3	6/10	7/10	5/10	Green	Orange	Yellow	Green	Orange	Red	Red	Yellow	Green	Green
15KUFC25	3	8/10	7/10	8/10	Green	Green	Yellow	Green	Green	Green	Red	Red	Green	Green

Legend	
Red	0 successful attempts
Orange	1 successful attempt
Yellow	2 successful attempts
Green	3 successful attempts

Text summary of results for validation of the FMS Trunk Stability Push-Up screening test scoring criteria

All participants were awarded a final real-time score of three. For the final real-time scores, five out of the 24 participants were assigned to the correct scoring category (15KUFC02, 15KUFC03, 15KUFC09, 15KUFC15 and 15KUFC19) and 19 participants were assigned to the incorrect scoring category. There were no flag conditions consistently not met over the three attempts by all participants.

6.2.7 Results for validation of the FMS Rotary Stability screening test scoring criteria

The FMS Rotary Stability test has two variations, one without an adjustment (unilateral repetition) and one with an adjustment (diagonal repetition). These are completed for both the left and right sides. Additionally a spinal flexion clearing test was conducted. As per the FMS protocol the lowest score is used to determine the final score. For this subtest, a table of results for the Rotary Stability unilateral left subtest has been presented first (table 6.18) followed by a text summary of the results. The same format has been used for the Rotary Stability unilateral right subtest (table 6.19), Rotary Stability diagonal left subtest (table 6.20), Rotary Stability diagonal right subtest (table 6.21) and final score results (table 6.22).

Table 6.18 Results for validation of the FMS Rotary Stability screening test scoring criteria (Unilateral Left)

Rotary stability Unilateral repetition - Left - 23 variables																											
ID	FMS subscore	Criteria met			Flag conditions																						
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
15KUFC01	2	15/23	11/23	15/23																							
15KUFC04	2	9/23	10/23	8/23																							
15KUFC06	2	9/23	11/23	13/23																							
15KUFC07	2	9/23	13/23	11/23																							
15KUFC08	2	13/23	11/23	13/23																							
15KUFC09	2	10/23	9/23	13/23																							
15KUFC10	2	9/23	10/23	13/23																							
15KUFC11	2	15/23	15/23	16/23																							
15KUFC12	2	13/23	10/23	13/23																							
15KUFC13	2	9/23	10/23	7/23																							
15KUFC14	2	13/23	13/23	13/23																							
15KUFC15	2	7/23	10/23	11/23																							
15KUFC16	2	8/23	10/23	6/23																							
15KUFC17	2	10/23	9/23	14/23																							
15KUFC18	2	11/23	9/23	13/23																							
15KUFC19	2	9/23	8/23	8/23																							
15KUFC21	2	6/23	15/23	13/23																							
15KUFC23	2	5/23	10/23	12/23																							
15KUFC24	2	13/23	13/23	14/23																							
15KUFC25	2	8/23	8/23	8/23																							
15KUFC02	1	11/23	12/23	10/23																							
15KUFC03	1	9/23	8/23	10/23																							
15KUFC05	1	13/23	10/23	13/23																							
15KUFC22	1	14/23	12/23	12/23																							

Legend
0 successful attempts
1 successful attempt
2 successful attempts
3 successful attempts

Text summary of results for validation of the FMS Rotary Stability screening test scoring criteria (Unilateral Left)

For this subtest, no participants were awarded a score of three. To check if those not awarded a three were assigned to the correct scoring category; see results for validation of the Rotary Stability (diagonal repetition) test scoring criteria.

Flag condition (4), used to check the stabilising ankle angle remains unchanged throughout attempts, was consistently met by all participants over the three attempts. No flag conditions were consistently not met by all participants over three attempts.

Table 6.19 Results for validation of the FMS Rotary Stability screening test scoring criteria (Unilateral right)

Rotary stability Unilateral - Right - 23 variables																											
ID	FMS subscore	Criteria met			Flag conditions																						
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
15KUFC11	3	18/23	16/23	15/23	3	3	1	3	0	0	3	1	1	3	1	0	0	3	3	3	3	3	3	3	3	3	3
15KUFC01	2	18/23	18/23	11/23	2	2	2	3	0	2	3	3	3	3	3	0	0	1	3	3	2	2	2	0	3	3	2
15KUFC03	2	14/23	12/23	9/23	3	3	1	3	0	0	1	0	0	0	3	0	0	0	3	3	3	2	2	0	3	3	2
15KUFC04	2	12/23	6/23	12/23	2	1	0	3	0	0	1	0	3	3	2	0	0	0	3	2	1	2	1	0	3	2	1
15KUFC05	2	14/23	16/23	11/23	1	1	0	3	0	0	3	3	3	3	3	0	0	1	3	3	2	3	2	0	3	3	1
15KUFC06	2	11/23	14/23	9/23	0	0	2	3	0	0	3	2	3	3	3	0	0	0	3	3	1	1	0	0	3	3	1
15KUFC07	2	8/23	12/23	14/23	2	1	0	3	0	0	2	2	1	1	2	0	0	1	3	3	2	3	1	2	3	1	1
15KUFC08	2	14/23	15/23	12/23	2	2	0	3	0	0	2	1	2	3	1	0	0	2	3	3	0	3	2	3	3	3	3
15KUFC09	2	14/23	14/23	12/23	2	2	2	3	0	0	3	1	1	1	1	2	0	0	3	3	3	3	2	0	3	3	2
15KUFC10	2	6/23	13/23	11/23	2	0	0	3	0	1	0	0	1	1	3	0	0	0	3	3	2	2	2	0	3	2	2
15KUFC12	2	11/23	11/23	13/23	1	1	1	3	0	0	3	3	0	0	2	0	0	0	3	3	3	2	1	0	3	3	3
15KUFC13	2	10/23	14/23	6/23	1	2	0	3	0	0	1	1	1	1	2	1	0	2	3	3	0	1	0	1	3	3	1
15KUFC14	2	10/23	14/23	13/23	2	2	1	3	0	0	3	2	3	0	3	0	0	0	3	3	1	2	2	0	3	2	2
15KUFC15	2	16/23	10/23	18/23	3	3	1	3	0	0	3	3	3	3	1	1	0	0	3	3	3	2	2	1	2	2	2
15KUFC16	2	12/23	10/23	16/23	3	2	3	3	0	0	0	1	3	2	2	2	0	0	3	3	3	1	1	0	3	2	1
15KUFC17	2	11/23	7/23	12/23	2	2	0	3	0	1	3	0	1	1	0	0	0	0	3	3	2	1	1	0	3	3	1
15KUFC18	2	13/23	11/23	9/23	1	2	1	3	0	0	3	3	0	0	2	0	0	2	3	3	3	2	0	0	3	1	1
15KUFC19	2	10/23	13/23	13/23	2	3	1	3	0	0	2	3	0	0	3	0	0	0	3	3	3	3	1	0	3	2	1
15KUFC21	2	14/23	7/23	7/23	0	2	1	3	0	0	2	2	2	2	1	0	0	2	1	3	2	1	0	1	0	2	1
15KUFC23	2	8/23	17/23	9/23	3	2	2	3	0	0	3	2	0	1	3	0	0	1	3	2	1	2	0	1	3	1	1
15KUFC24	2	12/23	11/23	10/23	1	1	1	3	0	0	3	3	3	3	2	0	0	1	3	3	1	0	0	0	3	2	0
15KUFC25	2	11/23	8/23	10/23	2	1	1	3	0	2	1	0	3	2	3	1	0	1	3	2	0	1	0	0	3	0	0
15KUFC02	1	10/23	9/23	8/23	2	0	1	3	0	0	1	0	3	3	2	1	0	0	3	3	0	1	0	0	2	2	0
15KUFC22	1	14/23	12/23	11/23	2	1	2	3	0	0	3	3	3	2	2	0	0	3	3	3	3	1	0	0	3	0	0

Legend	
0	0 successful attempts
1	1 successful attempt
2	2 successful attempts
3	3 successful attempts

Text summary of results for validation of the FMS Rotary Stability screening test scoring criteria (Unilateral Right)

For this subtest, one participant was awarded a real-time assessor score of three (15KUFC11). On review of the three attempts, they failed to meet all 23 criteria in any attempt. In this instance, a score of three should not have been awarded and the participant has been classified incorrectly. The remaining participants were correctly not awarded a real-time assessor score of three.

Flag condition (4), used to check the stabilising ankle angle remains unchanged throughout attempts, was consistently met by all participants over the three attempts. All participants failed to consistently meet flag conditions (5) and (13) over the three attempts. Flag condition (5) checked the stabilising limb foot position was perpendicular to the horizontal axis for the start of the attempt. Flag condition (13) checked that the moving leg remained in line over the board throughout the attempt.

To check if those not awarded a three were assigned to the correct scoring category; see results for validation of the Rotary Stability (diagonal repetition) test scoring criteria.

Table 6.20 Results for validation of the FMS Rotary Stability screening test scoring criteria (diagonal left)

Rotary stability - diagonal repetition - Left - all attempts																											
ID	FMS subscore	Criteria met			Flag conditions																						
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
15KUFC01	2	19/23	17/23	17/23	2	2	3	3	0	0	3	3	3	3	3	3	2	2	0	3	3	3	3	3	3	0	3
15KUFC04	2	16/23	14/23	16/23	2	3	1	3	0	0	1	0	3	3	3	3	2	1	0	3	3	3	3	3	3	0	3
15KUFC06	2	19/23	19/23	15/23	2	3	2	3	0	0	3	3	3	2	3	2	3	2	1	3	3	3	3	3	3	0	3
15KUFC07	2	14/23	19/23	16/23	3	3	2	3	0	0	1	1	1	2	3	3	3	1	1	3	3	3	3	3	3	1	3
15KUFC08	2	15/23	17/23	18/23	1	3	2	3	0	0	3	3	3	3	3	3	2	3	0	2	3	3	3	3	3	0	1
15KUFC09	2	16/23	14/23	17/23	3	2	0	3	0	0	1	3	0	0	2	3	2	1	3	3	3	3	3	3	3	3	3
15KUFC10	2	16/23	17/23	19/23	2	3	2	3	0	2	0	0	3	2	3	3	1	2	3	3	3	3	3	3	3	2	3
15KUFC11	2	18/23	17/23	18/23	1	2	0	3	0	0	2	3	1	3	3	3	3	2	3	3	3	3	3	3	3	3	3
15KUFC12	2	17/23	11/23	14/23	2	3	2	3	0	0	1	1	1	2	2	3	1	0	0	3	3	3	3	3	3	0	3
15KUFC13	2	16/23	15/23	15/23	2	3	1	3	0	0	2	0	2	1	3	3	2	3	0	3	3	3	3	3	3	0	3
15KUFC14	2	16/23	15/23	16/23	3	1	1	3	0	0	3	1	3	2	3	3	2	2	0	3	3	2	3	3	3	0	3
15KUFC15	2	17/23	20/23	19/23	3	2	1	3	1	0	3	3	3	3	3	3	2	2	2	3	3	3	3	3	3	1	3
15KUFC16	2	16/23	17/23	17/23	2	3	3	3	0	0	1	0	3	3	3	3	3	2	0	3	3	3	3	3	3	0	3
15KUFC17	2	14/23	12/23	14/23	2	2	1	3	0	0	1	0	1	0	2	3	2	3	0	3	3	3	3	3	2	0	3
15KUFC18	2	18/23	16/23	14/23	2	1	0	3	0	0	3	3	2	1	2	3	2	3	2	3	3	3	3	3	2	1	3
15KUFC19	2	17/23	15/23	17/23	0	3	2	3	0	0	3	2	3	3	3	3	2	1	0	3	3	3	3	3	3	0	3
15KUFC21	2	20/23	18/23	18/23	2	2	3	3	0	0	3	3	2	3	2	3	1	2	3	3	3	3	3	3	3	3	3
15KUFC23	2	18/23	16/23	15/23	1	3	3	3	0	0	3	1	0	0	3	2	2	1	3	3	3	3	3	3	3	3	3
15KUFC24	2	18/23	15/23	18/23	1	3	2	3	0	0	3	3	3	3	2	3	2	0	1	3	3	3	3	3	3	1	3
15KUFC25	2	13/23	19/23	16/23	2	2	2	3	0	0	3	3	3	2	1	3	2	2	0	3	3	2	3	3	3	0	3
15KUFC02	1	13/23	14/23	15/23	3	3	3	3	0	0	3	0	3	3	2	3	3	1	0	3	3	3	3	0	0	0	0
15KUFC03	1	14/23	14/23	17/23	2	3	2	3	0	0	1	1	0	0	2	3	2	2	2	3	3	3	3	3	3	1	3
15KUFC05	1	17/23	14/23	15/23	1	2	0	3	0	0	3	3	3	3	3	0	2	3	0	3	3	3	3	3	2	0	3
15KUFC22	1	15/23	13/23	15/23	2	1	0	3	0	0	3	3	1	1	2	3	0	3	0	3	3	3	3	3	3	0	3

Legend	
red	0 successful attempts
orange	1 successful attempt
yellow	2 successful attempts
green	3 successful attempts

Text summary of results for validation of the FMS Rotary Stability screening test scoring criteria (diagonal left)

For this subtest, 20 participants were awarded a real-time score of two and four participants were awarded a score of one. None of the 20 participants were correctly assigned to the scoring category of two as they failed to meet all the required 23 criteria in at least one attempt. All four participants were correctly assigned to the scoring category of one as they did not meet all the criteria (15KUFC02, 15KUFC03, 15KUFC05 and 15KUFC22). All 20 participants awarded a real-time score of two should therefore have been assigned to scoring category one.

Flag conditions (4), (17) and (19) were consistently met by all participants over the three attempts. Flag condition (4) was used to check the stabilising ankle angle remains unchanged throughout attempts. Flag condition (17) was used to check if participants fully extended their elbow and flag condition (19) was used to check that no contact was made between the floor and the moving limb during the attempt. No flag conditions were consistently not met by all participants over three attempts.

Table 6.21 Results for validation of the FMS Rotary Stability screening test scoring criteria (diagonal right)

Rotary stability - diagonal repetition - Right - 23 flag conditions																											
ID	FMS subscore	Criteria met			Flag conditions																						
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
15KUFC11	2	19/23	20/23	18/23																							
15KUFC01	2	16/23	16/23	15/23																							
15KUFC03	2	15/23	12/23	15/23																							
15KUFC04	2	16/23	15/23	15/23																							
15KUFC05	2	17/23	18/23	19/23																							
15KUFC06	2	19/23	20/23	20/23																							
15KUFC07	2	12/23	15/23	14/23																							
15KUFC08	2	17/23	16/23	17/23																							
15KUFC09	2	12/23	14/23	14/23																							
15KUFC10	2	13/23	15/23	17/23																							
15KUFC12	2	17/23	14/23	13/23																							
15KUFC13	2	15/23	15/23	11/23																							
15KUFC14	2	14/23	17/23	15/23																							
15KUFC15	2	18/23	16/23	18/23																							
15KUFC16	2	14/23	14/23	14/23																							
15KUFC17	2	13/23	15/23	15/23																							
15KUFC18	2	17/23	15/23	14/23																							
15KUFC19	2	17/23	17/23	13/23																							
15KUFC21	2	18/23	20/23	18/23																							
15KUFC23	2	15/23	14/23	16/23																							
15KUFC24	2	15/23	17/23	17/23																							
15KUFC25	2	15/23	16/23	14/23																							
15KUFC02	1	11/23	14/23	14/23																							
15KUFC22	1	13/23	13/23	12/23																							

Legend
0 successful attempts
1 successful attempt
2 successful attempts
3 successful attempts

Text summary of results for validation of the FMS Rotary Stability screening test scoring criteria (Diagonal right)

For this subtest, 22 participants were awarded a real-time score of two and two participants were awarded a score of one. None of the 22 participants were correctly assigned to the scoring category of two as they failed to meet all the required 23 criteria in at least one attempt. Both participants were correctly assigned to the scoring category of one as they did not meet all the criteria (15KUFC02 and 15KUFC22). All 22 participants awarded a real-time score of two should therefore have been assigned to scoring category one.

Flag conditions (4), (16), (17), (19) and (21) were consistently met by all participants over the three attempts. Flag condition (4) was used to check the stabilising ankle angle remains unchanged throughout attempts. Flag condition 16 was used to check if participants fully extended their knee during the first part of the movement. Flag condition (17) and (21) were used to check if participants fully extended their elbow for both parts of the movement. Flag condition (19) was used to check that no contact was made between the floor and the moving limb during the attempt. No flag conditions were consistently not met by all participants over three attempts.

Table 6.22 Results for validation of the FMS Rotary Stability screening test scoring criteria (Final)

Rotary stability - Final - all attempts																											
ID	FMS subscore	Criteria met			Flag conditions																						
		Attempt 1	Attempt 2	Attempt 3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
15KUFC01	2	16/23	16/23	15/23																							
15KUFC04	2	16/23	15/23	15/23																							
15KUFC06	2	19/23	19/23	15/23																							
15KUFC07	2	14/23	19/23	16/23																							
15KUFC08	2	15/23	17/23	18/23																							
15KUFC09	2	12/23	14/23	14/23																							
15KUFC10	2	13/23	15/23	17/23																							
15KUFC11	2	18/23	17/23	18/23																							
15KUFC12	2	17/23	11/23	14/23																							
15KUFC13	2	15/23	15/23	11/23																							
15KUFC14	2	14/23	17/23	15/23																							
15KUFC15	2	18/23	16/23	18/23																							
15KUFC16	2	14/23	14/23	14/23																							
15KUFC17	2	14/23	12/23	14/23																							
15KUFC18	2	17/23	15/23	14/23																							
15KUFC19	2	17/23	17/23	13/23																							
15KUFC21	2	20/23	18/23	18/23																							
15KUFC23	2	15/23	14/23	16/23																							
15KUFC24	2	15/23	17/23	17/23																							
15KUFC25	2	15/23	16/23	14/23																							
15KUFC02	1	11/23	14/23	14/23																							
15KUFC03	1	14/23	14/23	17/23																							
15KUFC05	1	17/23	14/23	15/23																							
15KUFC22	1	13/23	13/23	12/23																							

Legend
0 successful attempts
1 successful attempt
2 successful attempts
3 successful attempts

Text summary of results for validation of the FMS Rotary Stability screening test scoring criteria (Final)

For the final scores, no participants were awarded a score of three, 20 participants were awarded a score of two and four participants were awarded a score of one. All four participants, awarded a score of one, were assigned to the correct scoring category (15KUFC02, 15KUFC03, 15KUFC05 and 15KUFC22). All of the 20 participants awarded a real-time score of two were incorrectly assigned to the category and should have been assigned to the scoring category of one.

Flag conditions (4), (16), (17), (19) and (21) were consistently met by all participants over the three attempts. Flag condition (4) was used to check the stabilising ankle angle remains unchanged throughout attempts. Flag condition 16 was used to check if participants fully extended their knee during the first part of the movement. Flag condition (17) and (21) were used to check if participants fully extended their elbow for both parts of the movement. Flag condition (19) was used to check that no contact was made between the floor and the moving limb during the attempt. All participants failed to consistently meet flag conditions (5) and (6) over the three attempts. Flag conditions (5) and (6) checked the stabilising and mobilising limb foot position relative to the horizontal axis for the start of the attempt.

6.3 Discussion of results for the validity of the FMS conceptual framework as a measurement and assessment tool (Construct and content validity)

The underlying assumptions and theoretical basis on which the FMS was created will be evaluated, alongside the performance of the FMS as a measure, to assess its validity. As identified, there are other reported roles in which the FMS has been used. It is reportedly used to assess muscle strength, range of motion, asymmetry, balance and kinaesthetic awareness, despite not quantifying any of these parameters in absolute units (Cook et al 2006a, Cook et al 2006b, Kiesel et al 2007). For all the aforementioned variables, the FMS does not quantify a single dimension or aspect and therefore cannot be considered able to measure these. Neither can it be used for assessment of these variables, as in the absence of a measurement; no subjective judgement or quantitative comparison of one measure to another can be made.

Fundamentally, the FMS is a test which evaluates an individual's ability to perform a series of movements against set criteria. The criteria are determined by rules, some of which are common between subtests and some of which are specific to each subtest. For a score to be awarded, the assessor is required to check the participant's compliance with the FMS rules. In order to do this, the assessor is also required to work within the framework determined by the FMS rules. The rules, specific to each subtest have been described in Chapter 5. The common rules between subtests are:

1. A maximum of three attempts is allowed for each subtest.
2. If the initial movement falls within the criteria for a score of three, there is no need to complete the remaining attempts.

These rules will be discussed as they determine:

- the number of attempts a participant may carry out in order to be awarded the highest score, and,
- the number of attempts the assessor has to observe the movement in order to accurately award a score

It is therefore necessary to investigate if the assumptions related to observational rules and the numbers of attempts are feasible. The FMS handbook provides the following information regarding the assessors standing position during the screening. The assessor is advised to observe from the side or facing the person, although there is no standardised starting position or sequential fields of view to follow. Distance must be sufficient so that the assessor can "*view the entire movement and let the test criteria become evident*". Further instructions to the assessor include "*don't be afraid to move around during the test … move around if the score is not obvious from one point of view*" and "…*let the test criteria become evident."*

As the observational positions for the assessor have not been operationalised, it could result in a condition in which, two assessors, observing the same movement from different planes, would award different scores. This measurement process can result in an error whereby, the participant is allocated to two different scoring categories as opposed to a single category. This source of error, resulting from no implicit operationalised positions, creates variability between assessors observing the same movement, affecting inter-rater reliability and compounding sources of error.

During the test the assessor is required to interpret a complex three dimensional movement whilst being limited to a two dimensional field of view at any time. The number of variables the assessor needs to consider ranges from three to 23, dependant on the subtest being carried out. All of the subtests require the left and right limbs to be observed. Six out of the seven subtests require both the upper and lower limbs to be observed. In order to accurately observe the movements occurring in one plane, the assessor is required to remain in a single field of view for each attempt. Therefore to accurately observe movements in two planes, at least two attempts are required. Whilst the assessor may be able to simultaneously observe multiple segments of a single limb, they would be unable to accurately observe multiple limbs simultaneously throughout the movement. When we therefore consider the theoretical constructs of the FMS and its rules, it is apparent that the maximum number of three attempts is insufficient for the assessor to accurately confirm if the participant has complied with all the required rules. This can be evidenced by evaluating one of the simpler tests, the Shoulder Mobility test, which:

- has only an upper limb component
- has the least number of variables of all the subtests (3)
- requires both left and right limbs to be observed

At a minimum, the participant would be required to carry out at least four attempts. This is so that, both the left and right upper limbs could be observed, from at least two fields of view. Subtests of the FMS which have more variables and an additional lower limb component would therefore require the participant to undergo more attempts. This is so that the assessor could accurately ensure all the criteria were met. Therefore, the maximum number of attempts allowed for each subtest is insufficient when considering that the assessor is required to observe multiple variables from a minimum of two planes for both the upper and lower limbs and for left and right. Given the previous argument it is unlikely that the assessor would be able to accurately observe all the required variables in a single attempt. The rule, *"If the initial movement falls within the criteria for a score of three, there is no need to complete the remaining attempts*", is invalidated as all the criteria required to achieve the highest score cannot be accurately checked in a single attempt. Awarded scores, based on a single attempt, may introduce further error into the scoring system.

For score allocation, when conducting the real-time assessment, the highest scoring criterion of a three requires the assessor to check that the participant is complying with multiple variables. For the lessor scores, the assessor only has to identify that the participant cannot comply with one of the criteria. Therefore during the assessment process, it is easier to check if the participant fails to comply with a single rule, as opposed to checking if they comply with all the rules. This may result in a situation where the highest score is awarded based on the observation of only a few observed variables that have been performed correctly. As discussed previously the assessor is unable to check all the variables given the number of attempts and limited fields of view. The assessor may therefore select a reduced number of variables to observe. Selection or prioritisation of these variables is likely to change between assessors and arguably participants, as there are no operationalised viewing positions or order in which to view the variables. The awarded score would then not be a true representation of the participants' performance introducing further error into the scoring system and compounding score allocation error as observed in the results.

The process by which a score is allocated is prone to significant error given the points discussed in the above sections. Other sources of error, associated with score allocation, stems from the terminology and constructs used to determine the different scoring categories. The allocation of the subtest score is determined by the assessor's subjective interpretation of the scoring criteria rules. As identified in the methodology section, there is a lack of clearly stipulated clinical or biomechanical definitions for some of the subtest scoring criteria rules and categories. The Hurdle Step test criteria "*minimal to no movement is noted in the lumbar spine"* (section 5.1.2 - table 5.7) can be used to highlight this problem which is present in all of the subtests, with some subtests having multiple ambiguous criteria. This criterion does not provide quantified thresholds or units to clarify what constitutes a tolerable amount of movement. The level of tolerance is therefore arbitrarily established by the assessor and may vary between attempts and participants. A lack of clearly stipulated thresholds, coupled with poor or erroneous use of biomechanical definitions, further compounds the problems associated with score allocation. Poor use of biomechanical terms is also a common problem between subtests. Another example that can be used to highlight this problem was identified in the Inline Lunge subtest. Within this subtest the rule *"feet remain in sagittal plane*" (section 5.1.3 – table 5.8), is used to in one of the scoring categories. This rule does not stipulate if this is in reference to the sagittal plane of the lab or the foot. Again, no absolute level of tolerance has been determined. The lack of established thresholds alongside poorly defined and erroneous use of clinical and biomechanical terms, introduces inconsistency and error into the FMS measurement process. Furthermore the terminology that is used to inform the scoring categories is prone to the same flaws and will negatively affect the performance of the FMS scale as measure. The performance of the FMS scale as a measure will be discussed kfurther in section (6.4).

It was recognised that these rules provided challenges when determining thresholds for comparison against the photogrammetric system and would also therefore provide challenges in the real-time evaluation which may contribute to scoring allocation error. Further sources of variation, associated with inconsistent nomenclature, arise from discrepancies between the instructions to the assessor as stated in the test description, and the verbal instructions to the participant from the assessor. This was identified for the Active Straight-Leg Raise, Trunk Stability Push-Up and Rotary Stability tests. For these tests the description to the assessor *"ankles are neutral and the soles of the feet perpendicular to the floor*" indicates a specified position for the feet. However the verbal instruction to the participant "*pull your toes towards your shins*" does not clearly stipulate a position or threshold for how far the person is to pull their toes. These sources of variation further compound the error associated with score allocation and affect the validity of the FMS.

The use of clear terminology is also important for determining the role of the FMS and its validity as a measurement tool. As identified previously the FMS cannot be considered a valid measure of muscle strength, range of motion, asymmetry, balance and kinaesthetic awareness given that it does not quantify these variables. It has also been identified that there is inconsistent reporting within the FMS's own framework around its role. The FMS handbook states it was "*not intended to diagnose or measure isolated joint movements*" (Functional Movement Systems and Gray Cook 2012). However, this contradicts the role of the assessor, who is required to measure isolated joint movements which make up the test scoring criteria. Disambiguation around the role of the FMS is needed for it to be considered valid so that it may be implemented appropriately; ensuring it accurately measures what it was intended to measure.

The other reported role of the FMS is that it is an Indicator of injury risk through identification of a final composite score informed by the scale. The original intended purpose of the FMS was for rating and ranking movement patterns in high school athletes, through development of a scale. The same scale was then used within different active populations for determining injury risk from a final score. "A prerequisite for using any measurement scale is knowledge of its performance characteristics and limitations, as these will play a part in data interpretation and analyses (Pandyan et al 1999)." Given that the validity of the FMS as an indicator of injury risk is dependent on the validity of the scale from which it is calculated, the next step is therefore to assess the performance of the measurement scale.

6.4 Discussion of results for the performance of FMS scale as a measure

An important characteristic of a scale is understanding the level of measurement it is able to achieve. This is imperative as it can affect the way in which the results are analysed and interpreted. Application of the FMS and interpretation of its results would suggest that confusion exists at the level of measurement it can achieve. To assess the level of measurement the FMS can achieve, it will be compared against the measurement level hierarchy starting with nominal. There are four identified levels of measurement, namely nominal (categorical), ordinal interval and ratio level, their characteristics are further described in table 6.23. (Hicks 2009).

Table 6.23 Key characteristics of nominal, ordinal, interval and ratio levels of measurement

	Characteristics					
Level	Mutually exclusive categories [a]	Logical order	Quantitative measurement	Equal interval lengths	True zero point	Example
Nominal[b]	✓	×	×			Injury status e.g. injured or not injured
Ordinal	✓	✓	×			RPE measured by the Borg Scale
Interval	✓	✓	✓	✓	×	Range of movement
Ratio	✓	✓	✓	✓	✓	Number of days injured

✓ condition has to be satisfied

× condition need not be satisfied

[a] Implies that any object belongs to one and only one category

[b] Nominal is the same as categorical

For a process to be called a measurement, it is required to ensure that people or events are assigned into mutually exclusive categories. The FMS scale does not fulfil this definition given that a participant may be assigned to multiple categories within the same scale. Additionally the FMS sub scores and final scores are informed by two different scales of different units. This results in instances in which a participant is able to be assigned to multiple categories. For example, in the Shoulder Mobility exercise test (scored on an ordinal scale from zero to three (section 5.1.4), a participant scoring a two, for both the left and right side, who then has pain on the shoulder clearing test (a dichotomous outcome of pain or no pain (section 5.1.4.1) would have a final sub score of zero. This problem is also evident within the scale associated with the exercise tests. The FMS scale also assumes there are distinct mutually exclusive categories in all tests. However, as discussed previously, the terminology used to define these categories is comprised of poor biomechanical definitions and thresholds which create ambiguity. This ambiguity compounds the problem in which a participant is assigned to multiple categories. It also creates significant overlap between categories, reducing the true number of scoring categories. This is seen in the Inline Lunge test. When evaluating the scoring criteria (section 5.1.3), the rule *"inability to complete a movement pattern"* is associated with the scoring criteria of a one. This indicates the participant was unable to comply with all the criteria. However the rules which make up the scoring category of a two are also related to the participant's inability to comply with all the criteria. Within this sub test there are therefore in reality only two categories to which a participant may be assigned.

As the scale was intended to allow for ranking, it is sometimes referred to as an ordinal level measurement. However, as it does not fulfil the first requirement of a measurement, it is questionable whether it can be considered as an ordinal level of measurement. The failure of the FMS to perform as an ordinal measure is also apparent on review of the results for all the FMS subtests. The FMS does not demonstrate itself as a scale in any structured order regardless of if participants are ranked according to subscore, final score, number of injuries or injury severity as per the heat maps (Appendix XVI). Given that the FMS scale does assign people to mutually exclusive categories or allow for ranking, it is unlikely that the lengths between scores would be equal and that the scale would have a true zero point. These therefore disqualify it from being an interval or ratio level measurement. The inability of the FMS to fulfil any of the definitions associated with measurement therefore disqualifies it from being considered a measurement.

Furthermore, as a scale, the presence of universally met or not met flag conditions within the FMS suggests that there may be redundancies within the FMS scoring process. These flag conditions may be considered superfluous as they are non-discriminatory. A flag condition met by all participants may be an achievable requirement of the test, however as it is non-discriminatory, it may have limited value in classifying participants and its relevance to the demands of the movement are questionable. Given the large amounts of variables the assessor needs to consider, the non-discriminatory variables may add unnecessary noise into an already complex scoring procedure. An inability for all participants to meet a flag condition may also indicate an unrealistic biomechanical demand as a part of the test. For example, in the Hurdle Step test, it is a requirement that the *"Hips… remain aligned in the sagittal plane"*. However, as the test involves weight transfer onto the stabilising leg, the participant will have to move their hip joint in the coronal plane, consequently resulting in the hip losing alignment with the sagittal plane. Additionally it was identified that for some subtests, instances existed where the scoring criteria do not account for some movement combinations. For example in the Active Straight-Leg Raise test (section 5.1.5), all three scoring categories include the rule "*The non-moving limb remains in a neutral position".* This rule is non-discriminatory, and does not allow for situations in which participants move their "non-moving limb" during the test, irrespective of the moving limb heel position. The scale does not therefore account for all movement possibilities and results in participants being assigned to a category that is not reflective of their performance. The FMS scale cannot therefore accurately measure quality of movement. Furthermore the scales' lack of distinct categories, non-mutually exclusive categories and its inability to account for some movement combinations would compound scoring allocation errors and negatively affect its validity.

6.5 Conclusions and further work

Valid clinical measurements are necessary for monitoring changes in performance related to injury risk, informing injury prevention programs and evaluating the efficacy of current treatment approaches in rehabilitation (Pandyan et al 1999). As a scale, it has been identified that the FMS can neither be considered valid or a measurement. The inability of the FMS to fulfil any definitions associated with measurement or levels of measurement therefore disqualify it as a measure. The FMS does not demonstrate itself as a score in any structured order. There are also multiple sources of error within the conceptual framework of the FMS which are compounded by faults within the construct of the scale. Previously identified flaws that are common to all subtests, causing score allocation error and negatively affecting the validity of the FMS were:

- Non operationalised viewing positions and distance for the assessor.
- Too many variables for the assessor to accurately observe in a single attempt, given that the scoring process requires multiple segments for both the upper and lower limbs and for left and right to be observed.
- An insufficient number of attempts to accurately observe if the participant has complied with all the scoring rules.
- The assessor being limited to a two dimensional view whilst trying to interpret a complex three dimensional movement.
- Poor clinical and biomechanical definitions or lacking clearly stipulated thresholds that inform scoring of performance.
- Unachievable requirements for some variables resulting from unrealistic biomechanical demands.

For the FMS to be implemented as a measure, future work should look to address the failings of the conceptual framework and construct of the scale that disqualify it from being a measure. Clarification on the intended purpose of the test is required alongside the constructs it is concerned with measuring. The level of measurement the scale can achieve should also be implicitly stated given that it can affect the interpretation of observed results. This is evident in studies (specific to football and other sporting/occupational disciplines) which erroneously identified thresholds for injury risk by using the FMS and treating the data as interval or ratio level measurement (Kiesel et al 2007, O'Connor et al 2011, Zalai et al 2014, Schroeder et al 2016, Lloyd et al 2014).

The original intended purpose of the FMS was to rank observed movement patterns. As stated the scale should therefore reflect the characteristics associated with movement. The FMS should be clear whether it is testing to rank movement quality or identify the absence or presence of pain. Once the desired construct has been selected, the categories that are used should be mutually exclusive so that at the very least the scale can be considered a categorical level of measurement. Establishing mutually exclusive categories would be facilitated by the use of well-defined biomechanical and clinical terminology, for example currently there are no definitions within the FMS framework for what is meant by terms such as alignment or stability. The levels of tolerance should also be clearly stipulated to minimise ambiguity which would result in categorical variations or errors. Future work should also look towards simultaneous improvement of the scoring system and scale, ensuring that consistency exists between instructions to the assessor and instructions from the assessor to the participant, alongside clearly stipulated thresholds and defined biomechanical principles. The rules which determine the scoring categories should also be realistic in that currently they do not allow for situations that are unachievable due to them being biomechanically or anatomically impossible e.g. in the Hurdle Step test.

After clarification regarding purpose of the test, level of measurement and provision of suitable definitions, further work is needed to ensure the scoring process is valid i.e. able to accurately capture the performance of the individual. The scoring process should establish operationalised methods for carrying out the assessment process alongside an adequate number of attempts to ensure accurate observations. This may be further facilitated by reducing the number or variables the assessor is required to consider through removal of redundant variables and selection of appropriate variables.

As stipulated previously, for a test to be considered valid, it must accurately measure what it claims to measure. It has been established that the theoretical framework for the FMS measurement process is either unachievable or flawed, resulting in erroneous score allocation. The FMS as it is used in its current form has moved beyond its original intended purpose. Whilst the FMS is used in injury prediction, for which there is no evidence linking the occurrence of injury to the demands of the test, it is evident that bigger problems exist at the fundamental levels of the scale and scoring process. Measurement of physical performance is not possible with the FMS in its current state. Changes to a participant’s movement, based on this measurement process may lead to increased injury risk, as this may have a detrimental effect on physical performance consequently lowering the functional capacity of the individual. Given the FMS's current lack of validity and measurement capability, it should not be used to inform clinical decision making processes related to quality of movement or injury risk.

The researcher acknowledges that multiple versions of the FMS scoring handbook are available (most recent Functional Movement Sytems 2015 version 10). However, it does not change the framework and principles investigated within this thesis, given that the original remains an underpinning component of the existing FMS framework and has been used for informing the existing literature.

7 SUMMARY OF THE DATABASE THAT INFORMED THE MODELLING PROCESS

7.1 Introduction

Before development of a model to address the research question i.e. Can injuries be predicted based on currently advocated risk factors for prospective injury modelling? It was necessary to develop a database, comprised of variables that reflected the literature. As a part of routine clinical practice, a database for the football club had been established prior to the study. This was conducted by the researcher, who was the team physiotherapist, in order to meet the recommendations advocated by professional football bodies and the literature. Once the database that reflected the published literature had been completed, it was necessary to continue populating the database and investigate whether the database on which the model will be developed was representative of a typical football team. This allowed for an appropriate evaluation of the models performance and evaluation of its wider clinical applicability. Additionally, the variables which inform the model should reflect those currently used in clinical practice or those advocated by the professional and governing bodies. This chapter will therefore investigate whether injury trends and variables within the database being used for model development are reflective of a typical football team. The injury reporting methods, variables, results for subject details and injury occurrence will be reported within this chapter.

7.2 Methodology

The database selected for model development was an existing database originally set up by the Keele Men's Football Club to meet the requirements of the standards set out by FIFA and the Football Association according to the consensus statement by Fuller et al (2006). The database was comprised of 24 subjects, who, following completion of the pre-season measures (including FMS), were prospectively monitored for injuries throughout a competitive season (12th September 2015 to 14 May 2016 - 8 months). The database contained variables related to self-reported injury history, injury audit data, skin fold measurements, previous FMS scores, fitness testing scores, all strength testing, muscular activity profiles during strength testing, time spent involved in football specific training, match play and additional training, as well as any video recordings of matches.

7.2.1 Participants

Participants for the FMS testing were recruited from the Keele University Men's Football Club following ethics approval (Appendix I). The inclusion and exclusion criteria are listed below.

Inclusion Criteria

- Participants above 17 years of age
- Participants within the Keele University Men's Football team (British University and Colleges Sports (BUCS) league and standards)
- Participants who provide informed consent

Exclusion Criteria

- Participants undergoing rehabilitation from surgery or previously diagnosed injury at time of screening.

7.3 Methodology for injury definitions, injury reporting, training and match exposure

Injury reporting, definitions and data collection procedures were carried out according to the consensus statement produced by Fuller et al (2006). For this chapter, the relevant justification has been provided for definitions, injury reporting or data collection procedures, which were modified or differed from those used in the consensus statement.

7.3.1 Injury definitions

An **injury** was defined as "*any physical complaint sustained by a player that results from a football match or football training, irrespective of the need for medical attention or time loss from football activities*". An injury in which the participant received medical attention, but did not miss any days of training or match play, was documented as a "medical attention" injury. An injury that resulted in a player being unable to take full part in future football training or match play is referred to as a "time loss" injury. The ability of a player to take a full part in future training or match play was independent of whether a training session actually took place on the day after the injury or whether a player was selected to play in the next match. If a player sustained multiple injuries in a single event, these were recorded as one injury with multiple diagnoses. Illness, diseases, mental complaints and injuries not related to football were not included in this study as per the consensus statement.

A **recurrent injury** was defined as "*an injury of the same type and at the same site as an index injury and which occurs after a player's return to full participation from the index injury*". Recurrent injuries were classified according to their time since the index injury:

- Early recurrence – a recurrent injury occurring less than two months following a player's return to full participation.
- Late recurrence – a recurrent injury occurring more than two months but less than 12 months following a player's return to full participation.
- Delayed recurrence - a recurrent injury occurring more than 12 months following a player's return to full participation.

Index injuries sustained before the start of the study were also considered when identifying an injury as a recurrence injury. Injuries such as contusions lacerations, and concussions and sequelae resulting from an index injury were not recorded as recurrences.

7.3.2 Injury reporting and classification

During the pre-season measures, participants were informed to contact the team physiotherapist if they sustained an injury, i.e. *any physical complaint sustained resulting from a football match or football training irrespective of the need for medical attention or time loss from football activities*. Additionally, participants were contacted via email on a weekly basis regarding their injury status. If a player reported an injury they were followed up by the team physiotherapist where they received an assessment and routine physiotherapy management. Injuries were recorded and classified according the consensus statement as described below (Fuller et al 2006).

Injury severity was defined as "*The number of days that have elapsed from the date of injury to the date of the player's return to full participation in team training and availability for match selection."* The day on which an injury occurred and day zero and was not counted when determining the severity of that injury. Therefore, if a player could not participate fully on the day of an injury but was available for full participation the next day, the incident was recorded as a time loss injury with a severity of zero days. Injuries could be classified according to their severity (number of days missed). The categories for describing injury severity are described below

- Slight (< 1 day)
- Minimal (>1day and <3days)
- Mild (>3days and <7days)
- Moderate (>8days <28days)
- Severe (>28days) or a career ending injury

7.3.2.1 Injury classification

As per the consensus statement injuries were classified by

- Location
- Type
- Body side
- Mechanism of injury (overuse or trauma)

A traumatic injury was defined as an injury resulting from a specific identifiable event. An overuse injury was defined as one caused by repeated micro trauma without a single, identifiable event responsible for the injury. For injury diagnosis, the Orchard sports injury coding system was used (Orchard 1993). This is a widely used and commonly accepted sports injury classification system.

7.3.2.1.1 Injury location

As per the consensus statement, injuries were classified according to their anatomical locations (Table 7.1).

Table 7.1 Main groupings and categories for classifying injury location

Main Grouping	Category
Head and Neck	head/face
	neck/cervical spine
Trunk	sternum/ribs/upperback
	abdomen
	lowback/sacrum/pelvis
Upper Limbs	upper arm
	elbow
	forearm
	wrist
	hand/finger/thumb
Lower Limbs	hip/groin
	thigh
	knee
	lower leg/achilles tendon
	ankle
	foot/toe

7.3.2.1.2 Injury Type

As per the consensus statement, injuries were classified according to the type of injury (table 7.2).

Table 7.2 Main groupings and categories for classifying type of injury

Main Grouping	Category
Fractures and Bone stress	Fracture
	other bone injury
Joint(non- bone) and ligament	dislocation/subluxation
	sprain/ligament injury
	lesion of meniscus or cartilage
Muscle and Tendon	muscle rupture/strain/tear/cramps
	tendon injury/rupture/tendinosis/bursitis
Contusions, Lacerations and skin lesions	haematoma/contusion/bruise
	Abrasion
	Laceration
Central/peripheral nervous system	concussion with or without loss of consciousness
	nerve injury
other	dental injury
	other (please specify)

Additional information relevant to injury reporting and classification were recorded as per the consensus statement (Fuller et al 2006) namely:

- The setting in which the injury occurred such as a match or training
- The surface on which they trained (sand Astroturf, grass, Artificial 3G Astroturf, wood)
- Whether the injury was the result of contact with another player or with an object
- For cases in which contact occurred with another player, whether the action causing the injury was a violation of the laws of football, and any subsequent disciplinary action.

Injuries will be reported as the incidence of injury per 1000 hours of exposure. Definitions for exposure classification are presented in the section below.

7.3.3 Training and match exposure

Alongside information regarding injury status, participants were contacted weekly via email to collect their daily exposure for that week. Exposure, reported in hours, refers to the amount of time a player spent participating in match or training activities. The surface type on which the activity took place was also recorded alongside the total duration.

7.3.3.1 Match exposure

Match exposure was defined as "*play between teams from different clubs*." Matches that took place between members of the same were regarded as training exposure. No match activity that formed a part of a player's rehabilitation from injury was recorded as match exposure.

7.3.3.2 Training exposure

Training exposure was defined as "*team based and individual physical activities under the control or guidance of the team's coaching or fitness staff that are aimed at maintaining or improving players' football skills or physical condition.*" Pre-match warm up and post-match cool down sessions were recorded as training exposure. Motivational team talks, classroom discussions about tactics, and sessions with sports psychologists, nutritionists, etc. were not recorded as training exposure. Any training activity forming a part of a player's rehabilitation from injury was not recorded as training exposure. The consensus statement stipulates that *"Personal training activities undertaken by players away from their team and which are not planned by the team's coaching or fitness staff should not be recorded as training exposure"*. For this study, all physical activity undertaken by participants was recorded to investigate its effect on performance and fatigue. The incidence of injury for training exposure (as per the consensus definition) was reported separately to the total training exposure (as recorded for this study). Activities undertaken by participants during this study, that would not fulfil the consensus definition for training exposure, were conditioning and Futsal. For this study, conditioning was defined as any physical activity such as progressive strength/resistive weight or cardiovascular fitness training undertaken by the participants. Futsal is a modified football game, usually five-a-side and played on a flat indoor pitch (in this study, a wooden floor). It uses a smaller ball (size four), with a reduced bounce. The game duration is usually 20 minutes per half (40 minutes in total) and the emphasis is on technical skill development and quick passing in small spaces (The FA 2017).

7.4 Results

7.4.1 Results for participant demographics

Twenty five male footballers (aged between aged 19 -22), competing in the British University and College Sports leagues, volunteered to participate in this study. One participant was excluded at the start of this study due to an injury sustained the day prior to the pre-season testing. Individual subject characteristics can be seen in table 7.3. Participants had a mean age of 19 years (range 19 to 22) and had been playing football for a mean duration of 12.13 years (SD ± 2.1). The mean number of self-reported injuries during this time was 1.42 (SD ± 1.2). The anthropometric characteristics of the participants were a mean standing height of 1.79 meters (SD ± 0.06), mean weight of 77.75 kilograms (SD ± 9.7) and a mean skinfold thickness (sum of four sites biceps, triceps, subscapular and anterior superior iliac spine) of 40.98 millimetres (SD ± 17.0). Twenty two participants reported their preferred kicking leg as being their right leg and the remaining two participants reported their preferred kicking leg as being their left leg. The number of participants in each playing position were attackers n =4, Midfielders n = 13, Defenders n =4 and goalkeepers n=3.

Table 7.3 Individual subject characteristics

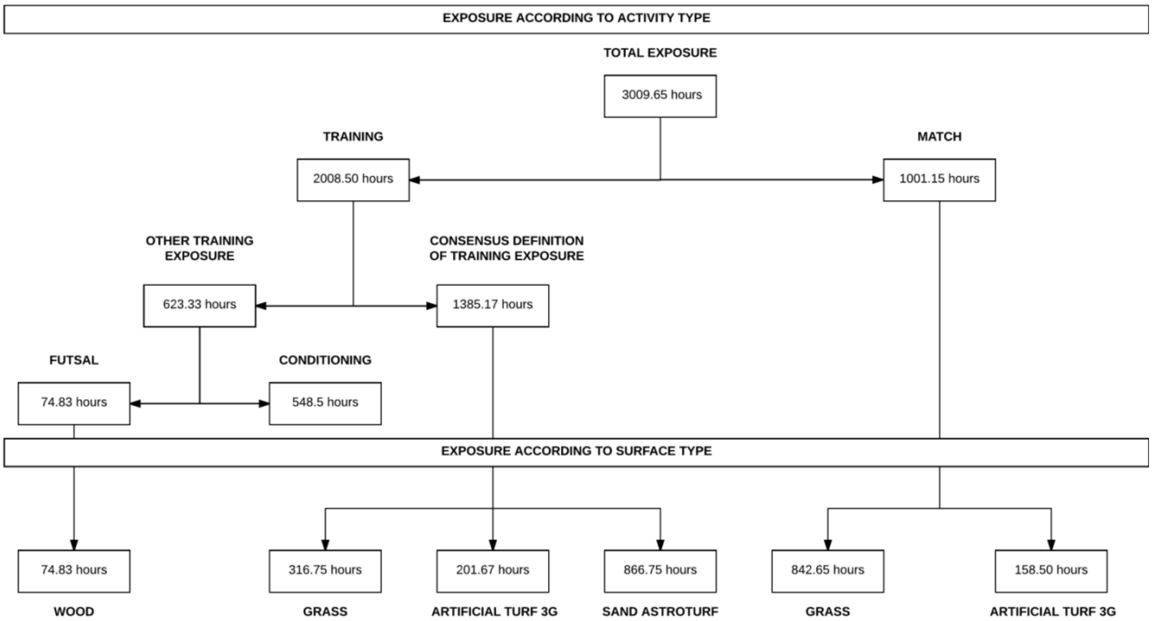
ID	Age	Standing Height (m)	Weight (kg)	Years playing	No. previous self-reported injuries	Position	Kicking leg
15KUFC01	21	1.82	96.8	14	1	Goalkeeper	Right
15KUFC02	19	1.82	84.1	12	1	Defender	Right
15KUFC03	19	1.73	64.1	13	1	Midfielder	Right
15KUFC04	19	1.83	73.5	10	1	Attacker	Right
15KUFC05	21	1.82	85	12	0	Midfielder	Right
15KUFC06	20	1.91	90.6	12	3	Defender	Right
15KUFC07	19	1.85	87.7	13	1	Goalkeeper	Right
15KUFC08	19	1.74	83.7	12	1	Midfielder	Right
15KUFC09	20	1.78	85.9	13	1	Attacker	Left
15KUFC10	20	1.80	82	15	3	Midfielder	Right
15KUFC11	19	1.81	80.3	12	1	Midfielder	Right
15KUFC12	20	1.80	70.3	16	1	Defender	Right
15KUFC13	19	1.83	93.4	10	3	Goalkeeper	Right
15KUFC14	19	1.79	71.4	10	0	Midfielder	Right
15KUFC15	19	1.76	74.2	10	0	Midfielder	Right
15KUFC16	19	1.67	59.9	7	3	Midfielder	Right
15KUFC17	18	1.76	77	15	1	Defender	Right
15KUFC18	19	1.75	70.1	11	0	Attacker	Right
15KUFC19	19	1.69	67.3	14	3	Midfielder	Right
15KUFC21	20	1.75	82	12	3	Midfielder	Right
15KUFC22	18	1.77	69.8	10	0	Midfielder	Right
15KUFC23	20	1.81	78.4	15	4	Midfielder	Right
15KUFC24	20	1.87	64.5	10	1	Attacker	Left
15KUFC25	18	1.74	74	13	1	Midfielder	Right

7.4.2 Results for match and training exposure including surface type

Figure 7.1 illustrates the breakdown of exposure hours according to activity and surface type. In total 3009.65 hours of exposure were reported throughout the season. Match exposure accounted for 1001.15 hours (33.3%) and training (inclusive of all physical activity) accounted for 2008.50 hours (66.7%). Of the total training exposure hours, 623.33 hours were made up by futsal and conditioning (74.83 and 548.50 hours respectively). The remaining 1385.17 hours consisted of football specific training as per the consensus statement training exposure definition. Participants on average participated in 30.7 matches (median = 31.5) and 61.1 (median = 63) football specific training sessions. The mean number of Futsal and conditioning sessions was 3.14 (median = 2.5) and 20.75 (median = 12) respectively.

For exposure relative to surface type, a total of 1159.40 hours was spent on grass. Match exposure on grass accounted for 842.65 hours whilst training exposure (football specific) accounted for 316.75 hours. The mean number of matches and training sessions that occurred on grass was 26.0 (median = 27) and 25.1 (median = 26.0) respectively. Training exposure on sand AstroTurf accounted for the total 866.75 hours. The mean number of training sessions on sand AstroTurf was 28.0 (median =28.5). No match exposure took place on the sand AstroTurf. Total exposure for the artificial turf (3G) surface was 360.17 hours. Match exposure on this surface accounted for 158.50 hours and training exposure accounted for 201.67 hours. A mean number of 4.8 matches (median = 4.0) and 8.0 training sessions (median = 6.5) took place on the artificial turf (3G) surface. All Futsal exposure took place on a wooden floor, accounting for 74.83 hours. The mean number of Futsal sessions was 3.4 (median = 2.5). Surface type was not recorded for the conditioning sessions. The mean number of conditioning sessions was 20.8 (median = 12).

Figure 7.1 Breakdown of exposure hours according to activity and surface type.



7.4.3 Results for total injuries

7.4.3.1 Results for total number of injuries and severity

In total, 44 injuries were reported throughout the season, resulting in 465 days lost through injury. The mean number of injuries sustained for each player was 1.8 (95% CI 1.4 - 2.4) and the overall injury incidence for all activities was 14.6/1000h. The total injury incidence increased to 31.8/1000h when the hours that accounted for conditioning and futsal were removed. Side of injury was similar for left and right, with 21 and 23 injuries respectively. Of the 44 injuries sustained, 37 injuries were classified as time loss injuries with a mean severity of 12.6 days (95% CI 8.7 - 16.4) and a median severity of 10 days. For injury severity classification, moderate injuries (> 7 days < 28 days) were the most common (n = 18, 40.9%, 95% CI 26.3% - 55.4%), followed by the categories of slight (≤1 day) and minimal (>1 day < 3 days), with a total number of 11 (25.0%, 95% CI 12.2% - 37.8%) and seven (15.9%, 95% CI 5.1% - 26.7%) injuries in each category respectively. Six injuries (13.6%, 95% CI 3.5% - 23.8%) were classified as mild (>3days <7days) and the remaining two injuries (4.5%, 95% CI -1.6% - 10.7%), which occurred in training, were classified as severe. For separate match and training injury severity see table 7.4. No career ending injuries were sustained throughout the season. The remaining seven injuries were classified as medical attention injuries. Time loss and medical attention injuries had an incidence of 12.3/1000h and 2.3/1000h respectively.

Table 7.4 Number of injuries for match and training according to injury severity categories.

		Number of injuries	
Injury severity	**Severity Category**	**Match**	**Training**
≤ 1day	slight	7	4
>1 day and < 3 days	minimal	5	2
>3 days and < 7 days	mild	5	1
> 7 days and < 28 days	moderate	10	8
> 28 days	severe	0	2
	career ending	0	0

Match injuries accounted for 27 of the 44 injuries (61.4%, 95% CI 47.0% - 75.8%) and the remaining 17 out of 44 injuries (38.6%, 95% CI 24.2 - 53.0%) were sustained during training. The incidence of injury for match play was higher than that of all training types, with an incidence of 27.0/1000h. For all forms of training the incidence of injury was 8.5/1000h compared to 12.3/1000h for training exposure as per the consensus definition. The mean number of days missed through injury was higher for training activity when compared to match play with a mean of 14.6 days (95% CI 7.2 - 22.0) median = 10, and 8.0 days (95% CI 4.9 - 11.2) median = 4 respectively. More injuries were sustained in the second half of matches compared to the first (16 compared to 7 respectively). Further information regarding match time injury was available for 23 of the 27 injuries and can be seen in table (7.5).

Table 7.5 Number of injuries sustained during periods of match play

	Time in match	Number of injuries
1st Half		
	0-15 minutes	1
	16-30 minutes	4
	31-45 minutes	2
	1st half +"injury time"	0
2nd Half		
	46-60 minutes	4
	61-75 minutes	7
	76-90 minutes	5
	2nd half +"injury time"	0

A traumatic mechanism was reported for 29 out of the 44 injuries (65.9%, 95% CI 52.0% - 80.0%). The remaining 15 injuries (34.1%, 95% CI 20.1% - 48.0%) were classified as "overuse" injuries as they did not have an identifiable traumatic event. There were 29 new (65.9%, 95% CI 52.0% - 80.0%) and 15 recurrent (34.1%, 95% CI 20.1% - 48.0%) injuries sustained during the season. The total incidence for recurrence injuries was 5.0/1000h. Eight of the 15 recurrent (53%, 95% CI 28% - 78.5%) injuries occurred during match play and the remaining seven recurrence (46.7%, 95% CI 21.4% - 72.0%) injuries were sustained during training. The incidence of recurrent match injuries was higher than that of recurrent training injuries with incidences of 8.0/1000h and 2.3/1000h respectively. Of the 15 recurrent injuries, six were classified as early (<2months), five were classified as late (>2 months <12 months) and two were classified as delayed recurrence injuries (>12 months). On average, recurrent injuries were more severe, resulting in more days missed through injury. The mean number of days missed for recurrent injuries was 14.1 (95% CI 6.7 - 21.5) median = 12 days, compared to non-recurrent injuries for which the mean number of days missed was 8.7 (95% CI 5.1 - 12.4) median = 5 days.

7.4.3.2 Results for total injuries mechanism

Twenty five injuries (56.8%, 95% CI 42.1% - 71.5%) were considered non-contact injuries and 19 injuries (43.2%, 95% CI 25.5% - 57.8%) had an associated mechanism of contact. The majority of contact injuries (n = 16, 80%, 95% CI 67.8% - 100%) occurred through contact with another player. Three injuries occurred through contact with the ball and the remaining contact injury was associated with an object (training barrier). Of the 44 injuries, five injuries (11.7%, 95% CI 2.0% - 20.7%) were sustained through foul play (violation of the rules) by an opposition team player, resulting in four free kicks and one yellow card. There were no injuries to any of the participant's resultant from foul play on their behalf.

7.4.4 Results for Injury location and type

7.4.4.1 Results for total injury location

No upper limb injuries were reported throughout the season. The majority of injuries occurred in the lower limbs (n = 42, 95.5%, 95% CI 89.3% - 100%) and the remaining injures occurred in the trunk (n =2, 4.5%). Ankle (n=12, 27.3%), knee (n=8, 18.2%) and hip/groin injuries (n=8, 18.2%) were the most common injury location subtype. Further information for other injury location subtypes can be seen below in table (7.6).

Table 7.6 Injury location subtype

Injury Location	Number of injuries	Percentage of total injuries %	95% CI
head/face	-	-	-
neck/cervical spine	-	-	-
sternum/ribs/upper back	-	-	-
Abdomen	-	-	-
lowback/sacrum/pelvis	2	4.5	-1.6 – 10.7
Upper arm	-	-	-
Elbow	-	-	-
Forearm	-	-	-
Wrist	-	-	-
hand/finger/thumb	-	-	-
hip/groin	8	18.2	6.8 – 29.6
Thigh	6	13.6	3.5 – 23.8
Knee	8	18.2	6.8 – 29.6
lower leg/achilles tendon	5	11.4	2.0 -20.7
Ankle	12	27.3	14.1- 40.4
foot/toe	3	6.8	- 0.6 – 14.2

For all injury location subgroups there was a higher incidence of injury associated with injuries sustained during match play (table 7.7).

Table 7.7 Incidence for match and training injury location subgroups

	MATCH		TRAINING	
Injury Location	**Number of injuries**	**Incidence/1000h**	**Number of injuries**	**Incidence all /1000h**
lowback/sacrum/pelvis	1	1.0	1	0.5
hip/groin	4	4.0	4	2.0
Thigh	4	4.0	2	1.0
Knee	6	6.0	2	1.0
lower leg/achilles tendon	4	4.0	1	0.5
Ankle	7	7.0	5	2.5
foot/toe	1	1.0	2	1.0

7.4.5 Results for total injury type

The most common injury classification type was muscle rupture/strain/tear/cramps with a total of 15 injuries (34.1%). Haematomas/contusions/bruises were the second most common injury type with a total of 12 injures (27.3%) followed by sprain/ligament injuries (n=7, 15.9%) and tendon injuries/rupture/tendinosis/bursitis (n=6, 13.6%). Further information for other injury subtypes can be seen in table 7.8.

Table 7.8 Injury subtype - number of injuries and percentages

Injury type	Number of injuries	Percentage of total injuries %	95% CI
concussion with or without loss of consciousness	-	-	-
lesion of meniscus or cartilage	1	2.3	-2.1 – 6.7
haematoma/contusion/bruise	12	27.3	14.1 – 40.4
Fracture	2	4.5	-1.6 – 10.7
muscle rupture/strain/tear/cramps	15	34.1	20.0 – 48.1
Abrasion	-	-	-
other bone injury	-	-	-
dislocation/subluxation	-	-	-
sprain/ligament injury	7	15.9	5.1 – 26.7
tendon injury/rupture/tendinosis/bursitis	6	13.6	3.5 – 23.8
Laceration	-	-	-
nerve injury	-	-	-
dental injury	-	-	-
other (please specify) (HERNIA)	1	2.3%	-2.1- 6.7

There was a higher incidence for injury subtypes haematomas/contusions/bruises in matches compared to training (8.0/1000h and 2.0/1000h respectively). This was also evident in the injury subcategories of muscle ruptures/ strains/ tears/cramps and tendon injury/ rupture/ tendinosis/ bursitis with matches having an injury incidence of 9.0/1000h and 4.0/1000h respectively, and training having an incidence of and 3.0/1000h and 1.0/1000h respectively. Further information for match and training injury subtype incidence can be seen below (table 7.9)

Table 7.9 Incidence for match and training injury subtypes

	MATCH		TRAINING	
Injury type	Number of injuries	Incidence/1000h	Number of injuries	Incidence all /1000h
lesion of meniscus or cartilage	1	1.0	0	-
haematoma/contusion/bruise	8	8.0	4	2.0
Fracture	1	1.0	1	0.5
muscle rupture/strain/tear/cramps	9	9.0	6	3.0
sprain/ligament injury	3	3.0	4	2.0
tendon injury/rupture/tendinosis/bursitis	4	4.0	2	1.0
other (please specify) (HERNIA)	1	1.0	0	-

7.4.6 Results for injury type as classified by anatomical location

Injury subtypes were further classified according to their anatomical location. For the categories of lowback/sacrum/pelvis, hip/groin and lower leg/achilles tendon, the most prevalent injury type was muscle rupture/strain/tear/cramps with a total of two, seven and three injuries respectively. The most common ankle injury was subtype sprain/ligament injury with six injuries, and the number of injuries (n = 3) was the same for ankle haematoma/ contusion/ bruise subtype and tendon injury/ rupture/ tendinosis/ bursitis subtype injuries. For further information regarding injury subtype according to anatomical location see table 7.10 below.

Table 7.10 Total injury subtypes as classified by anatomical location

Injury location	Injury subtype	Number of Injuries	Percentage of total injuries %	95% CI
lowback/ sacrum/ pelvis	muscle rupture/strain/tear/cramps	2	4.5	-1.6 – 10.7
hip/groin	muscle rupture/strain/tear/cramps	7	15.9	5.1 – 26.7
	Other (hernia)	1	2.3	-2.1 – 6.7
Thigh	haematoma/contusion/bruise	3	6.8	- 0.6 – 14.2
	muscle rupture/strain/tear/cramps	3	6.8	- 0.6 – 14.2
Knee	haematoma/contusion/bruise	4	9.1	0.6 – 17.6
	lesion of meniscus or cartilage	1	2.3	-2.1 – 6.7
	sprain/ligament injury	1	2.3	-2.1 – 6.7
	tendon injury/rupture/tendinosis/bursitis	2	4.5	-1.6 – 10.7
lower leg/ achilles tendon	haematoma/contusion/bruise	1	2.3	-2.1 – 6.7
	muscle rupture/strain/tear/cramps	3	6.8	- 0.6 – 14.2
	tendon injury/rupture/tendinosis/bursitis	1	2.3	-2.1 – 6.7
Ankle	haematoma/contusion/bruise	3	6.8	- 0.6 – 14.2
	sprain/ligament injury	6	13.6	3.5 – 23.8
	tendon injury/rupture/tendinosis/bursitis	3	6.8	- 0.6 – 14.2
foot/ toe	fracture	2	4.5	-1.6 – 10.7
	haematoma/contusion/bruise	1	2.3	-2.1 – 6.7

When evaluated according to match or training activity the number of injuries per injury subtype was similar for the anatomical locations of lowback/sacrum/pelvis, hip/groin, thigh and foot/toe. For match activity, more injury subtypes were associated with the anatomical locations of knee and lower leg/achilles tendon compared to training. Further information for injury subtypes as classified by anatomical location for match and training activity can be seen in table 7.11 below.

Table 7.11 Total injury subtypes as classified by anatomical location for match and training activity

	Match		Training	
Injury location	**Injury subtype**	**Number of Injuries**	**Injury subtype**	**Number of Injuries**
lowback/sacrum/ pelvis	muscle rupture/strain/tear/cramps	1	muscle rupture/strain/tear/cramps	1
hip/groin	muscle rupture/strain/tear/cramps	3	muscle rupture/strain/tear/cramps	4
	Other (hernia)	1		
thigh	haematoma/contusion/bruise	2	haematoma/contusion/bruise	1
	muscle rupture/strain/tear/cramps	2	muscle rupture/strain/tear/cramps	1
knee	haematoma/contusion/bruise	2	haematoma/contusion/bruise	2
	lesion of meniscus or cartiladge	1		
	sprain/ligament injury	1		
	tendon injury/rupture/tendinosis/bursitis	2		
lower leg/achilles tendon	haematoma/contusion/bruise	1		
	muscle rupture/strain/tear/cramps	3		
			tendon injury/rupture/tendinosis/bursitis	1
ankle	haematoma/contusion/bruise	3		
	sprain/ligament injury	2	sprain/ligament injury	4
	tendon injury/rupture/tendinosis/bursitis	2	tendon injury/rupture/tendinosis/bursitis	1
foot/toe	fracture	1	fracture	1
			haematoma/contusion/bruise	1

7.4.7 Results for total injuries according to surface and activity type

The only surface types common between training and match activities were natural grass and the artificial surface 3G. For surface type, natural grass, sand astroturf and the artificial surface 3G, had the highest number of injuries with 21 (47.7%), 11 (25.0%) and nine (20.5%) injuries respectively. Of the remaining injuries, one injury was sustained playing Futsal (wooden floor), one injury was sustained during road running (tarmac) and the remaining injury was sustained during lower limb resistive exercise in the gym (no surface available). Further information for number of injuries and incidences for each surface type can be seen below (7.12)

Table 7.12 Total number of injuries and incidence/1000h for surface type and activity

	Total injuries		Training Injuries		Match injuries	
Surface type	**Injuries**	**Incidence**	**Injuries**	**Incidence**	**Injuries**	**Incidence**
Artificial Surface 3G	9	25.0	2	9.9	7	29.7
Natural Grass	21	18.1	1	3.2	20	16.4
Wooden (Futsal)	1	-	1	13.4	0	-
Sand astroturf	11	-	11	12.7	0	-
Other*	2	-	2	3.2	0	-

*road running (tarmac) and gym (no surface type available)

For surface types common to match and training activities, the artificial surface 3G had the higher overall incidence of 25.0/1000h compared to natural grass which had an incidence of 18.1/1000h. For these surfaces, the incidence of injury was higher for match play than for training, with the artificial surface 3G having incidences of 29.7/1000h and 9.9/1000h respectively and natural grass having incidences of 16.4/1000h and 3.2/1000h respectively.

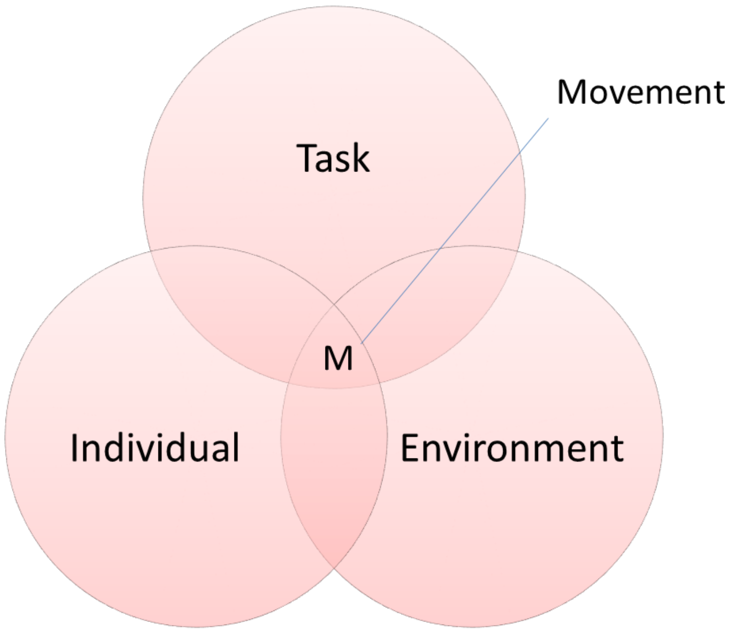
For match activity, the incidence for injuries on the artificial surface 3G was higher than that of natural grass (29.7/1000h and 16.4/1000h respectively). This was also true when the surfaces of artificial turf 3G and natural grass were compared for training activity (9.9/1000h and 3.2/1000h respectively). For training activity, Futsal (wooden floor) had the highest injury incidence of 13.4/1000h. Sand AstroTurf was associated with the second highest injury incidence of 12.7/1000h, followed by the artificial surface 3G with an incidence of 9.9/1000h. The lowest injury incidences (3.2/1000h) were associated with natural grass and other forms of training on different surfaces.

7.5 Discussion of results for injuries and exposure

It has previously been identified that the existing framework by Fuller et al (2006) may result in between study differences for injury incidence, severity of injuries and clustering of injury subtypes. Comparison against the existing literature is therefore difficult and these factors must therefore be taken into consideration when comparing the results of the database against the existing literature as they may account for some of the observed variation. To allow for comparison against the existing literature the framework by Fuller et al (2006) will be used. However given that it has been identified as inadequate, when evaluating injury risk factors for injury in football, a different framework will also be considered alongside it.

Participation in football requires repeated intermittent efforts of running alongside a level of technical skill and ability. Players are required to perform a series of complex movements, whilst interacting with opposing players and other environmental factors. Where, the occurrence of injury, may be affected by an individual's functional capacity, which is in turn, determined by their capacity to meet interacting task and environmental demands. A method which evaluates risk factors for injury by only focusing on processes within the individual, without consideration of the environment in which the individual moves, or the task that they are performing, will produce an incomplete picture (Shumway-Cook and Woollacott 2010). Therefore, methods of data collection and injury reporting should accurately reflect these processes, in order to better inform our understanding of injury risk factors for football (Bahr 2009). Injury in football must be considered within the constraints of the individual, the task and the environment (Shumway-Cook and Woollacott 2010) (figure 7.2).

Figure 7.2 Movement emerging from the interactions between the individual, the task and the environment Shumway-Cook and Woollacott (2010)



Within this study each player sustained on average 2 injuries throughout the season. This is similar to injury rates reported in other studies, where the average outfield player sustained at least 1-2 injuries throughout a competitive season (Hawkins et al 2001; Ekstrand et al 2013). Within the existing literature, reported incidence of injury for match play ranged between 10.2/1000h to 35.5/1000h as reported in a review by Junge and Dvorak (2004). The match injury incidence of 27.0/1000h reported in this study is therefore within the range of reported match injury incidences. Given that study populations were similar (male footballers over 17 years of age at varying levels of competition) it would be expected that results between this study and the published literature for match injury incidence would be similar. Between studies, it was also identified that the injury incidence rate was consistently higher for match play when compared to training. Despite similar injury patterns between our study and the reported literature, the incidence for training injuries was higher within this study. For all forms of training within this study, the incidence of injury was between 8.5/1000h to 12.3/1000h depending on the definition of training. Training injury incidence rates identified by Junge and Dvorak (2004) ranged from 1.5/1000h to 7.6/1000h.

A possible reason for the increased incidence of training injuries within our study may stem from the amount of exposure on sand AstroTurf. As none of the studies identified by Junge and Dvorak (2004) reported the training surface type, a direct comparison is not possible. However, within our study players had more exposure on the surface of sand AstroTurf compared to any of the other surface types. Sand AstroTurf surfaces, such as the one trained on within this study, are associated with an increased injury incidence for some sporting disciplines. This is due to the increased hardness, stiffness and frictional properties of the sand AstroTurf playing surface (Williams et al 2011). The results observed in our study demonstrate this, as sand AstroTurf had the highest incidence of training injuries (12.7/1000h) when compared to natural grass and the 3G AstroTurf (incidences of 3.2/1000h and 9.9/1000h respectively). It is acknowledged that injury causation is multifactorial and training surface may not entirely account for the difference in injury rates. Additional factors known to affect the incidence of training injuries are player age, duration of training sessions, intensity of training, rate of training load increase, fixture congestions and time between events (Ekstrand et al 1983; Bengtsson et al 2013; Carling et al 2012; Bowen et al 2017). These factors, either independent of, or in conjunction with surface type, may account for the difference in the injury rates observed between our study and the published literature (Aoki et al 2010; Kristenson et al 2013).

Further variations of training injury incidences may stem from differences in methodology or application and interpretation of the consensus statement. For this study, all physical activity undertaken by participants was recorded and classified as training exposure. In studies that used the consensus definition of training exposure, any physical activity undertaken by players that wasn't prescribed by a member of the medical or coaching team would have been excluded. For our study, we felt it necessary to include all forms of physical activity undertaken by the player as this could have an effect on their fitness and fatigue, which would affect injury. It is also acknowledged that more professional teams may have all exercises prescribed and therefore the definition may be suitable for capturing all the relevant forms of training. Examples of how training exposure definitions can affect training injury incidences can be demonstrated within our study. Depending on the definition used, the incidence of training injuries was to 8.5/1000h (all forms of training) and 12.3/1000h (training according to the consensus definition). It is therefore necessary to ensure current methods of data collection and injury reporting accurately captures the true incidence of injury and the relevant factors associated with it. By excluding some forms of training it may overestimate the incidence of injury as identified in our study, or conversely underestimate the true incidence of injury (Bjorneboe et al 2010; Ekstrand et al 2006; Kristenson et al 2013).

For injury location, type, mechanism and severity, the results obtained within this study are similar to results within the published literature. The majority (87%) of injuries sustained in football affect the lower limbs with muscular strains, ligament sprains and contusions being the most common injury types (Ekstrand et al 2011, Hawkins et al 2001). Within in our study, lower limb injuries accounted for 96% of the injuries (95% CI 89.3% - 100.0%), with hip/groin, knee and ankle injuries being the most common injury location subgroups. Injury category subtypes of muscle rupture/strain/tear/cramps and haematoma /contusion /bruise accounted for 61% of the total injuries in this study (95% CI 47.0% - 75.7%); similar to injuries classified as strains, sprains, or contusions that accounted for 65% of the injuries reported by Hawkins et al (2001). For injury mechanism, traumatic injuries account for approximately 80% and 60% for match and training injuries in the published literature respectively. Within this study, a traumatic mechanism was attributable to 74% (95% CI 57.5% - 90%) and 53% (95% CI 29.2% - 76.7%) of the match and training injuries sustained and are therefore similar. Within our study foul play by an opposing team member accounted for 18.5% of the traumatic injuries sustained in match play (95% CI 3.9% - 33.2%). This again is similar to the published literature in which foul play by opposition teams can account for 12% to 28% of traumatic injury occurrence (Ekstrand et al 2009, Hawkins and Fuller 1999, Hawkins and Fuller 1998).

Given that football is a sport that predominantly involves the lower limbs, it would be expected that the majority of injuries would affect the lower limbs. The demands of football are broadly a requirement to repeat intermittent efforts of running alongside technical ball control, kicking and interaction with opposing players and the environment. Running speeds in football can reach in excess of 19km/h (Carling et al 2012) and associated with this are periods of acceleration and deceleration. In order to achieve this, muscles and joints are required to generate and sustain repetitive forces of varying magnitude. The demands of the sport, compounded with other factors related to injury (identified in the literature review) may place these structures under greater strain and increase the occurrence of these injury types. Given the contact nature of football, the mechanism of contact coupled with the high running speed, accelerations and decelerations may explain the higher number of injuries within the category of haematomas/contusions/bruises. Within the framework discussed previously, the severity and the occurrence of these injury subtypes may be a result of individual, task and environmental factors. Examples of this would be a player who is fatigued and be unable to get out of the way of a tackle, likewise a player with poorer technical skill may not be able to control the ball and their subsequent position well enough to minimise situations in which they could be tackled.

Within our study “overuse injuries” accounted for 34.1% of the total injury burden (95% CI 20.1% - 48.0%) which is similar to the published literature values of 30% (Ekstrand et al 2011). Comparison against the existing literature is difficult, as a result of the multiple injury subclusters and exclusion of overuse injuries by several studies. Exclusion of overuse injuries within the published literature stems from the inability of the existing framework to identify injury causes. Evidence of this can be seen in current injury documentation practice, which requires the practitioner to record information related to the injury mechanism in terms of a traumatic circumstance, which can be attributed to a single event, or an overuse circumstance, which cannot be attributed to a single event. Due to this definition, the term overuse is ambiguous implying that either the athlete has trained or played too much, a consequence of which could be fatigue, or that there is no identifiable mechanism for injury. The categories of overuse and traumatic also imply two distinct categories, comprised of separate injury mechanisms. However, within the conceptual framework discussed earlier, a player who has trained too much and is fatigued will have a lower functional capacity during match play. As a result of this, it would affect their ability to control their movement (move out the way/ fall appropriately) relative to an opposing player who has committed to a tackle (with or without intent to cause harm), resulting in injury. In this case, the injury mechanism would be recorded as traumatic, resulting in the causative influence of overtraining being masked. Any subsequent injury prevention programs that are developed will therefore be targeted towards preventing “traumatic injuries” and the causative factor of overtraining will not be addressed. Within this example, the injury would then be further classified as being caused by contact or non-contact (Ekstrand and Gillquist 1983a). Several important factors are neglected in this approach of injury recording such as preceding circumstances as well as body and limb positioning at the time of injury, further compounding the previously identified problem.

In addition to the aforementioned problems associated with the existing framework and exclusion of overuse injuries, the role of alternate factors such as the effect of training surface on injury occurrence in conjunction with other factors may be underestimated (Bjorneboe et al 2010; Ekstrand et al 2006; Kristenson et al 2013). Additionally, numerous different injury types such as tendonopathies, bursitis and stress responses are all assumed to have common mechanisms with no identifiable cause, whereas this is not a true representation of these injury types as identified by Aoki et al (2010). It was identified inadequate or excessive training load is associated with injury and may play a role in the occurrence of acute and overuse injuries alike. Therefore when comparing the results observed in this study against the published literature a true comparison is not possible as a result of limitations identified within the data collection and injury reporting methodology.

The amount of time missed through injury is influenced by the soft tissue healing timeframes of that tissue type and the degree of initial injury. When considering the soft tissue healing timeframes, it would be expected, that an injury causing no disruption to a muscle belly (strain) would result in less time missed when compared to an injury causing disruption to the muscle belly (tear). Based on this premise, as some injury types are more common than others, the time needed to recover from these injuries (severity) would be similar, resulting in some injury severity categories being more common. Whilst the prevalence of each injury severity category varies between studies, the largest injury category consistently appears to be moderate injuries (> 7 days and < 28 days) which account for approximately 30% to 50% of injuries (Carling et al 2010; Ekstrand et al 2009; Hawkins et al 2001). Within our study moderate injuries were the most common, accounting for 50% of all injuries (95% CI 35.2% - 64.7%). Given that the most common injury types identified were muscular ruptures/strains/tear/cramp injuries it would therefore be expected that time lost through injury (severity) would be in line with the time the soft tissues needed to repair (soft tissue healing timeframes). In view of the underlying physiological healing processes, injuries in which there is minimal disruption to the soft tissue structures would be expected to take up to six weeks for sufficient healing to occur depending on the magnitude of disruption (Brukner and Khan 2009). For larger ruptures/strains/tears, the healing time frame would be longer given the larger soft tissue structure disruption and subsequent underlying physiological healing processes. More moderate injuries may therefore occur as a result of the most common injury location and subtype healing timeframes falling in line with the range of days used to determine the category.

Patterns for recurrent injury occurrence were similar between our study (34.1%, 95% CI 28.0% - 48.0%) and the published literature (12% to 35%) (Ekstrand et al 2009; Hagglund et al 2016, Hagglund et al 2005). The existence of a previous injury has been identified as a specific risk factor in relation to injury type and location (Arnason et al 2004; Dvorak et al 2000; Engebretsen et al 2010b; Hagglund et al 2013, Venturelli et al 2011). Recurrent injuries are associated with a greater injury severity and higher incidence rate compared to new injuries, as was evident in our study. It has also been identified that more significant injuries within football have been preceded by minor injuries or acute complaints (Ekstrand and Gillquist 1983b). Proposed reasons for recurrent injury occurrence identified were inappropriate rehabilitation and insufficient rehabilitation time (Ekstrand and Gillquist 1983b, Gajhede-Knudsen et al 2013). Players may sustain an injury which is not significant enough for them to stop playing, or due to insufficient allowance of rehabilitation time, results in them playing with an injury that has not sufficiently recovered. Players may therefore compensate for their existing or previous injury resulting in inefficient performance due to pain or a player trying to protect themselves or the injury site. There may additionally be compensation that the player is not consciously aware of which would affect their performance. This may therefore increase their chances of injury if they are asked to perform outside of their functional capacity. As a result of this further injury, further damage or disruption, may be caused to the previously injured structure resulting in more time needed for recover and therefore a greater injury severity. Situations which demand a higher functional capacity, such as match play, may therefore result in a higher injury incidence.

It has also been identified that the more injuries sustained by a player the greater the risk of injury, for example players with more than six previous injuries are more at risk of sustaining further injury than those with fewer injuries (Dvorak et al 2000). Previous injuries are also a significant risk factor for the occurrence of injury in locations not previously exposed to injury (Hagglund et al 2006). As a consequence of repeated injuries players are removed from training for rehabilitation. It has already been identified that insufficient rehabilitation could be a cause for recurrent injury. If the level of functional capacity developed during rehabilitation is less than the functional demand of training and match play, the player may be at risk of developing further injury when returning to participation. If the rehabilitation is not adequate, further episodes of injury and subsequent rehabilitation would result in a cycle of recurrent injury and lowered functional capacity.

Despite the proportion of recurrent injuries and trend for match and training injuries being similar, within our study the incidence of recurrent injury was higher (5.0/1000h) than values within the literature (1.54/1000h (±1.13 to 2.11) (Hagglund et al 2016, Hagglund et al 2006). As identified, insufficient rehabilitation is a factor for recurrent injuries. Use of a return to play protocol has been shown to prevent recurrence injuries (Hagglund et al 2007). Given that players within our study did not receive a prescribed return to play rehabilitation program in line with the functional demands of the game, it could be argued that they had not completed an adequate level of rehabilitation. It has also been identified that professional teams a lower prevalence and incidence of recurrent injuries when compared to amateur teams. Professional teams have squads ranging from 25 and in excess of 30 players (Hagglund et al 2016). A proposed reason for reduced injury rates in professional teams is the wider availability of players, which would allow for injured players to gain sufficient recovery time through player rotation. This may be confounded by the increased frequency of competitive matches and external pressures associated with professional football. Players may have had shorter recovery time due to required participation in important games; as a result they may not achieve sufficient recovery or complete the full rehabilitation process. The number of participants within our study (24) is reflective of the number of players that may be expected within a football squad, but smaller when compared to some studies investigating risk at a higher level of competition. Despite a smaller sample size then some of the published literature, trends in injury patterns are similar for injury location, type and mechanism. As the team within our study was not national or professional level, the observed prevalence of repeat injuries 34.1% (95% CI 20.1% to 48.1%) is similar to the values within the published literature (up to 35%). It is acknowledged that this is at the higher end of the range, although other factors such as the surface type, availability of coaching and level of training may have elevated the injury incidence and prevalence. However, given that published studies have also excluded the injury subtypes of contusions, lacerations and abrasions, the incidence of recurrent injuries may be underreported (Hagglund et al 2016).

7.6 Conclusions and further work

Injury trends identified within our study are similar to that of the published literature for injury mechanism, location, type and severity. For training and recurrent incidence rates, increased rates within our study could be partly attributed to surface type and lack of return to play protocols. Professional clubs would likely have better facilities and medical/coaching staff availability resulting in a lower rate of injury through rectification the issues identified (Hagglund et al 2016). It is acknowledged that despite similar injury trends between our study and the published literature, vigilance must be taken when interpreting these results to other football teams given the smaller sample size. Another factor that must be considered is the length of follow up for our study, as players were followed up for a single season and Injury patterns are known to fluctuate between seasons (Ekstrand et al 2013, Hagglund et al 2016). Similar injury rates between studies may be expected given the demands of the sport. The overall training structure and demands from competitive matches may therefore influence injury occurrence and type. These factors must be considered alongside the individual's functional capacity which is affected by the constraints of the individual, the task and the environment.

Implementation of the consensus statement by Fuller et al (2006) has bought parity between studies for data collection and injury reporting procedures in football. However, current terminology and methodology is not adequate for capturing all the details relevant to injury causation. Current methods do not allow for identification of injury risk factors within the conceptual framework where movements related to injury occurrence is a result of individual, task and environmental constraints. The categories for recording and classifying injury mechanism are fairly broad and as a result may dismiss any detail that is relevant to injury causation. Important causative factors that precede injury occurrence may be omitted, and in addition, factors and circumstances concurrently present at the time of injury may become falsely associated with injury causation. Furthermore some studies exclude details relevant to injury causation due to differing interpretations and applications of the consensus statement (Bjorneboe et al 2010; Ekstrand et al 2006; Hagglund et al 2016; Kristenson et al 2013). As a result of this the true incidence of injury (also used as a measure of injury prevention effectiveness and injury mechanism understanding) may not be reflective of true injury patterns but rather variations in data collection and injury reporting mechanisms.

Currently no universally accepted and implemented injury screening process exists within football. There is therefore no agreement on which injury risk factors need to be considered for injury prediction, a necessary step in injury prevention. This affects the number and combinations of interactions that may occur, reinforcing the incomplete picture around injury mechanisms. Further work should look to standardise pre-season and inseason measures to investigate their role in causation. As injury risk occurrence is multifactorial, discussed previously within the framework of the individual, the environment and the task. When reporting the effect of identified risk factors, all factors relevant to injury and their effect should be included to allow for a complete understanding of injury mechanism and severity. In order to better understand the role of individual factors alongside the combinations of interactions that may affect injury risk, data relevant to injury should be recorded within a format suitable for injury modelling processes.

8 CAN WE PREDICT INJURIES BASED ON EXISTING RISK FACTORS ADVOCATED FOR PROSPECIVE INJURY MODELLING?

8.1 Introduction

It was identified at the start of the PhD process, that within the sporting discipline of football, a range of methods exist that have been advocated for use in injury prediction. This led to the development of the main research question

1. Can we predict injuries based on existing risk factors advocated for prospective injury modelling?

This chapter will therefore look to address the first aim of this study and associated research question. Within football, development of a clinically applicable model for injury prediction would inform clinical decision making processes related to injury prevention programs, return to play decisions and training program development. A preliminary step is therefore to evaluate if injury can be predicted based on the existing framework and advocated methods.

8.2 Model selection for addressing the research question

The research question is concerned with evaluating whether we are able to predict injury based on the use of currently advocated methods. In order to best address the research question, a neural network was selected; specifically a Bayesian regularized artificial neural network (BRANN) (Mackay 1992; Neal 1996). This was a logical decision, taken after an evaluation of the modelling methods and data set available to us. A requirement for regression is that the selected inputs are numerical; given that not all of our selected inputs were numerical, the use of regression methods would not have been suitable. Further justification for selection of a BRANN is described in the following section alongside the properties of the model that informed the selection process.

Selection of a model that adequately answers the research question is imperative (Steyerberg 2009). The selected model was appropriate for answering our research question, given that the primary aim was to identify if an accurate prediction could be made. Neural networks are recommended for datasets in which the rules that underlie the data are unknown or only partially understood (Cartwright 2009). It is recognised that the selected neural network model is considered a "black box" or opaque one and as a result, we are unable to evaluate any underlying assumptions such as non-linearity, additivity or proportionality of hazards (Burden and Winkler 2009). Whilst testing for such assumptions is standard practice for modelling, this is only beneficial if it is likely to improve the prediction performance of the model (Steyerberg 2009). The "black box" property of the model was therefore considered apt, given that our research question was "*Can we predict the occurrence of injury based on the current advocated methods?*" and not "*Which of the current advocated methods are better for predicting injury*?".

8.2.1 Properties of the Bayesian Regularised Artificial Neural Network (BRANN)

A BRANN has been identified as having several advantages over other classifier/regression techniques. In general, neural networks are universal approximators, capable of modelling any continuous nonlinear function given suitable data and training (MacKay 1992). Despite this, some limitations of existing neural networks have been identified, namely that they can be subject to overtraining, overfitting and consequently lose their prediction ability (Burden and Winkler 2009). Validation of these models can also be problematic with processes around optimization of network architecture being time consuming. These limitations can be addressed through a modification of the standard back propagation process used by these modelling techniques, and the inclusion of a regularisation step that incorporates Bayesian statistics. The advantages of the BRANNs are that:

- They are less prone to overtraining; training is stopped based on an objective criterion determined by an evidence procedure. This removes the need for a separate validation set usually required to detect the onset of overtraining.
- They are robust and less computationally complex when compared to the validation process used in traditional normal regression methods.
- These networks automatically solve a number of important problems such as choice of model, robustness of model, choice of validation set, size of validation effort, and optimization of network architecture.
- They are less prone to overfitting, as they calculate and train on the effective number of parameters (non-trivial weights in the trained neural network). This is notably less than the

number of weights in the trained neural network that uses a standard fully connected back-propagation methods. BRANNs automatically and optimally penalize complex models. As the architecture complexity increases (e.g., by increasing the number of hidden-layer nodes), the number of effective parameters converge to a constant. An optimum balance between bias (where the model is too simple to explain the underlying structure-activity relationships) and variance (where the model is excessively complex and fits the noise)

- BRANNs are less sensitive to the architecture of the network, providing the network architecture is minimal.

No principle component analysis was performed on the data, as it was established that the model-regularisation process accommodates for problems usually associated with too many variables, namely multi co-linearity and overfitting. Removal of any variable without a clinically or pragmatically justifiable reason may affect the performance of the model. Additionally, given that all inputs are advocated for injury prediction, inclusion of all variables would therefore emulate current practice (Fuller et al 2006; Hulin et al 2016). Inputs were therefore selected based on current recommendations by governing bodies, previous studies and feasibility of collection.

8.2.2 Selection of model output (dependant variable)

Injury can be considered as a binary outcome (injured versus not injured), or as a continuous outcome (injury severity i.e. number of days missed through injury). For the model, the dependant variable selected was injury severity (continuous outcome). A continuous variable was selected, as within a statistical framework they are preferable, given that they provide more power in the analysis compared with a binary outcome (Steyerberg 2009). The selection of injury severity (continuous variable) is also supported within a pragmatic framework, as the severity of an injury, as opposed to the occurrence of an injury is more likely to inform clinical decision making processes. For example, an injury with a severity of 14 days is more consequential than an injury with a severity of one day. The reduction of this information to a binary outcome would mask this information.

8.2.3 Selection of model inputs (independent variables)

A total of 34 inputs were included for the modelling process and can be seen in table 8.1. Methods for recording and reporting factors relevant to injury have been reported in Chapter 7. These inputs were selected according to a recognised framework currently used in football (Fuller et al 2006). Additional inputs included within the model were anthropometric characteristics of height, weight and skinfold thickness (6 to 8 respectively); an additional two measures of training load (21) and fitness (34) were also included. Justification for their selection will be discussed in the following section.

Anthropometric measures, namely height, weight and skinfold thickness, were included as inputs in the model. Based on the literature review, it was identified that no consensus exists regarding their role in the occurrence of injury. Some studies have identified these factors as risk factors for injury and so they were therefore included as inputs (Ekstrand et al 1983; Arnason et al 2004; Soluken 1994; Henderson et al 2009;Frisch et al 2011; Fousekis et al 2011; Venturelli et al 2011; Gajhede-Knudsen et al 2013).

Player fitness and playing load i.e. training and match load, fixture congestion and rate of load increase, have been identified as risk factors for injury (Eriksson et al 1986; Arnason et al 2004; Bangsbo et al 2008; Frisch et al 2011; Venturelli et al 2011; Bowen et al 2016, Malone et al 2017). The Yo-Yo intermittent recovery test and acute to chronic workload ratio were selected in order to quantify these variables respectively. The characteristics of the acute to chronic workload ratio were evaluated prior to its inclusion into the model (Appendix XVII). The Yo-Yo intermittent recovery test score was selected as a measure of player fitness. It is a widely known and well validated test within the sporting discipline of football (Krustrup et al 2003; Bangsbo et al 2008).

Table 8.1 Selected model inputs (independent variables)

Category	Number	Input
Position	**1**	Attacker
	2	Midfielder
	3	Defender
	4	Goalkeeper
Anthropometric	**5**	Kicking Leg
	6	Height
	7	Weight
	8	Sum of 4 sites skinfold thickness (biceps, triceps, subscapular suprailiac)
	9	Activity duration
Activity type	**10**	Match
	11	Training
	12	Futsal
	13	Conditioning
Surface type	**14**	Sand Astroturf
	15	Natural grass
	16	Artificial Astroturf (3G)
	17	Wooden
Injuries	**18**	Previous injuries
	19	Inseason injuries
	20	Cumulative number of injuries (to case)
Variables related to training / match activities / fitness	**21**	Acute to Chronic workload ratio
	22	Cumulative match load
	23	Cumulative match grass load
	24	Total match Artificial Astoturf (3G) load
	25	Total training (all types) load
	26	Total training load (excluding futsal and conditioning)
	27	Total training grass load (excluding futsal and conditioning)
	28	Total training Sand Astroturf load (excluding futsal and conditioning)
	29	Total training Artificial astroturf (3G) load (excluding futsal and conditioning)
	30	Total training futsal load
	31	Total training load (with futsal) excluding conditioning
	32	Total training conditioning load
	33	Cumulative Match + Training load (22 + 23)
	34	Yo-Yo fitness score

*load refers to time in minutes

The correlation between the selected inputs and output was calculated. As the selected modelling method is a “black box”. This was done as an exploratory exercise in order to understand how individual input variables may affect the output in a linear fashion. Results can be seen in tables 8.2 and 8.3.

Table 8.2 Correlation for continuous inputs and injury output (Parametric Pearsons)

Inputs	Injury (output)			
	Pearson Correlation	Sig. (2-tailed)	N	N
Height	0.123	0.143	144	144
Weight	0.124	0.138	144	144
Sum of 4 sites skinfold thickness (biceps, triceps, subscapular suprailiac)	.171*	0.04	144	144
Activity duration	-0.012	0.885	144	144
Previous injuries	-0.126	0.132	144	144
Inseason injuries	.282**	0.001	144	144
Cumulative number of injuries (to case)	0.093	0.269	144	144
Cumulative match load	0.048	0.571	144	144
Cumulative match grass load	0.04	0.634	144	144
Total match Artificial Astoturf (3G) load	0.075	0.373	144	144
Total training (all types) load	-0.004	0.964	144	144
Total training load (excluding futsal and conditioning)	0.053	0.526	144	144
Total training grass load (excluding futsal and conditioning)	0.073	0.386	144	144
Total training Sand Astroturf load (excluding futsal and conditioning)	0.048	0.566	144	144
Total training Artificial astroturf (3G) load (excluding futsal and conditioning)	0.005	0.951	144	144
Total training futsal load	-0.039	0.638	144	144
Total training load (with futsal) excluding conditioning	0.045	0.594	144	144
Total training conditioning load	-0.07	0.407	144	144
Cumulative Match + Training load (22 + 23)	0.013	0.875	144	144

**.Correlation is significant at the 0.01 level (2-tailed).

*.Correlation is significant at the 0.05 level (2-tailed).

Table 8.3 Correlation for discrete inputs and injury output (Non parametric Spearman's)

Inputs	Injury (output)		
	Spearman's		
	Correlation Coefficient	Sig. (2-tailed)	N
Attacker	.	.	144
Midfielder	0.092	0.27	144
Defender	-0.13	0.119	144
Goalkeeper	0.07	0.402	144
Kicking Leg	.	.	144
Match	.264**	0.001	144
Training	-0.077	0.36	144
Futsal	-0.052	0.534	144
Conditioning	-.205*	0.014	144
Sand Astroturf	-0.006	0.941	144
Natural grass	-0.007	0.929	144
Artificial Astroturf (3G)	0.05	0.555	144
Wooden	-0.052	0.534	144
Acute to Chronic workload ratio	0.049	0.558	144
Yo-Yo fitness score	0.159	0.057	144

**.Correlation is significant at the 0.01 level (2-tailed).

*.Correlation is significant at the 0.05 level (2-tailed).

8.2.4 Selection of model parameters

Data were analysed using the Matlab R2016a Neural fitting toolbox v9.0. A BRANN with 15 hidden neurones was selected. Following randomisation of subjects (initial step in the BRANN), the data was split into a:

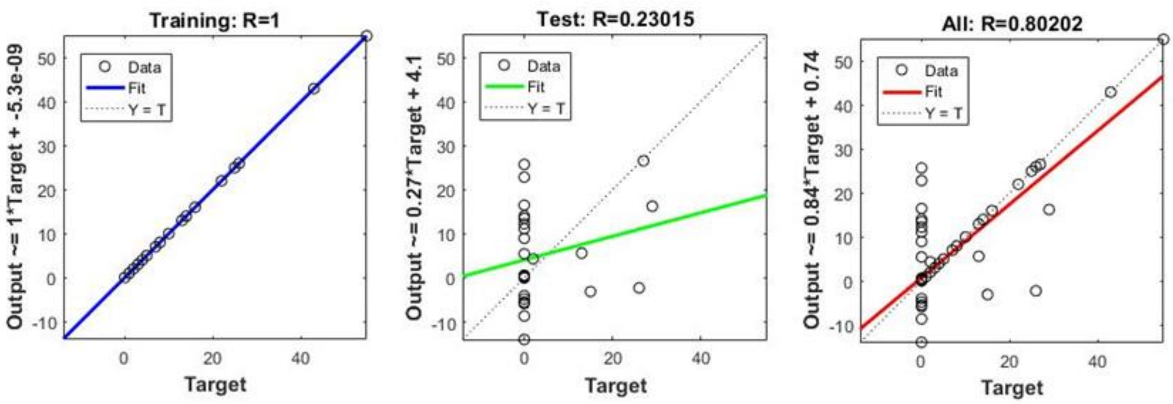
- Training set = 60% (n=86)
- Validation set = 20% (n=29)
- Test set = 20% (n=29)

Training of the BRANN was then conducted after which the results were analysed.

8.3 Results for predicting injury in football with a BRANN

Results for the training and test sets and overall performance of the model are shown in figure 8.1. The vertical axis labelled "Target" represents the observed outcome whilst the horizontal axis starting with "Output" represents the predicted outcome from the model. The predicted outcome is therefore plotted against the observed outcome to evaluate how well the model predicted the outcome. A case in which the predicted outcome was the same as the observed outcome would be represented by a point which falls on the diagonal dashed black line. Visually this can therefore be represented by a comparison of the coloured solid lines in relation to the dashed black line (target line). The better the performance of the model, the more closely the solid coloured line will match the dashed black line (target line). This is known as fitting, the process by which the results of the observed sample are compared against the learning model output.

Figure 8.1 Results for BRANN model performance



Another indication of the model's capability is the correlation co-efficient (represented by the value of R). The correlation co-efficient ranges between +1 and -1. A value of +1 indicates a perfect direct linear correlation whilst a value of -1 indicates a perfect inverse linear correlation. If there is no linear correlation the value of R will equal 0 (Daniel 2005). An R value closer to +1 or -1 would be an indication of how well the predicted outcome matched the observed outcome.

8.3.1 Results for training set

The first plot shows the results of the training set. The blue line overlies the dashed line, in what is known as a "perfect fit" also represented by the R value of +1. A perfect fit indicates that the BRANN has undergone sufficient training (learning) so that it is able to match the learning model outputs to the observed model. It has also been identified that there are a significant number of points superimposed at (0, 0) indicating that there were several cases in which the BRANN correctly predicted that no injury would occur.

8.3.2 Results for test set

The trained model is then applied to the test set, which contains new data not included in the Training set. The second plot shows the results of the test set, in which the model identified in the training set is applied to a new set of data. The fit line shows a positive gradient indicating it was able to identify an increased likelihood of injury for cases in which injury occurred. The fit is however affected by the column of points located at point 0 on the target axis. This indicates that there were several cases for which the BRANN predicted the occurrence of injury but no injury reportedly occurred within in the observed sample. The identified R value of 0.23015 would be considered a small correlation (Cohen 1988).

8.3.3 Results for all sets

The third plot represents the overall performance of the model determined by combining the performance results of the model for the training and test sets.

8.4 Discussion of results for predicting injury in football with a BRANN

On evaluation of the results, it has been identified that we are unable to predict injuries based on the selected injury predictors (independent variables) and modelling methods (BRANN). A trend of increased injury likelihood in players sustaining injury was identified based on the selected method, although this was only small (R value = 0.23015). Several factors that may have affected the performance of the model have been identified and will be discussed within this chapter. It has been acknowledged that factors surrounding the cause of injury are multifactorial. It has also been identified that the existing framework for recording and reporting injury risk factors is inadequate, given that it does not identify injury mechanisms or encompass all factors that may be relevant to injury within the literature review (Chapter 1). Within our model, the selection of inputs was based on an existing framework currently used within football for recording and reporting predictors of injury (Fuller et al 2006). An inability of the existing framework to identify the appropriate injury predictors and associated mechanisms would therefore negate the ability of the model, regardless of model type, if the selection of model inputs was based on this framework. An inability of the selected variables to predict injury is evident in the performance of our model test set.

If we consider injury occurrence within the previously discussed constraints; namely the functional capacity of the individual alongside the demands of the environment and the task, utilisation of this framework may help to evaluate the efficacy of selected predictors and their subsequent effect on model performance. Additionally this framework may be used to identify better predictors for injury. Whilst overall performance of the model was poor, it was still able to identify an increased injury risk for injured players compared to non-injured players. This suggests that some of the selected inputs may account for increased injury risk, although they do not have sufficient prediction ability either independently or in conjunction with the other variables. Several instances were identified, on evaluation of the models performance, in which the model predicted an injury when no injury had occurred. Both these situations may stem from inadequate prediction ability of existing variables and omission of other relevant variables for injury prediction. Clinical application of the model would therefore have consequences as a result of these errors. This can be described in terms of the cost of the wrongly predicted outcome classified as false positives or false negatives, i.e. comparing the consequences of cases in which the model:

- Predicts an injury but no injury would have occurred (false positive), or
- Predicts no injury but an injury would occur (false negative).

This is done in order to evaluate if some types of errors (false positives versus false negatives) could be considered more acceptable than the alternate in clinical application of the model. Neither type of error is without consequences. The acceptability of one type of error compared with the other is heavily context dependent and affected by factors such as the type and severity of the injury, level of competition and characteristics of the player.

If we consider that the primary purpose of injury prediction is to prevent injury, and that the occurrence of an injury further increases the risk of more frequent and severe injuries (Ekstrand and Gillquist 1983b; Dvorak et al 2000), the occurrence of a false positive, in which the model predicts injury but no injury occurred, could be considered more acceptable than the alternative. Players removed from training or match play could engage with alternate forms of conditioning related to their athletic development or recovery. Overall this may result in players having more availability given that fewer days are lost to injury. This is assuming that players are able to maintain the required level of conditioning which allows them to compete (Hulin et al 2016). However, at a professional level, a false positive which results in a player, or players, being removed from an important match could potentially affect the performance of the team in a competitive league. In this context, a false positive would be considered worse than a false negative, in which the player sustains a minor injury during the game. The occurrence of false positives could also potentially result in situations in which players are omitted from training sessions or matches that provide opportunities for them to become recognisable for selection into the team or higher levels of competition. This may be considered an unacceptable error by the respective player given that this arguably is more detrimental to their development or career.

Furthermore, the acceptability of a false negative is dependent upon the severity and consequence of the injury. For example, when compared with the consequences of a false positive, failing to predict the occurrence of a slight injury (< 1day) may be considered acceptable, where as failing to predict a career ending injury would be considered unacceptable. It is therefore difficult to conclusively identify which type of error is more acceptable given the contextual dependence. A better understanding of factors resulting in the occurrence of errors within our model is therefore required and will be evaluated below.

For instances in which the model predicted an injury and no injury occurred, it has been identified that this may stem from inadequacies with existing predictors consequently affecting model performance. This will be elaborated on in the following section. Another explanation is that the model correctly predicted injury, but the injury was not reported. During the FMS screening, prior to the start of the season, the team was instructed to report any injuries that occurred to the team physiotherapist, after which they received an assessment to record injury details in the team's database, as per the consensus statement (Fuller et al 2006). Additionally players received a weekly email regarding their injury status in addition to match and training volumes. An injury was defined as "*any physical complaint sustained resulting from a football match or football training irrespective of the need for medical attention or time loss from football activities"* as per the consensus definition. Despite a clear injury definition and regular evaluation of injury status, it was identified by the team physiotherapist that some injuries were initially unreported. Identification of these injuries was usually following an assessment of a more severe injury. All preceding injury details were recorded by the team physiotherapist and included in the database and analysis. However, this demonstrates that some injuries as per the consensus definition may not have been reported given that the participant did not feel the injury was severe enough. It is known that more severe injuries can be preceded by less severe injuries (Ekstrand and Gillquist 1983b). It has also been identified that player reported injuries may be subject to recall bias when compared with objective recording of injury occurrence (Junge and Dvorak 2000). It is therefore plausible that the model may have predicted an injury that did occur, but one which the player did not report. Within the conceptual framework, this can be explained further.

We can consider injury to be the result of an individual's functional capacity not being sufficient for meeting the task and environmental constraints. Players may therefore not consider the occurrence of a physical complaint e.g. pain, an injury unless it lowers there functional capacity beyond the point in which they are unable to participate within the required constraints. For example, players may sustain an injury which is not significant enough for them to stop playing. Inefficient performance due to pain, or a player trying to protect themselves or the injury site, may therefore increase their chances of injury given that they are being asked to perform outside of their functional capacity. However, if the functional demands of the training session or game are such that the player is not required to go beyond their functional capacity, they may continue to participate without the exacerbation of the existing injury. They would therefore consider themselves uninjured.

Given this understanding, two measures were used as indicators of the participant's functional capacity, namely the Yo-Yo intermittent recovery score and the acute to chronic work load ratio (Eriksson et al 1986; Arnason et al 2004; Bangsbo et al 2008; Frisch et al 2011; Venturelli et al 2011; Bowen et al 2016, Malone et al 2017). Total time in activity was used as a measure of player load (task constraints) when undertaking training and match play, which subsequently informed the acute to chronic workload ratio. It has been identified that players with a lower level of fitness may fatigue quicker, which would affect lower their functional capacity and affect their risk of injury. It has also been identified that players with an increase in their load that is beyond their level of conditioning may be subject to injury as they are going beyond their functional capacity. This is however assuming that the demands of the training session or match are greater than the functional capacity of the participant. Comparison of the individuals' capacity against the constraints of the task is therefore necessary. However, it is acknowledged that time/exposure alone may not be a suitable metric in isolation for quantifying the constraints of the task. The constraints of training and match play may be determined by several other factors such as total distance run, running speed and not time alone (Hulin et al 2014, Hulin et al 2016, Moller et al 2017). Two separate training sessions with an equal time may differ in distance run and intensity. Quantification of these variables requires individual player global positioning (GPS) units which were not available to the researcher and therefore time/ exposure was selected as a solution to this.

On evaluation of the acute to chronic workload ratio, the ratio was applied to the metric of time/exposure for training and match sessions. Given the identified limitations of time/exposure as a measure for task constraints, it is therefore unlikely to be useful for informing any other measures such as the acute to chronic workload within our model. Studies which identified the acute to chronic workload as predictor of injury in football based it on total distance (Malone et al 2017). The acute to chronic workload has been identified as a predictor of injury when based on time/ exposure or running speed in other sports, but not within football (Hulin et al 2014, Hulin et al 2016, Moller et al 2017). The nature of football may be such that the selected metrics are not suitable for predicting injury, given that they do not accurately capture the constraints of the task. This may account for poor model performance based on these metrics alone.

The Yo-Yo test score was used as an indicator of player fitness (individual constraint) and included as a predictor in the model. We have identified that injury occurrence is multifactorial and can be expressed within the context of individual, task and environmental constraints. Evaluation of a single factor may not provide adequate explanation for injury occurrence and therefore negate its ability as a predictor. For example, in the literature review it was identified that surface type alone was not suitable for injury prediction, but surface type and the activity duration were (Aoki et al 2010; Kristenson et al 2013). When considering the constraints of the individual, the Yo-Yo test, while providing an indication of player fitness, may not capture other factors relevant to the functional capacity of the individual and motor control. In the literature review, physical and subjective levels of player fatigue were identified as a risk factor for injury (Dvorak et al 2000, Brink 2010, Frisch et al 2011). Fatigue may occur as a result of inadequate training that is manifested in match play or as a consequence of overtraining which may affect a player in either training or match play. The term fatigue is used in order to encompass all forms of fatigue. It was also identified that within the existing literature, there appears to be no relationship between physical markers of performance or injury subjective reports of footballers. The omission of variables related to fatigue from our model could account for the poor performance of the model. Predictors such as Yo-Yo test score, which does not provide a measure of fatigue are therefore limited in their ability to predict injury. The selected inputs of our model may therefore not be adequate for capturing the relevant information and complexity of these interactions associated with injury risk.

It has been identified that there is a lack of suitable predictors available which can be used to inform existing modelling processes for injury prediction. In addition to the selected inputs, other explanations for the model’s performance have been identified. Within the results section performance of the model in the training set achieved a perfect fit with an R value of one, indicating the BRANN was able to match the learning systems outputs to the observed system. However, for the test set, the model was not able to match the learning systems outputs to the observed system as accurately, achieving an R value of 0.23015. It was recognised that there is a large number of points, established as column above the point 0 on the target axis, indicating there were cases for which the model predicted injury but no injury was observed. The possibility of the model correctly predicting injury despite injury not being reported has already been discussed. The poor performance of the model is likely to stem from an insufficient amount of injury cases in the test set for the model (sample size). Whilst a larger sample size may improve the performance of the model statistically, it calls into question its clinical applicability given that sample size within this study is representative of a typical football squad. It is recognised that other football institutions may have access to several teams with the ability to follow them up for longer periods of time, allowing for a higher number of injury cases. However this will not be the case for the majority of football teams.

When developing the research question in the primary phases of the PhD, the aim was to validate existing models for injury and their clinically application. In order to do this, it was necessary to develop a database, comprised of variables that reflected the literature. This was done. Once the database that reflected the published literature had been completed, it was necessary to continue populating the database and investigate whether the database on which the model will be developed was representative of a typical football team. Following these processes, a model based on currently advocated methods was selected for validation on the database available to the researcher. As a result of this process we have been unable to validate existing models for prospectively identifying injury. Factors that negatively impact the performance of modelling methods are an insufficient sample size not representative of the population, inappropriate model selection and inadequate predictor variables. Within this study, the database used has been identified as suitable given that it is representative of a typical football team. Justification for the selected modelling method has also been provided, having been identified as appropriate for addressing the research question. From the aforementioned factors that are known to negatively affect the performance of the model, it has been identified that the predictor variables are likely to have a significant effect on model performance. Currently the existing framework used to inform injury recording and reporting methods omits factors that are relevant to injury causation. Additionally, whilst studies advocate the identified risk factors for prospective injury modelling, it has been recognised that these variables are identified as retrospectively being associated with injury. Omission of other variables for injury causation through use of the existing framework and use of variables that have only been retrospectively associated with injury are therefore likely to negatively affect the performance of the model.

8.5 Conclusion and further work for modelling injury prediction in football

On evaluation of the results, it has been identified that we are unable to predict injuries based on the selected injury predictors (independent variables) and modelling methods (BRANN). It is acknowledged that interpretation of these results must be conducted alongside knowledge of the models limited ability to accurately predict injury in football, and the implications of these errors in any clinical application. It was identified that the existing framework which informs the selection of injury predictors is not adequate and this negates the performance of the model. For the selected inputs within our model, further work may look to evaluate the strength of the relationship between the selected inputs and the output of injury, in order to identify which factors had a greater impact on injury occurrence. Omission of other factors related to injury occurrence may have also contributed to the models performance. Further work may look to identify other variables (within the constraints of the individual, the environment and the task) with better prediction ability, through amendments to the existing injury recording and reporting framework. Included within this is the acute to chronic work load ratio, informed and quantified by GPS units as opposed to total time, in order to investigate if this improves the performance of the model.

Several cases were identified in which the model predicted an injury when no injury was observed. It has been highlighted this may stem from the existing framework inability to accurately classify cases of injury, underreporting of injury episodes by players and lack of objective measures for recording injury. Future work may look to identify alternate methods, either subjective or objective, which improve identification of injury status, thus addressing the issues that have affected the performance of the model. Additionally there were a limited number of injury cases within our test data set. Other football institutions may have access to several teams with the ability to follow them up for longer periods of time, allowing for a higher number of injury cases. Future work may look to improve the performance of the model through the availability of more injury cases. However, it has been stated that the sample size within our study was reflective of a typical football squad and therefore, whilst it is recognised that a larger sample size may improve the performance of the model; the development of a model to predict injury should be clinically applicable. Future work may look to identify alternate methods and appropriate predictors for developing a clinically applicable model that can be used for injury prediction in football.

9 SUMMATIVE CONCLUSION AND FUTURE WORK

The purpose of this concluding chapter is to bring together the discussions from individual chapters, in order to draw meaningful conclusions. At the start of this PhD, we set out to address the research question, *Can we predict injuries based on existing risk factors advocated for prospective injury modelling?* On evaluation of the existing literature, it was recognised that despite a consensus for injury reporting, the existing framework allowed for multiple variations in which injury subcategories can be clustered. Thus, interpretation of results and comparison between studies was difficult when attempting to identify risk factors for prospective injury modelling. Additionally, whilst several studies advocated variables for prospective injury modelling, these were based on retrospective studies with small clinical differences between injured and uninjured groups. Existing models neglect the multifactorial and complex nature of injury occurrence, failing to incorporate all relevant factors which may precede or occur at the time of injury. Further work may therefore look to evaluate the existing framework in order to ensure mechanisms relevant to injury are recorded, alongside standardisation of the way in which injury subgroups can be clustered.

Within the literature review, the FMS was identified as a significant component of the injury prediction process, despite lacking validation. Before progressing to the modelling stages, the validity of the FMS was evaluated. This was done against the Vicon motion capture system (©Vicon Motion Systems Ltd). It was identified that measurement of physical performance is not possible with the FMS in its current state. The FMS's conceptual framework and construct of the scale disqualify it from being a measure. Therefore, future work should look to address the failings through clarification on the intended purpose of the test and constructs it is concerned with measuring. The level of measurement the scale can achieve should also be implicitly stated given that it can affect the interpretation of observed results. Several contributing sources to score allocation error were identified namely, unrealistic and undefined anatomical or biomechanical thresholds, non-operationalised assessment processes, multiple variables required for assessment and an inadequate number of attempts to ensure accurate observations. For the FMS to be considered valid for use in clinical practice or injury modelling, future work should look to determine clearly stipulated thresholds and biomechanically realistic requirements. This should be done alongside operationalisation of the methods used for carrying out the assessment process. The assessor should additionally be provided with an adequate number of attempts to ensure accurate observations or, future work could look to reduce the number of variables the assessor is required to consider. This can be achieved through removal of redundant variables.

The failure of the FMS to perform as a measure excluded it from prospective injury modelling. Before development of the model, methods for injury recording and reporting were investigated within the existing database. This was conducted alongside injury trends to ensure the database was suitable. It was established that the database was appropriate. A Bayesian Regularised Artificial Neural Network (BRANN) was selected for use on the existing database. Selection of model inputs was based on variables advocated for use within the literature and by professional governing bodies of football. It was recognised that the selected model's ability to predict injury was limited. As identified, the existing framework which informs the selection of injury predictors and classification of injury cases is not adequate. As a result, this negated the performance of the model. Future work may look to identify other variables (within the constraints of the individual, the environment and the task) with better prediction ability, through amendments to the existing injury recording and reporting framework.

Whilst a limited number of injury cases were available within our test data set, it has been recognised that the sample size within our study was reflective of a typical football squad. Whilst a larger sample size may improve the performance of the model; it would bring into question the clinical applicability of the model. Future work may look to identify alternate methods and appropriate predictors for developing a clinically applicable model that can be used for injury prediction in football. Currently no universally accepted and implemented injury screening process or prospective injury models exists within football. There is therefore no agreement on which injury risk factors need to be considered for injury prediction, a necessary step in injury prevention. This affects the number and combinations of interactions that may occur, reinforcing the incomplete picture around injury mechanisms. Further work should look to standardise pre-season and inseason measures for development of clinically applicable prospective injury models.

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APPENDICES CONTENT LIST

APPENDIX I - Letter of ethical approval Keele University Ethical Review Panel

Keele University

Ref: ERP1237

25th June 2015

Fraser Philp
Institute of Science and Technology in Medicine (ISTM)
School of Health and Rehabilitation
Mackay Building
Keele University
Keele
ST5 5AZ

Dear Fraser

Re: Predicting injury in football - Risk factors for injury in football as evaluated by the Functional Movement Screen (FMS)

Thank you for submitting your revised application for review.

I am pleased to inform you that your application has been approved by the Ethics Review Panel. The following documents have been reviewed and approved by the panel as follows:

Document(s)	Version Number	Date
Summary Document	2	24/06/2015
Information Sheet	2	24/06/2015
Consent Form	2	24/06/2015
Anthropomorphic measurements & recording sheet	1	13/05/2015
Marker placement for data capture	1	13/05/2015
Functional Movement Screen (FMS) protocol	1	13/05/2015
Keele University Men's Football Club Injury Reporting Standard Operating Procedure		13/05/2015

If the fieldwork goes beyond the date stated in your application (1st August 2016), you must notify the Ethical Review Panel via the ERP administrator at uso.erps@keele.ac.uk stating ERP1 in the subject line of the e-mail.

If there are any other amendments to your study you must submit an 'application to amend study' form to the ERP administrator stating ERP1 in the subject line of the e-mail. This form is available via http://www.keele.ac.uk/researchsupport/researchethics/.

If you have any queries, please do not hesitate to contact me via the ERP administrator on uso.erps@keele.ac.uk stating ERP1 in the subject line of the e-mail.

Yours sincerely

pp C H Bonneman

Dr Andrew Rutherford
Vice Chair – Ethical Review Panel

CC RI Manager
Supervisor

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APPENDIX II - Letter of ethical approval National Research Ethics Service

Health Research Authority

NRES Committee West Midlands - Solihull
East Midlands REC Centre
The Old Chapel
Royal Standard Place
Nottingham
NG1 6FS

Telephone: 0115 8839437

12 April 2013

Dr Caroline Stewart
Senior Bioengineer/ORLAU Manager
RJAH Orthopaedic Hospital
RJAH Orthopaedic Hospital
Oswestry
SY10 7AG

Dear Dr Stewart

Study title:	**Collection of normal reference data for understanding human movement**
REC reference:	**13/WM/0045**
Protocol number:	**N/A**
IRAS project ID:	**116011**

Thank you for your letter of 25 March 2013, responding to the Committee's request for further information on the above research and submitting revised documentation.

The further information was considered at the meeting of the Committee held on 12 April 2013. A list of the members who were present at the meeting is attached.

We plan to publish your research summary wording for the above study on the NRES website, together with your contact details, unless you expressly withhold permission to do so. Publication will be no earlier than three months from the date of this favourable opinion letter. Should you wish to provide a substitute contact point, require further information, or wish to withhold permission to publish, please contact the Co-ordinator Maria Morledge, NRESCommittee.EastMidlands.Leicester@nhs.net.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation subject to the conditions specified below.

Ethical review of research sites

NHS sites

The favourable opinion applies to all NHS sites taking part in the study, subject to management permission being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

Non-NHS sites

Conditions of the favourable opinion

The favourable opinion is subject to the following conditions being met prior to the start of the study.

<u>Management permission or approval must be obtained from each host organisation prior to the start of the study at the site concerned.</u>

Management permission ("R&D approval") should be sought from all NHS organisations involved in the study in accordance with NHS research governance arrangements.

Guidance on applying for NHS permission for research is available in the Integrated Research Application System or at http://www.rdforum.nhs.uk.

Where a NHS organisation's role in the study is limited to identifying and referring potential participants to research sites ("participant identification centre"), guidance should be sought from the R&D office on the information it requires to give permission for this activity.

For non-NHS sites, site management permission should be obtained in accordance with the procedures of the relevant host organisation.

Sponsors are not required to notify the Committee of approvals from host organisations

It is the responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*
Advertisement	1.1	01 January 2013
Covering Letter		16 January 2013
Covering Letter		25 March 2013
Investigator CV	Caroline Stewart	17 January 2013
Letter from Sponsor		01 January 2013
Letter of invitation to participant	1.2	01 January 2013
Other: RJAH NHS Trust Project Proposal Form		06 December 2012

Other: Recruitment Email	1.2	01 January 2013
Participant Consent Form: Adult	1.2	01 January 2013
Participant Consent Form: Parent/Guardian	1.2	01 January 2013
Participant Consent Form: Assent Form for Younger Children	1.1	25 March 2013
Participant Consent Form: Assent Form for Older Children	1.1	25 March 2013
Participant Information Sheet: Younger Childs Information Sheet	1.1	25 March 2013
Participant Information Sheet: Adults Information Sheet	1.2	25 March 2013
Participant Information Sheet: Parents/Guardians Information Sheet	1.2	25 March 2013
Participant Information Sheet: Child Information Sheet	1.2	25 March 2013
Protocol	1.1	13 January 2013
Questionnaire: ORLAU Normal Data Questionnaire	1.1	01 January 2013
REC application	116011/403487/1/309	16 January 2013
Response to Request for Further Information		25 March 2013

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

After ethical review

Reporting requirements

The attached document *"After ethical review – guidance for researchers"* gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Notification of serious breaches of the protocol
- Progress and safety reports
- Notifying the end of the study

The NRES website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

Feedback

You are invited to give your view of the service that you have received from the National Research Ethics Service and the application procedure. If you wish to make your views known please use the feedback form available on the website.

Further information is available at National Research Ethics Service website > After Review

13/WM/0045	**Please quote this number on all correspondence**

We are pleased to welcome researchers and R & D staff at our NRES committee members' training days – see details at http://www.hra.nhs.uk/hra-training/

With the Committee's best wishes for the success of this project.

Yours sincerely

pp

Dr Rex J Polson
Chair

Email:NRESCommittee.WestMidlands.Solihull@nhs.net

Enclosures:	*List of names and professions of members who were present at the meeting*
	"After ethical review – guidance for researchers" *[SL-AR2]*
Copy to:	*Mrs Teresa Jones* *Mrs Teresa Jones, RJAH Orthopaedic Hospital*

APPENDIX III - AMED database search strategy

Table A3.1 AMED database search strategy

		Risk		Predict		Recurrence		Prevent		Model		Functional Movement Screen		Performance		Injury		Sport
	S1	Risk (DE)	S7	Forecasting (DE)	S13	Recurrence (DE)	S16	Prevention (DE)	S20	Models (DE)	S26	"FMS" (keyword)	S29	perform* (keyword)	S30	Injuries (DE)	S59	Football (DE)
	S2	Risk factors (DE)	S8	Predictive value of tests (DE)	S14	recurr*	S17	prevent*	S21	Assessment (DE)	S27	"functional movement screen" (keyword)			S31	Injuries, connective tissue (DE)	S60	Soccer (DE)
	S3	risk* (keyword)	S9	forecast* (keyword)			S18	reduc*	S22	model* (keyword)					S32	Rupture (DE)	S61	football* (keyword)
	S4	prone* (keyword)	S10	predict* (keyword)					S23	screen* (keyword)					S33	Tendinitis (DE)	S62	soccer* (keyword)
	S5	predispos* (keyword)	S11	factor* (keyword)					S24	assess* (keyword)					S34	Tendinopathy (DE)		
															S35	Tendon injuries (DE)		
															S36	Sprains and Strains (DE)		
															S37	Sprains (DE)		
OR															S38	Pain (DE)		
															S39	Stress (DE)		
															S40	Stress Mechanical (DE)		
															S41	Fractures (DE)		
															S42	Fractures bone (DE)		
															S43	Fractures pain (DE)		
															S44	Injur* (keyword)		
															S45	ruptur* (keyword)		
															S46	avuls* (keyword)		
															S47	tendinitis (keyword)		
															S48	tendonitis (keyword)		
															S49	tendonosis (keyword)		
															S50	tear* (keyword)		
															S51	strain* (keyword)		
															S52	sprain* (keyword)		
															S53	pain* (keyword)		
															S54	overuse* (keyword)		
															S55	stress* (keyword)		
															S56	fractur* (keyword)		
															S57	overtrain* (keyword)		
	S6	S1 OR S2 OR S3 OR S4 OR S5	S12	S7 OR S8 OR S9 OR S10 OR S11	S15	S13 OR S14	S19	S16 OR S17 OR S18	S25	S20 OR S21 OR S22 OR S23 OR S24	S28	S26 OR S27			S58	S30 OR S31 OR S32 OR S33 OR S34 OR S35 OR S36 OR S37 OR S38 OR S39 OR S 40 OR S41 OR S42 OR S43 OR S44 OR S45 OR S46 OR S47 OR S48 OR S49 OR S50 OR S51 OR S52 OR S53 OR S54 OR S55	S63	S57 OR S58 OR S59 OR S60

		COMBINATIONS
	S64	S6 AND S58 AND S63
	S65	S12 AND S58 AND S63
AND	S66	S15 AND S58 AND S63
	S67	S19 AND S58 AND S63
	S68	S25 AND S58 AND S63
	S69	S28 AND S58 AND S63
	S70	S29 AND S58 AND S63

APPENDIX IV - CINHALPlus database search strategy

Table A4.1 CINHALPlus database search strategy

		Risk		Predict		Recurrence		Prevent		Model		Functional Movement Screen		Performance		Injury		Sport
	S1	Risk Assesment (MH)	**S7**	Forecasting (MH)	**S15**	Recurrence (MH)	**S18**	prevent*	**S21**	model* (keyword)	**S25**	"FMS" (keyword)	**S28**	Physical performace (MH)	**S31**	Wounds and Injuries (MH)	**S49**	Football (MH)
	S2	Risk Factors (MH)	**S8**	Forecasting (research) (MH)	**S16**	recurr* (keyword)	**S19**	reduc*	**S22**	screen* (keyword)	**S26**	"functional movement screen" (keyword)	**S29**	perform*	**S32**	Pain (MH)	**S50**	Soccer (MH)
	S3	risk* (keyword)	**S9**	Predictive Research (MH)					**S23**	assess* (keyword)					**S33**	Cumulative trauma disorder (MH)	**S51**	football (keyword)
	S4	prone* (keyword)	**S10**	Predictive value of tests (MH)											**S34**	Injur* (keyword)	**S52**	Soccer (keyword)
	S5	predispos* (keyword)	**S11**	forecast*(keyword)											**S35**	ruptur* (keyword)		
			S12	predict* (keyword)											**S36**	avuls* (keyword)		
OR			**S13**	factor* (keyword)											**S37**	tendinitis (keyword)		
															S38	tendonitis (keyword)		
															S39	tendonosis (keyword)		
															S40	tear* (keyword)		
															S41	strain* (keyword)		
															S42	sprain* (keyword)		
															S43	pain* (keyword)		
															S44	overuse* (keyword)		
															S45	stress* (keyword)		
															S46	fractur* (keyword)		
															S47	overtrain* (keyword)		
	S6	S1 OR S2 OR S3 OR S4 OR S5	**S14**	S7 OR S8 OR S9 OR S10 OR S11 OR S12 OR S13	**S17**	S15 OR S16	**S20**	S18 OR S19	**S24**	S21 OR S22 OR S23	**S27**	S25 OR S26	**S30**	S28 OR S29	**S48**	S31 OR S32 OR S33 OR S34 OR S35 OR S36 OR S37 OR S38 OR S39 OR S40 OR S41 OR S42 OR S43 OR S44 OR S45 OR S46 OR S47	**S53**	S49 OR S50 OR S51 OR S52

		COMBINATIONS
	S53	S6 AND S48 AND S53
	S54	S14 AND S48 AND S54
AND	**S55**	S17 AND S48 AND S55
	S56	S20 AND S48 AND S56
	S57	S24 AND S48 AND S57
	S58	S27 AND S48 AND S58
	S59	S30 AND S48 AND S59

APPENDIX V - MEDLINE database search strategy

Table A5.1 MEDLINE database search strategy

		Risk		Predict		Recurrence		Prevent		Model		Functional Movement Screen		Performance		Injury		Sport
	S1	Risk (MH)	**S8**	Forecasting (MH)	**S14**	Recurrence (MH)	**S17**	prevent*	**S20**	model* (keyword)	**S24**	"FMS" (keyword)	**S27**	Athletic Performance (MH)	**S30**	Wounds and Injuries (MH)	**S53**	Soccer (MH)
	S2	Risk Assessment (MH)	**S9**	Predictive Value of tests (MH)	**S15**	recurr* (keyword)	**S18**	reduc*	**S21**	screen* (keyword)	**S25**	"functional movement screen" (keyword)	**S28**	perform* (keyword)	**S31**	Sprains and Strain (MH)	**S54**	Football (MH)
	S3	Risk Factors (MH)	**S10**	forecast* (keyword)					**S22**	assess* (keyword)					**S32**	Tendon Injuries (MH)	**S55**	soccer (keyword)
	S4	Risk (keyword)	**S11**	predict* (keyword)											**S33**	Tendinopathy (MH)	**S56**	football (keyword)
	S5	Predispos* (keyword)	**S12**	factor* (keyword)											**S34**	Fractures Stress (MH)		
	S6	prone* (keyword)													**S35**	Ankle Fractures (MH)		
															S36	Pain (MH)		
															S37	Rupture (MH)		
OR															**S38**	Injur* (keyword)		
															S39	ruptur* (keyword)		
															S40	avuls* (keyword)		
															S41	tendinitis (keyword)		
															S42	tendonitis (keyword)		
															S43	tendonosis (keyword)		
															S44	tear* (keyword)		
															S45	strain* (keyword)		
															S46	sprain* (keyword)		
															S47	pain* (keyword)		
															S48	overuse* (keyword)		
															S49	stress* (keyword)		
															S50	fractur* (keyword)		
															S51	overtrain* (keyword)		
	S7	S1 OR S2 OR S3 OR S4 OR S5 OR S6	**S13**	S8 OR S9 OR S10 OR S11 OR S12	**S16**	S14 OR S15	**S19**	S17 OR S18	**S23**	S20 OR S21 OR S22	**S26**	S24 OR S25	**S29**	S27 OR S28	**S52**	S30 S31 OR S32 OR S33 OR S34 OR S35 OR S36 OR S37 OR S38 OR S39 OR S40 OR S41 OR S 42 OR S43 OR S44 OR S 45 OR S 46 OR S47 OR S 48 OR S 49 OR S 50 OR S51	**S57**	S53 OR S54 OR S55 OR S 56

		COMBINATIONS
	S58	S7 AND S52 AND S57
	S59	S13 AND S52 AND S57
AND	**S60**	S16 AND S 52 AND S57
	S61	S19 AND S52 AND S57
	S62	S23 AND S52 AND S57
	S63	S29 AND S52 AND S57
	S64	S26 AND S52 AND S57

APPENDIX VI - PsycINFO database search strategy

Table A6.1 PsycINFO database search strategy

		Risk		Predict		Recurrence		Prevent		Model		Functional Movement Screen		Performance		Injury		Sport
	S1	Risk Factors (DE)	S8	Predictability (Measurement) (DE)	S14	recurr* (keyword)	S15	Prevention (DE)	S19	Modles (DE)	S26	"FMS" (keyword)	S29	Performance (DE)	S32	injuries (DE)	S52	football (DE)
	S2	Risk Assessment (DE)	S9	Prediction (DE)			S16	prevent* (keyword)	S20	Screening (DE)	S27	"functional movement screen" (keyword)	S30	perform*	S33	tendons (DE)	S53	Soccer (DE)
	S3	Predisposition (DE)	S10	forecast*(keyword)			S17	reduc* (keyword)	S21	Screening Tests (DE)					S34	pain (DE)	S54	football* (keyword)
	S4	risk* (keyword)	S11	predict* (keyword)					S22	model* (keyword)					S35	stress (DE)	S55	soccer* (keyword)
	S5	prone* (keyword)	S12	factor* (keyword)					S23	screen* (keyword)					S36	Stress reations (DE)		
OR	S6	predispos* (keyword)							S24	assess*(keyword)					S37	Injur* (keyword)		
															S38	ruptur* (keyword)		
															S39	avuls* (keyword)		
															S40	tendinitis (keyword)		
															S41	tendonitis (keyword)		
															S42	tendonosis (keyword)		
															S43	tear* (keyword)		
															S44	strain* (keyword)		
															S45	sprain* (keyword)		
															S46	pain* (keyword)		
															S47	overuse* (keyword)		
															S48	stress* (keyword)		
															S49	fractur* (keyword)		
															S50	overtrain* (keyword)		
	S7	S1 OR S2 OR S3 OR S4 OR S5 OR S6	S13	S8 OR S9 OR S10 OR S11 OR S12			S18	S15 OR S16 OR S17	S25	S19 OR S20 OR S21 OR S22 OR S23 OR S24	S28	S26 OR S27	S31	S29 OR S30	S51	S32 OR S33 OR S34 OR S35 OR S36 OR S37 OR S38 OR S39 OR S 40 OR S41 OR S42 OR S43 OR S44 OR S45 OR S46 OR S47 OR S48 OR S49 OR S50	S56	S52 OR S53 OR S54 OR S55

		COMBINATIONS
	S57	S7 AND S51 AND S56
	S58	S13 AND S51 AND S56
AND	**S59**	S14 AND S51 AND S56
	S60	S18 AND S51 AND S56
	S61	S25 AND S51 AND S56
	S62	S28 AND S51 AND S56
	S63	S28 AND S51 AND S56
	S64	S31 AND S51 AND S56

APPENDIX VII - SPORTDiscus database search strategy

Table A7.1 SPORTDiscus database search strategy

		Risk		Predict		Recurrence		Prevent		Model		Functional Movement Screen		Performance		Injury		Sport
	S1	risk* (keyword)	S5	Forecasting (DE)	S10	recurr* (keyword)	S11	Prevention (DE)	S15	model* (keyword)	S19	"FMS" (keyword)	S22	Performance (DE)	S25	WOUNDS & injuries (DE)	S52	Football (DE)
	S2	prone* (keyword)	S6	forecast*(keyword)			S12	prevent* (keyword)	S16	screen* (keyword)	S20	"functional movement screen"	S23	perform*	S26	RUPTURE of organs, tissues, etc. (DE)	S53	Soccer (DE)
	S3	predispos* (keyword)	S7	predict* (keyword)			S13	reduc* (keyword)	S17	assess*(keyword)		(keyword)			S27	Tendinitis (DE)	S54	football* (keyword)
			S8	factor* (keyword)											S28	Tendinosis (DE)	S55	soccer* (keyword)
															S29	Tendons (DE)		
															S30	Strain (physiology) (DE)		
															S31	Sprains (DE)		
															S32	Pain (DE)		
OR															S33	OVERUSE injuries (DE)		
															S34	Stress (Physiology) (DE)		
															S35	Fractures (DE)		
															S36	Overtraining (DE)		
															S37	Injur* (keyword)		
															S38	ruptur* (keyword)		
															S39	avuls* (keyword)		
															S40	tendinitis (keyword)		
															S41	tendonitis (keyword)		
															S42	tendonosis (keyword)		
															S43	tear* (keyword)		
															S44	strain* (keyword)		
															S45	sprain* (keyword)		
															S46	pain* (keyword)		
															S47	overuse* (keyword)		
															S48	stress* (keyword)		
															S49	fractur* (keyword)		
															S50	overtrain* (keyword)		
	S4	S1 OR S2 OR S3	S9	S5 OR S6 OR S7 OR S8			S14	S11 OR S12 OR S13	S18	S15 OR S16 OR S17	S21	S19 OR S20	S24	S22 OR S23	S51	S25 OR S26 OR S27 OR S28 OR S29 OR S30 OR S31 OR S32 OR S33 OR S34 OR S35 OR S36 OR S37 OR S38 OR S39 OR S 40 OR S41 OR S42 OR S43 OR S44 OR S45 OR S46 OR S47 OR S48 OR S49 OR S50	S56	S52 OR S53 OR S54 OR S55

		COMBINATIONS
	S57	S4 AND S51 AND S56
	S58	S9 AND S51 AND S56
AND	S59	S10 AND S51 AND S56
	S60	S14 AND S51 AND S56
	S61	S18 AND S51 AND S56
	S62	S21 AND S51 AND S56
	S63	S24 AND S51 AND S56

APPENDIX VIII - Plug-in Gait Model details

Plug-in Gait Model details

Information on the Plug-in Gait model is derived from the Plug-in Gait handbook (©Vicon Motion Systems Ltd).

Static capture

Following completion of the marker placement, a static trial capture was taken and the Plug-in Gait model was applied. The static capture allows for the thigh, shank and feet marker rotation offsets relative to the knee to be calculated. The values derived from the static capture serve as a reference for correcting rotation offsets observed in the dynamic trials.

Plug-in Gait consists of three components, all individual pipeline processes.

1. A quintic spline filter based on code written by Herman Woltring (1986). This filter is intended to be applied to the real marker trajectory data before the modelling stage. No further explicit filtering of the data occurs during the modelling stage.
2. A process, which automatically detects and auto correlates events. For this study event markers were placed manually, corresponding to initial contact and foot off (labelled as heel strike and toe off in the Plug-in Gait model) for the walking trials. Event markers were placed to indicate the start and stop of an attempt within the FMS test. This was achieved in both instances by the assessor visually identifying the events in the processing stage.
3. The modelling stage, in which kinematic and kinetic quantities (angles, moments etc.) are calculated. For this study only the kinematic outputs were available.

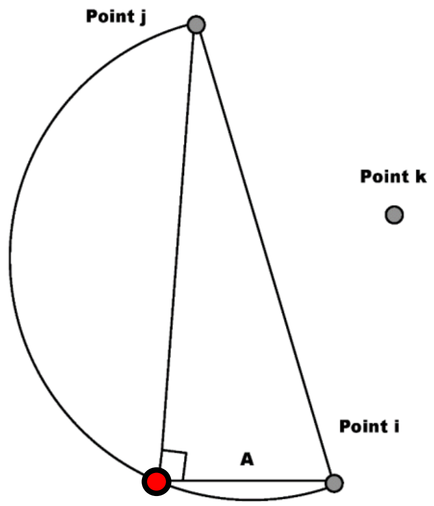
Multiple models

The modelling stage internally consists of four interdependent models. A kinematic lower body, a kinematic upper body, and kinetic lower and upper bodies. The kinematic models are responsible for the definitions of the rigid body segments, and the calculations of joint angles between these segments.

The "Chord" function

This function is used extensively in these models for defining joint centres (figure A8.1). Point at distance A from I in plane IJK such that IA is at 90 degrees to JA forming a right angle between I and J on the opposite side of IJ from K.

Figure A8.1 The Chord Function



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Fixed Values

A shoulder offset value is calculated from the Subject measurement value entered, plus half the marker diameter. Elbow, Wrist and Hand offset values are also calculated from the sum of the respective thickness with the marker diameter divided by two. A progression frame is independently calculated in just the same way as for the lower body. C7 is tested first to determine if the subject moved a distance greater than the threshold. If not, the other thorax markers T10 CLAV and STRN are used to determine the general direction the thorax was facing in from a mean of 10% of the frames in the middle of the trial.

Upper Body Kinematics

Head

The head origin is defined as the midpoint between the LFHD and RFHD markers (also denoted 'Front').The midpoint between the LBHD and RBHD markers ('Back') is also calculated, along with the 'Left' and 'Right' sides of the head from the LFHD and LBHD midpoint, and the RFHD and RBHD midpoint respectively. The predominant head axis, the X-axis, is defined as the forward facing direction (Front - Back). The secondary

Y-axis is the lateral axis from Right to Left (which is orthoganalized as usual). For the static processing, the YXZ Euler angles representing the rotation from the head segment to the lab axes are calculated. The Y rotation is taken as the head Offset angle, and the mean of this taken across the trial. For the dynamic trial processing, the head Offset angle is applied around the Y-axis of the defined head segment.

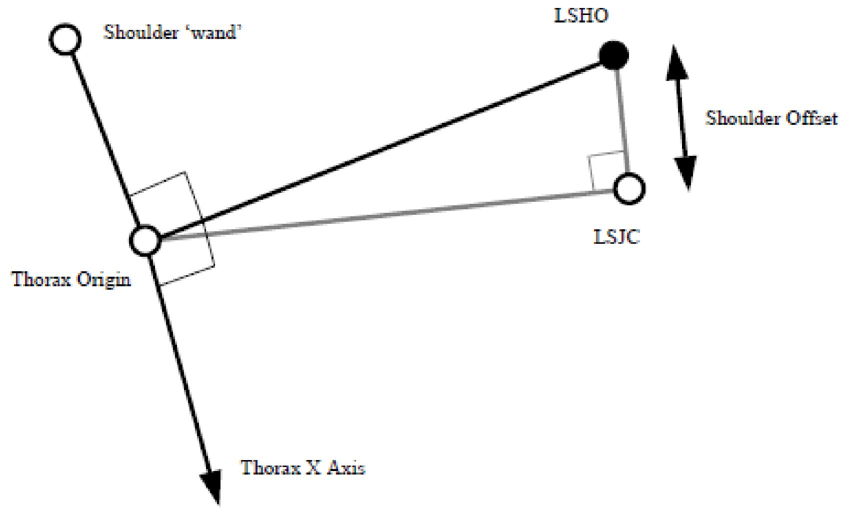
Thorax

The orientation of the thorax is defined before the origin. The Z-axis, pointing upwards, is the predominant axis. This is defined as the direction from the midpoint of the STRN and T10 to the midpoint of CLAV and C7. A secondary direction pointing forwards is the midpoint of C7 and T10 to the midpoint of CLAV and STRN. The resulting X axis points forwards, and the Y-axis points leftwards. The thorax origin is then calculated from the CLAV marker, with an offset of half a marker diameter backwards along the X-axis.

Shoulder Joint Centre

The clavicles are considered to lie between the thorax origin, and the shoulder joint centres. The shoulder joint centres are defined as the origins for each clavicle. The posterior part of the shoulder complex is considered too flexible to be modelled with this marker set. Initially a direction is defined, which is perpendicular to the line from the thorax origin to the SHO marker, and the thorax X-axis. This is used to define a virtual shoulder 'wand' marker. The chord function is then used to define the shoulder joint centre (SJC) from the shoulder offset, thorax Origin, SHO marker and shoulder 'wand'.

Figure A8.2 Shoulder joint centre



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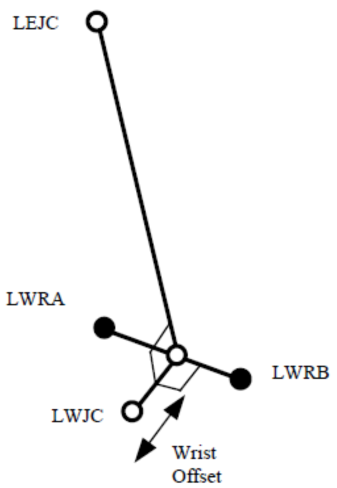
Clavicle

The clavicle segment is defined from the direction from the joint centre to the thorax origin as the Z-axis, and the shoulder wand direction as the secondary axis. The X-axis for each clavicle points generally forwards, the Y-axis for the left points upwards and the right clavicle Y-axis points downwards.

Wrist Joint Centre

The wrist joint centre (WJC) is then calculated. In this case the chord function is not used. The wrist joint centre is simply offset from the midpoint of the wrist bar markers along a line perpendicular to the line along the wrist bar, and the line joining the wrist bar midpoint to the elbow joint centre

Figure A8.3 Wrist joint centre



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Humerus

The humerus was defined using the shoulder joint centre (HUP) (previously identified in the Plug-in Gait model) to the lateral elbow marker (ELB).

Radius

The radius was defined from the wrist joint centre (WJC) to the elbow marker (ELB).

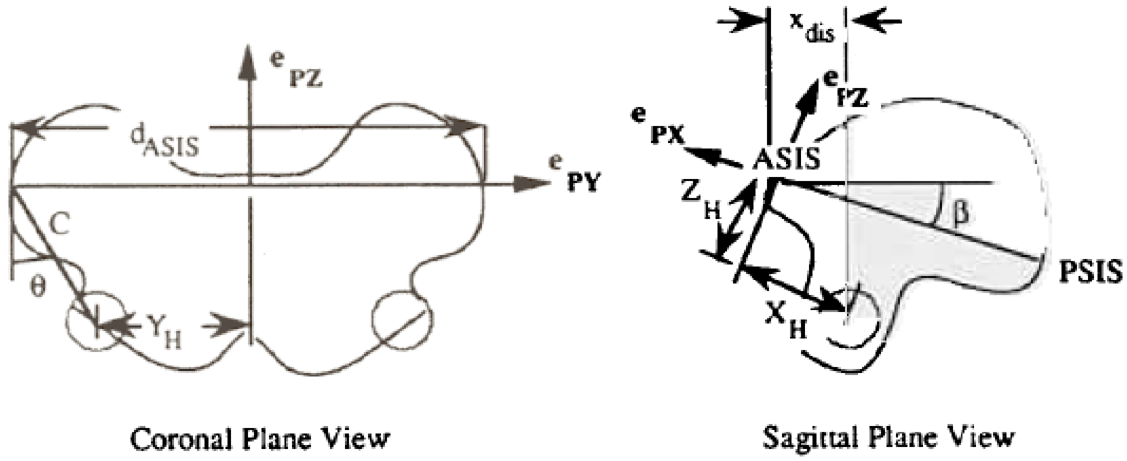
Hand

The hand is defined by first defining its origin. The chord function is used again for this, with the WJC, FIN marker and Hand Offset. The midpoint of the wrist bar markers is used to define the plane of calculation. The principal Z-axis is then taken as the line from the hand origin to the WJC, and a secondary line approximating the Y-axis is defined by direction of the line joining the wrist bar markers.

Lower Body Kinematics

The Newington - Gage model (Davis et al 1991) is used to define the positions of the hip joint centres in the pelvis segment.

Figure A8.4 Hip joint centre



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The coordinates for...

X = C*cos(θ)*sin(β) - (AsisTrocDist + mr) * cos(β)
Y = -(C*sin(θ) - aa)
Z = -C*cos(θ)*cos(β) - (AsisTrocDist + mr) * sin(β)

Where
C = MeanLegLength*0.115 - 15.3
θ is taken as 0.5 radians
β is taken as 0.314 radians
AsisTrocDist = 0.1288 * LegLength - 48.56
aa = half the InterAsis distance
mr= marker radius

This is done independently for each leg.

These are used to then calculate the offset vectors for the two hip joint centres (LHJC and RHJC) as follows:

For the right joint centre, the Y offset is negated (since Y is in the lateral direction for the pelvis embedded coordinate system).

The position of the top of the lumbar vertebra 5 (the reference point for Dempster data) is then estimated as

(LHJC + RHJC)/2 + (0.0, 0.0, 0.828) * Length(LHJC - RHJC)

where the value 0.828 is a ratio of the distance from the hip joint centre level to the top of the lumbar 5.

The general direction of the subject walking in the global coordinate system is then found, by looking at the first and last valid position of the LASI marker. The X displacement is compared to the Y displacement. If the X displacement is bigger, the subject is deemed to have been walking along the X-axis either positively or negatively, depending on the sign of the X offset. Otherwise, the Y-axis is chosen. These directions are used to define a coordinate system matrix (similar to a segment definition) denoted the Progression Frame. It is assumed that the Z-axis is always vertical, and that the subject is walking along one of these axes, and not diagonally, for example.

If the distance between the first and last frame of the LASI marker is less than a threshold of 800 mm however, the progression frame is calculated using the direction the pelvis is facing during the middle of the trial. This direction is calculated as a mean over 10% of the frames of the complete trial. Within these frames, only those which have data for all the pelvis markers are used. For each such frame, the rear pelvis position is calculated from either the SACR marker directly, or the centre point of the LPSI and RPSI markers. The front of the pelvis is calculated as the centre point between the LASI and RASI markers. The pelvis direction is calculated as the direction vector from the rear position to the front. This direction is then used in place of the LASI displacement, as described above, and compared to the laboratory X and Y-axes to choose the Progression Frame.

Pelvis

First the pelvis segment coordinate system is defined from the waist markers. The origin is taken as the midpoint of the two ASIS markers. The dominant axis, taken as the Y-axis, is the direction from the right ASIS marker to the left ASIS marker. The secondary direction is taken as the direction from the sacrum marker to the right ASIS marker. If there is no sacrum marker trajectory, the posterior markers are used. If both are visible, the mean is used. If just one is visible, then that one is used. The Z direction is generally upwards, perpendicular to this plane and the X-axis generally forwards.

The position and scale of the pelvis is thus determined by the two ASIS markers, since they determine the origin of the coronal orientation of the pelvis. The posterior sacral markers (or PSIS markers) determine only the anterior tilt of the pelvis. Their actual distance behind the ASIS markers and lateral position is immaterial, allowing a sacral wand marker to be used, for example.

The inter ASIS distance, required for the Plug-in Gait model, was manually entered for each participant into the VICON software

Knee Alignment Device

In this study a knee alignment device was not used. An additional medial knee marker was used to define the joint centre, from which a knee alignment device (KAD) was virtually created (see below).

Virtual reconstruction of the Knee alignment device

```
{*VICON BodyLanguage (tm) model*}
{*This Model repositions the KAD in the static trial*}

Gorigin = {0,0,0}
Global = [Gorigin,{1,0,0},{0,0,1},xyz]
mm = 7.5

{* Establish a KAD axis system using temp two markers KD1 (lateral) KD2 (medial) *}
RKAD = [RKD1,{0,0,1},(RKD1-RKD2),zyx]
LKAD = [LKD1,{0,0,1},(LKD2-LKD1),zyx]

{* Translate KAD axis system so origin is at centre point*}

RKAD = RKAD + 0*2(RKAD)
LKAD = LKAD - 0*2(LKAD)

{* Set up local coordinates for the KAD *}
%RKD1 = {0,-100,0}
%RKD2 = {0,0,-100}
%RKAX = {-100,0,0}

%LKD1 = {0,-100,0}
%LKD2 = {0,0,-100}
%LKAX = {100,0,0}

{* Create KAD *}
```

```
RKAX = %RKAX*RKAD
RKD1 = %RKD1*RKAD
RKD2 = %RKD2*RKAD

LKAX = %LKAX*LKAD
LKD1 = %LKD1*LKAD
LKD2 = %LKD2*LKAD

{*  Write out results *}
Output (RKAX,RKD1,RKD2,LKAX,LKD1,LKD2)
```

This was placed on the participants during the static trial to indicate the plane of the knee joint centre. The model calculates the relative angle of the thigh wand marker, and this angle is used in the dynamic trial to determine the joint centre without the KAD. This technique relies on the accurate placement of the markers for the KAD, rather than the accurate placement of the wand marker.

Knee joint centre

As a virtual KAD was used in the static model, firstly a virtual KNE marker is determined by finding the point that is equidistant from the three KAD markers, such that the directions from the point to the three markers are mutually perpendicular. There are two points that meet these criteria. The point which gives the line KAX -> KNE closest to parallel to the lateral direction of the pelvis is taken as being the correct solution. The joint centre KJC is then determined using the chord function with the HJC, KNE and KAX. The HJC-KJC and KJC-KNE lines will be perpendicular, and the KJC-KNE line has a length equal to the knee offset (KO). The thigh marker rotation offset is then calculated by projecting its position on to a plane perpendicular to the HJC-KJC line.

Figure A8.5 Knee alignment device

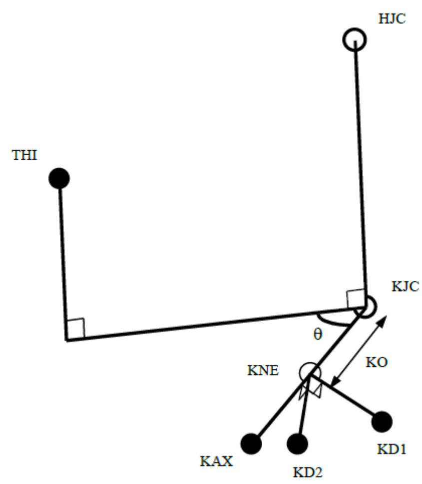

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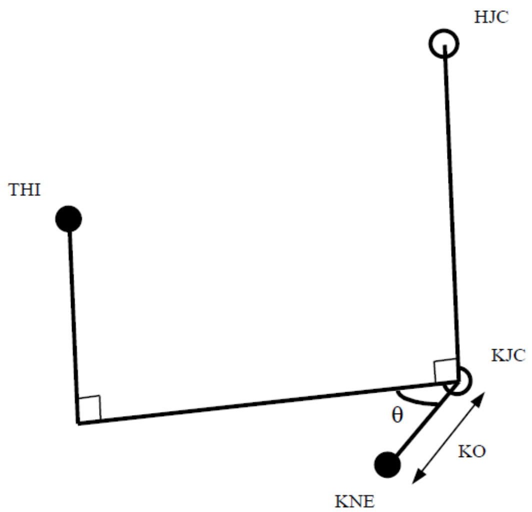
Figure A8.6 Knee joint centre



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Femur

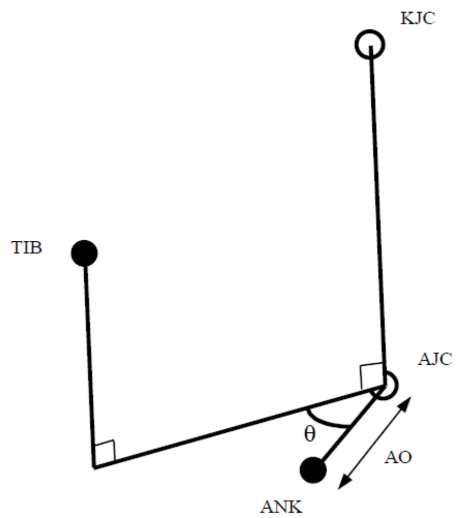
The femur origin is taken as the knee joint centre. The primary Z-axis is taken from the knee joint centre (KJC) to the hip joint centre (HJC). The secondary axis is taken parallel to the line from the knee joint centre to the knee marker. This directly gives the direction of the Y-axis. For both the left and the right femur, the Y-axis is directed towards the left of the subject. The X-axis for both femurs is hence directed forwards from the knee.

Ankle Joint Centre

The ankle joint centre is determined in a similar manner to the knee joint centre.

In the static trials with the KAD, the KAX marker was used to define the plane of the knee axis, and the plane of the ankle axis is assumed to be parallel to this. A value for tibial torsion can be entered, and the plane in which the Ankle joint centre lies will be rotated by this amount relative to the plane containing the KAX maker. Thus the AJC is found using the modified chord function, such that it has a distance equal to the ankle offset from the ANK marker (AO), and such that the ANK-AJC line forms an angle equal to the Tibial Torsion with the projection of the KAX-AJC line into the plane perpendicular to the KJC-AJC line. Note that a positive Tibial Torsion is thus considered as an internal rotation of the ankle axis relative to the knee axis.

Figure A8.7 Ankle joint centre



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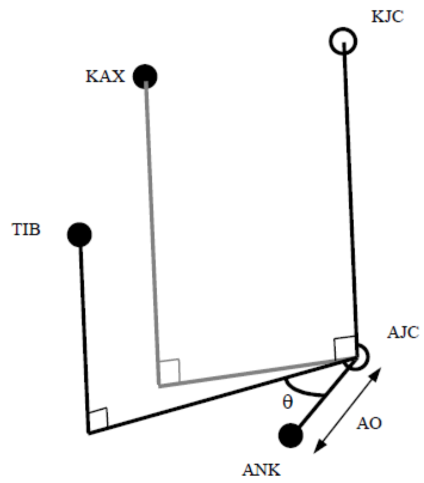
The shank marker rotation offset is then calculated by projecting its position onto the same plane. Note that this value takes into account the value of the tibial torsion, and in general, you would expect it to be slightly less than the value for Tibial Torsion, if the TIB wand marker is conventionally placed.

Figure A8.8 Shank marker rotation offset



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Tortioned Tibia

The tibial rotation offset as determined by the static trial already takes into account the tibial torsion. Thus a "Tortioned Tibia" is defined with an origin at the AJC, the Z Axis in the direction from the AJC to the KJC, the Y-axis leftwards along the line between the AJC and ANK marker, and the X-axis generally forwards. This is representative of the distal end of the tibia.

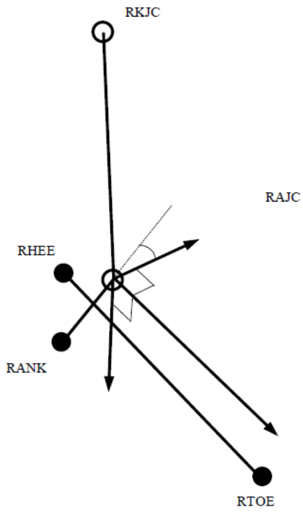
Untortioned Tibia

A second tibia is also generated representing the tibia before tibial torsion is applied, by rotating the X and Y-axes of the tortioned Tibia round the Z-axis by the negative of the tibial torsion (i.e. externally for positive values). This represents the proximal end, and is used to calculate the knee joint angles.

Foot

The heel marker is used in the static trial, and the model effectively makes two segments. For both segments, the AJC is used as the origin. The main foot segment is constructed using the TOE-HEE line as the primary axis. For this study the model had the foot flat box checked, thus the HEE is moved vertically (along the global Z axis) to be at the same height as TOE. This line is taken as the Z-axis, running forwards along the length of the foot. The direction of the Y-axis from the untortioned tibia is used to define the secondary Y-axis. The X-axis thus points down, and the Y-axis to the left.

Figure A8.9 Second foot segment construction



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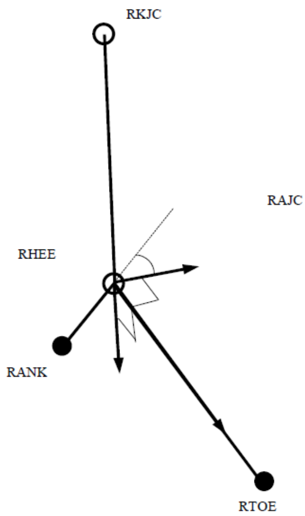
A second foot segment is constructed, using the TOE-AJC as the primary axis, and again the Y-axis of the untortioned tibia to define the perpendicular X-axis and the foot Y-axis (the 'uncorrected' foot).

Figure A8.10 Heel toe line created



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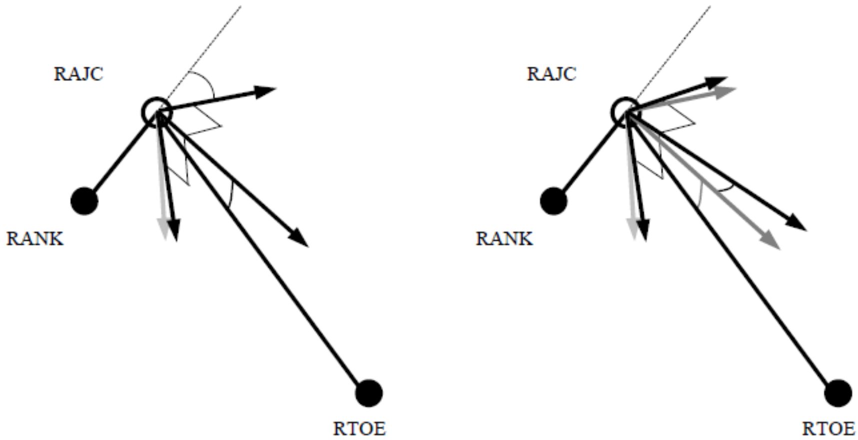
The Static offset angles (Plantar Flexion offset and Rotation offset) are then calculated from the 'YXZ' Cardan Angles between the two segments (rotating from the 'uncorrected' segment to the heel marker based foot segment). This calculation is performed for each frame in the static trial, and the mean angles calculated. The static plantar-flexion offset is taken from the rotation round the Y-axis, and the rotation offset is the angle round the X-axis. The angle round the Z-axis is ignored.

Dynamic Processing

In the dynamic trial, the foot is calculated in the same way as for the 'uncorrected' foot. The resulting segment is then rotated first round the Y-axis by the Plantar Flexion offset. Then the resulting segment is rotated around its X axis by the rotation offset.

Figure A8.11 Dynamic processing



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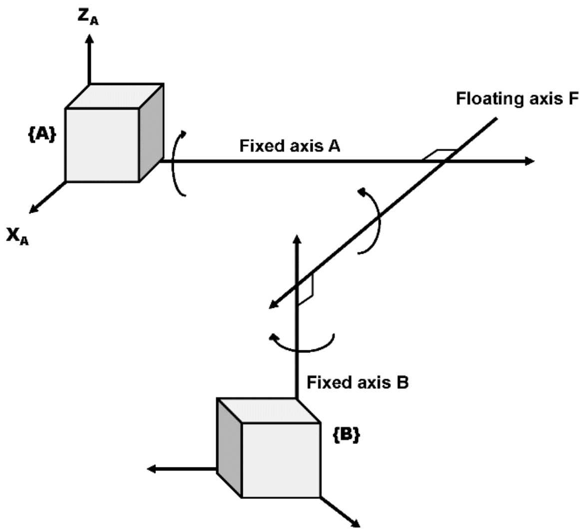
Angle Outputs

For the kinematic outputs of the lower limb, the rotation convention used was the Joint Co-ordinate System (Grood and Suntay 1983) (figure A8.12)

Figure A8.12 The Joint Co-ordinate System of Grood and Suntay (1983)



The output angles for all joints are calculated from the YXZ Cardan angles derived by comparing the relative orientations of the two segments. The knee angles are calculated from the femur and the untortioned tibia segments, whilst the ankle joint angles are calculated from the tortioned tibia and the foot segment. In the case of the feet, since they are defined in a different orientation to the tibia segments, an offset of 90 degrees is added to the flexion angle. This does not affect the Cardan angle calculation of the other angles since the flexion angle is the first in the rotation sequence. The progression angles of the feet, pelvis, thorax and head are the YXZ Cardan calculated from the rotation transformation of the subject's Progression Frame for the trial onto each segment orientation.

APPENDIX IX - Code for rotation of the knee joint centre

Rotation of the Knee joint centre {*VICON BodyLanguage (tm) model*}

```
{*This Model repositions the KAD in the static trial*}
Gorigin = {0,0,0}
Global = [Gorigin,{1,0,0},{0,0,1},xyz]
mm = 12.5

{* Find the centre of the 3 markers *}
RKADC = (RKAX+RKD1+RKD2)/3
LKADC = (LKAX+LKD1+LKD2)/3

{* Find the perpendicular to the plane containing the 3 markers *}
RKADV = NORM(RKAX,RKD1,RKD2)
LKADV = NORM(LKAX,LKD1,LKD2)

{* Find the apex of the pyramid *}
RKADO = RKADC + RKADV*57.75
LKADO = LKADC - LKADV*57.75

{* Set up the KAD axis system *}
RKAD = [RKADO,(RKADO-RKAX),(RKD1-RKADO),yzx]
LKAD = [LKADO,(LKAX-LKADO),(LKD1-LKADO),yzx]

{* Move the axis system in to the lateral knee pad and find that point for reference*}
RKAD = RKAD + 17*2(RKAD)
RLATPAD = {0,0,0}*RKAD

LKAD = LKAD - 17*2(LKAD)
LLATPAD = {0,0,0}*LKAD

{* Set up thigh axis system with axes parallel to the thigh but centred on lateral pad *}
RTHIGH = [RLATPAD,RFEP-RFEO,RFEO-RKAX,zxy]
LTHIGH = [LLATPAD,LFEP-LFEO,LKAX-LFEO,zxy]

{* Convert KAD co-ordinates, rotate and convert back *}
{* Left conventions have been kept as flex, add, rot so 2 need -ve signs *}
%RKAX = RKAX/RKAD
%RKD1 = RKD1/RKAD
%RKD2 = RKD2/RKAD

RKAD = ROT(RKAD,2(RTHIGH),(RKADFlex))
RKAD = ROT(RKAD,1(RTHIGH),(RKADAdd))
RKAD = ROT(RKAD,3(RTHIGH),(RKADRot))

RKAX = %RKAX*RKAD
RKD1 = %RKD1*RKAD
RKD2 = %RKD2*RKAD

%LKAX = LKAX/LKAD
%LKD1 = LKD1/LKAD
%LKD2 = LKD2/LKAD

LKADAdd = LKADAdd * (-1)
LKADRot = LKADRot * (-1)
```

```
LKAD = ROT(LKAD,2(LTHIGH),(LKADFlex))
LKAD = ROT(LKAD,1(LTHIGH),(LKADAdd))
LKAD = ROT(LKAD,3(LTHIGH),(LKADRot))

LKAX = %LKAX*LKAD
LKD1 = %LKD1*LKAD
LKD2 = %LKD2*LKAD

{*  Write out results *}
Param (%RKAX,%RKD1,%RKD2)
Output (RKAX,RKD1,RKD2)

Param (%LKAX,%LKD1,%LKD2)
Output (LKAX,LKD1,LKD2)
```

Return to Plug-in Gait model

APPENDIX X - Estimating maximum elbow angle error

Estimating Maximum elbow angle error

The maximum elbow width out of all the participants was identified = **110mm** (15KUFC01)

The distance between the wrist joint centre and the lateral elbow marker was calculated (LWJC to LELB) =

284.1094mm

To estimate the worst case angle error:

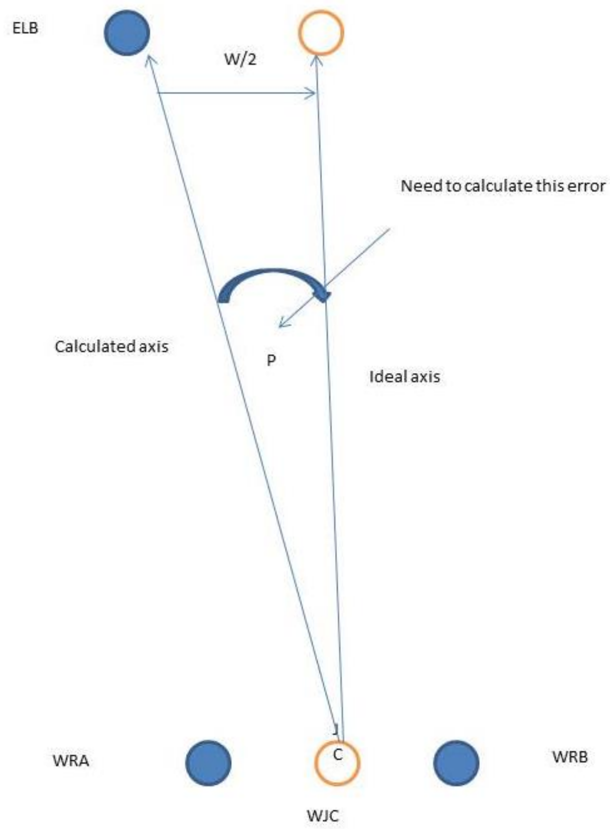
$$sinP = W/2l$$

Where:

W = maximum elbow width

L = distance between the wrist joint centre and the lateral elbow marker

P = estimated angle error



Therefore:

sinP = 110/284*2

P=arcsin(110/284*2)

P=arcsin(110/568)

P = 11.166570305791279529125245661562 degrees

P **= 11 degrees 0dp**

APPENDIX XI - Anthropometric measurements for inter and intra rater reliability testing

Anthropometric measurements for recording sheet for inter and intra rater reliability testing

ID reference nd301/nd302

	Anthropometric measurements	Recording
1.	**Height** The participant will be tested in their shorts and therefore asked to remove pieces of clothing not required. They will then be asked to stand on the scales.	1810 mm
2.	**Weight** Participants will be required to stand erect under the stadiometer.	86.6 kg
3.	**Inter ASIS distance** Subject supine the plinth a) For the palpation of each ASIS, stand on the side of the ASIS being palpated. b) Palpate the iliac crest to identify the general area of the ASIS. c) Palpate just below the ASIS, moving the hand up towards it. d) The first bony prominence should be the inferior edge of the ASIS: mark a dot on the middle of this inferior edge with an eye liner pencil.	205 mm
4.	**Leg Length** Measure with the patient supine, the knees maximally extended, and the operator stood on the side to be measured. Using a fabric tape measure hold the end on the point marking the ASIS with the proximal hand. Gently pull the tape taught on a direct line to the medial malleolus with the distal hand. Hold the tape here with a finger just distal to the MM. Gently slide this finger up the tape until a bony ledge is felt. At this point record the measurement. Repeat on the opposite side.	LEFT 925 mm RIGHT 925 mm
5.	**Knee Width** Identify and Surface Marking Knee Axis **Lateral surface marking** With the patient supine, stand at the side of the plinth, level with the knee. Flex the knee to 90° and palpate the lateral joint line. Use the other hand to identify the lateral epicondyle of the femur by sliding the hand along the outside of the femur. Now palpate the dip of the popliteal groove between the epicondyle and the joint line. Move along the popliteal groove until between the tendon of biceps femoris and the lateral collateral ligament. The iliotibial (ITB) band should be above the palpating finger, and the lateral head of gastrocnemius should be below. Move anteriorly and proximally onto a bony nodule - the origin of the lateral collateral. Keep this point under the palpating finger as an assistant slowly extends the knee. Re-palpate (the ITB tends to obscure the point of palpation on extension). In extension mark this point. **Medial surface marking** With the patient supine, stand at the side to be palpated level with the knee. Flex the knee to 90° and from the patella tendon palpate the medial joint line. Identify the broad tibial collateral ligament and grasp this loosely between the thumb and forefinger of the "distal" hand. Maintaining this grasp extend the knee with the other hand. Then run the flattened fingers of the proximal hand down the lower medial side of the thigh to find the adductor tubercle. Mark this with the middle finger and place the index finger on the mid-point of the line that joins the adductor tubercle to the middle of the collateral ligament at the joint line. This is a flat, rather featureless area, but a small depression may be felt. This should be distal and slightly anterior to the adductor tubercle. Remove the finger from this point and mark the same spot with a pen. The distance between the surface markings of the knee joint axis, measured using the callipers with the patient lying supine (cm).	LEFT 113 mm RIGHT 113 mm

ID reference nd301/nd302

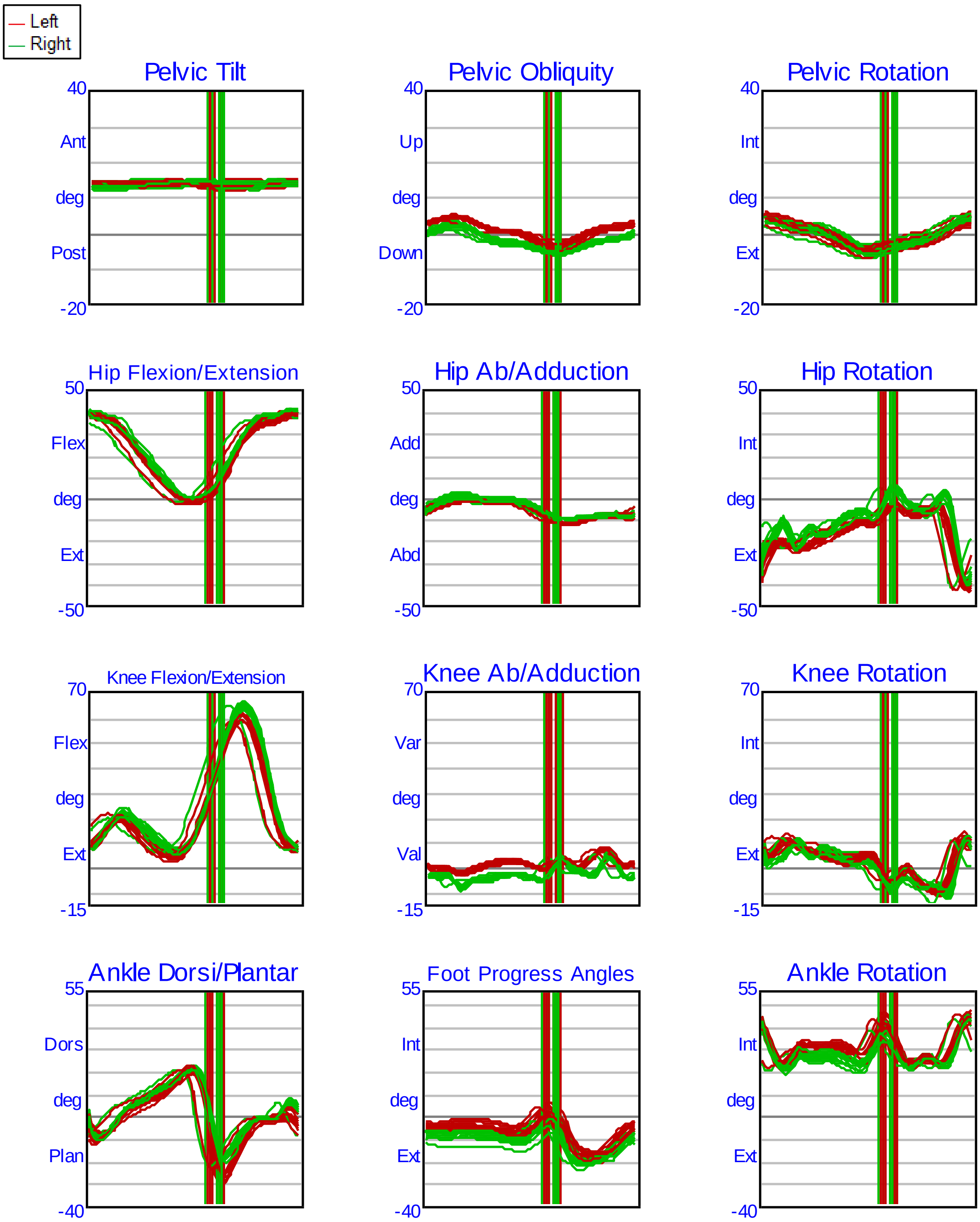
	Anthropometric measurements	Recording
6.	**Ankle Width** Measure the widest part of the ankle malleoli measured using the callipers with the patient lying supine (cm).	LEFT 79 mm RIGHT 79 mm
7.	**Tibial torsion** The midpoint of the medial malleolus and the posterior tip of the lateral malleolus are marked with eyeliner pen. The subject is prone and knee flexed at 900 so that the shank is vertical and ankle dorsiflexed to900, or as close as possible. The goniometer is place on the plantar surface of the heel so that the first arm is in line with both marks. The second arm is aligned parallel to an imagined line between the midpoint of the knee joint axis and the hip joint centre – the mid-line of the thigh. The angle recorded is from the line perpendicular to the mid-line of the thigh	LEFT - 25 degrees RIGHT -30 degrees

Return

APPENDIX XII - Individual gait graphs for ORLAU physiotherapist

Figure A12.1 Summary of gait graph variables for 12 dynamic walking trials (Experienced ORLAU physiotherapist)

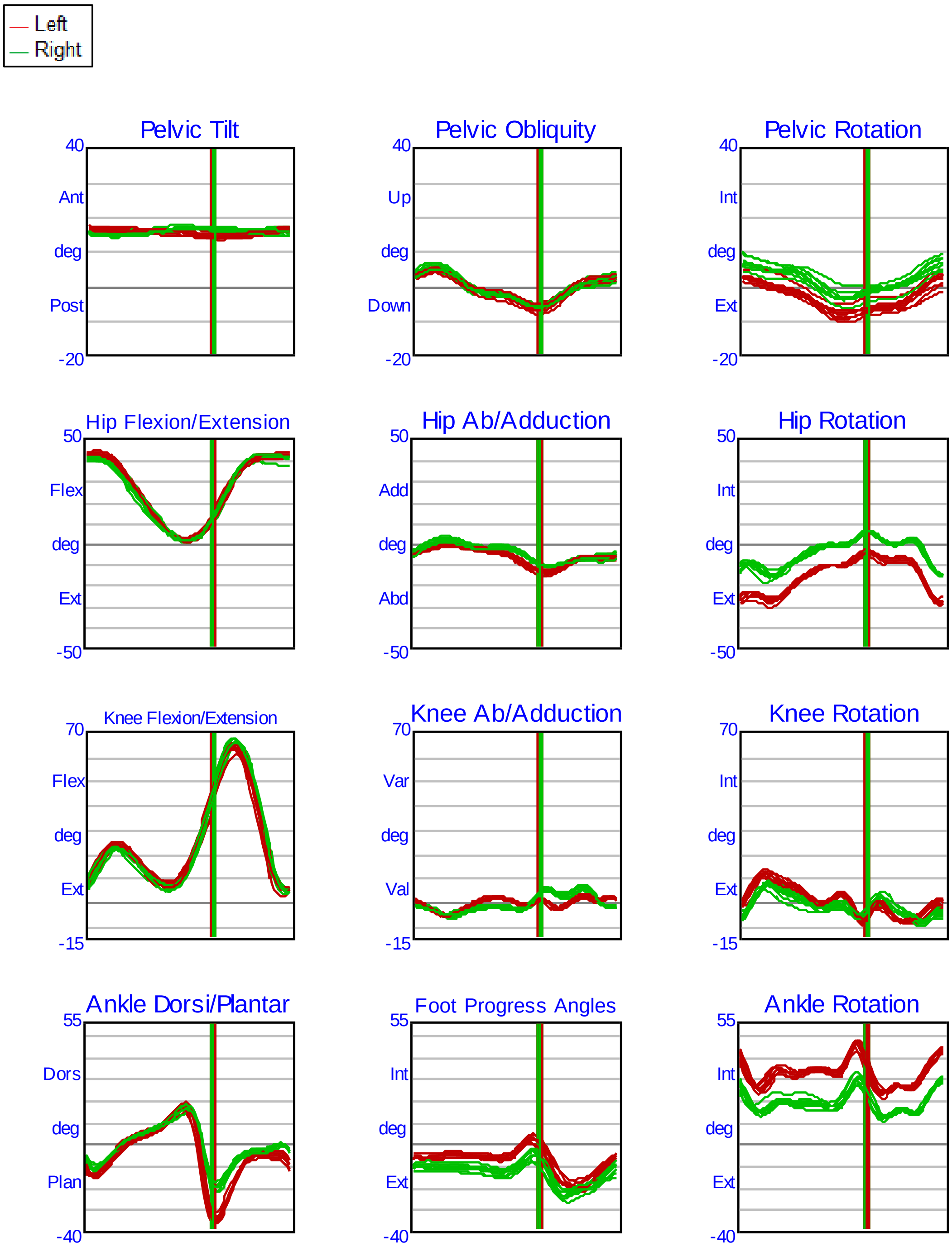
KEY



APPENDIX XIII - Individual gait graphs for Researcher

Figure A13.1 Summary of gait graph variables for 8 dynamic walking trials (Researcher)

KEY



APPENDIX XIV - Certification for Functional Movement Systems Screen

Figure A14.1 Certification for Functional Movement System Screen

FMS

Functional Movement Systems

This is to certify that

Fraser Philp

has fulfilled the requirements established by

Functional Movement Systems

and has successfully passed the Level 1 Certification Examination
in order to administer the Functional Movement Screen™.

Gray Cook, Founder

Lee Burton, President

Functional Movement Screen
Established
FMS
2001
Certified

Brett Jones, Director of Certification

May 11, 2014
Date

APPENDIX XV - Selection of appropriate levels of tolerance (Threshold setting)

Selection of appropriate levels of tolerance (Threshold setting)

Introduction

In order to operationalise the rules of the FMS, quantified thresholds for objective measures of performance needed to be determined. It was identified that selection of threshold values should take place prospectively not retrospectively i.e. before reviewing the kinematic values. This was to ensure that threshold values weren't influenced by observation of the quantified values and would therefore more closely reflect the real-time assessment process.

Methodology

For all subtests, the values selected for determining levels of tolerance (for comparison of the real-time assessor score to the photogrammetric system) were selected based on the following principles:

- To identify if a limb had moved (displacement of the markers) the selected value of 5mm was chosen as this value is greater than the residuals of the camera system following calibration. Therefore any movement greater than 5mm can be attributed to a true movement.
- To identify if a joint had moved, an angle greater than or equal to 10 degrees was selected. As the FMS requires the assessor to eyeball (visually estimate) movement at the joints, the selected threshold had to reflect a value that the real-time assessor would be sensitive to detect using this method, and also be larger than the error of measurement associated with this method (Allington et al 2002). The value of 10 degrees therefore meets these criteria.
- For minimal distances of test – these were based on anatomical thresholds as defined within the model or on pragmatic assumptions following consultation of the participants' anthropometric measurements.

For subtests in which the levels of tolerance differed from the one stated above, justification was provided along with the selected level of tolerance within the main body of the thesis.

It was recognised that the perceived performance of the participant, when reviewing the quantified data, may be affect by the selected threshold values of some flag conditions. Therefore the effects of increments of 5mm on the selected levels of tolerance for performance of a FMS subtest were investigated. The selected test was the FMS Deep Squat Final test. Rules for the FMS Deep Squat test have been operationalised in Section 5.1.1 described as flag conditions.

The thresholds selected were:

i. Knee position over the foot (increasing medial and lateral borders of tolerance determined by the foot) (flag conditions 4^1, 5^1)
ii. The amount by which the anterior border of the foot was moved relative to the toe marker. This determined the anterior level of tolerance to check if the dowel remained over the feet. (flag conditions 6^1, 7^1)
iii. Heel raise height tolerance (flag conditions 10^1, 11^1)

NB – for point ii. a +5mm increase for movement of the medial and lateral foot borders would result in a total increase of 10mm i.e. +5mm for medial border and +5mm for lateral border.

These flag conditions were selected as the underlying methods that determine these flag conditions inform multiple other subtest conditions. Additionally there was no reference value against which the thresholds could be determined. For example, in these same subtests, the level of tolerance for flag condition 1^1 (Thorax inclination angle must be less than the tibial inclination angle) is determined by the maximum tibial inclination angle.

Results

Results for the effect of increasing 5mm increments on the selected levels of tolerance on performance of the FMS Deep Squat subtest are presented in table (A15.1). An annotated guide to help with interpretation of the results has been provided below (figure A15.1). It was identified that incrementally increasing the threshold values did result in more criteria being met, but did not result in a change to the participants scoring classification. By increasing the levels of tolerance it negatively affected the discriminatory ability of the flag conditions.

Figure A15.1 An annotated guide to help with interpretation of the results

A. The **first row** indicates the **subtest** for which the results are being reported alongside the **number** of flag conditions

B. The **first column** contains the participants ID. Participants are ranked in descending order according to their real-time FMS assessor awarded score as shown in the **second column**.

Deep Squat - Final Score - 11 Flag conditions										
ID	FMS score	Original selected thresholds			"+5mm"			"+10mm"		
		Attempt 1	Attempt 2	Attempt 3	Attempt 1	Attempt 2	Attempt 3	Attempt 1	Attempt 2	Attempt 3
15KUFC10	3	3/11	4/11	3/11	4/11	7/11	6/11	5/11	7/11	6/11
15KUFC01	2	5/11	6/11	5/11	6/11	7/11	7/11	8/11	8/11	8/11
15KUFC06	2	7/11	10/11	10/11	8/11	10/11	10/11	8/11	10/11	10/11
15KUFC07	2	6/11	8/11	8/11	6/11	9/11	9/11	7/11	9/11	9/11
15KUFC02	1	5/11	5/11	5/11	7/11	7/11	5/11	7/11	7/11	7/11
15KUFC03	1	5/11	5/11	5/11	7/11	6/11	6/11	8/11	6/11	6/11

C. These **columns** indicate the originally selected thresholds and incremental 5mm increases

D. The **columns** **(C.)** contain a further three **columns**, each representing an attempt of the FMS subtest. The **number** in each column represents how many of the flag conditions were successfully met for that attempt,

A. The **first row** indicates the **subtest** for which the results are being reported alongside the **number** of flag conditions

B. These **columns** indicate the originally selected thresholds and incremental 5mm increases

C. Further subdivided into a three **columns**, each representing an attempt of the subtest. The **number** represents how many flag conditions were successfully met for that attempt.

D. The **first column** contains the participants ID. Participants are ranked in descending order according to their real-time FMS assessor awarded score as shown in the **second column**.

Deep Squat - Final Score - 11 Flag conditions										
ID	FMS score	Original selected thresholds			"+5mm"			"+10mm"		
		Attempt 1	Attempt 2	Attempt 3	Attempt 1	Attempt 2	Attempt 3	Attempt 1	Attempt 2	Attempt 3
15KUFC10	3	3/11	4/11	3/11	4/11	7/11	6/11	5/11	7/11	6/11
15KUFC01	2	5/11	6/11	5/11	6/11	7/11	7/11	8/11	8/11	8/11
15KUFC06	2	7/11	10/11	10/11	8/11	10/11	10/11	8/11	10/11	10/11
15KUFC07	2	6/11	8/11	8/11	6/11	9/11	9/11	7/11	9/11	9/11
15KUFC02	1	5/11	5/11	5/11	7/11	7/11	5/11	7/11	7/11	7/11
15KUFC03	1	5/11	5/11	5/11	7/11	6/11	6/11	8/11	6/11	6/11

Table A15.1 Results for the effect of increments in selected levels of tolerance for performance of the FMS subtest (Deep Squat flag conditions)

Deep Squat - Final Score- 11 Flag conditions										
ID	FMS score	**Original selected thresholds**			**"+5mm"**			**"+10mm"**		
		Attempt 1	Attempt 2	Attempt 3	Attempt 1	Attempt 2	Attempt 3	Attempt 1	Attempt 2	Attempt 3
15KUFC10	3	3/11	4/11	3/11	4/11	7/11	6/11	5/11	7/11	6/11
15KUFC01	2	5/11	6/11	5/11	6/11	7/11	7/11	8/11	8/11	8/11
15KUFC06	2	7/11	10/11	10/11	8/11	10/11	10/11	8/11	10/11	10/11
15KUFC07	2	6/11	8/11	8/11	6/11	9/11	9/11	7/11	9/11	9/11
15KUFC08	2	7/11	6/11	6/11	9/11	7/11	7/11	9/11	8/11	7/11
15KUFC09	2	9/11	7/11	8/11	9/11	7/11	8/11	11/11	9/11	9/11
15KUFC11	2	7/11	6/11	7/11	9/11	8/11	7/11	9/11	8/11	9/11
15KUFC13	2	5/11	6/11	6/11	5/11	6/11	7/11	6/11	7/11	8/11
15KUFC14	2	4/11	3/11	3/11	4/11	4/11	4/11	5/11	5/11	5/11
15KUFC15	2	11/11	10/11	11/11	11/11	10/11	11/11	11/11	10/11	11/11
15KUFC17	2	7/11	6/11	6/11	9/11	8/11	8/11	9/11	8/11	8/11
15KUFC18	2	7/11	9/11	9/11	10/11	10/11	11/11	10/11	10/11	12/11
15KUFC19	2	6/11	7/11	7/11	9/11	7/11	9/11	9/11	9/11	9/11
15KUFC21	2	6/11	9/11	8/11	6/11	10/11	9/11	7/11	10/11	9/11
15KUFC22	2	7/11	10/11	7/11	8/11	10/11	8/11	8/11	10/11	8/11
15KUFC23	2	6/11	8/11	6/11	8/11	8/11	8/11	8/11	8/11	8/11
15KUFC02	1	5/11	5/11	5/11	7/11	7/11	5/11	7/11	7/11	7/11
15KUFC03	1	5/11	5/11	5/11	7/11	6/11	6/11	8/11	6/11	6/11
15KUFC04	1	5/11	6/11	7/11	7/11	8/11	8/11	7/11	8/11	9/11
15KUFC05	1	4/11	3/11	5/11	6/11	5/11	6/11	6/11	5/11	6/11
15KUFC12	1	7/11	5/11	4/11	7/11	6/11	5/11	8/11	7/11	7/11
15KUFC16	1	3/11	3/11	5/11	6/11	4/11	5/11	6/11	6/11	6/11
15KUFC24	1	4/11	5/11	4/11	6/11	6/11	6/11	7/11	6/11	6/11
15KUFC25	1	6/11	6/11	6/11	6/11	6/11	6/11	6/11	6/11	6/11

Discussion

It has been identified that despite increments in the values used to determine thresholds, it did not result in participants becoming reclassified based on the photogrammetric system. Participants would not have changed from the scoring category to which they were allocated. Therefore the participants were either not meeting other criteria (in which the level of tolerance is implicit and cannot be changed), or had violated the threshold by a significant value.

Conclusion

Increasing the values used to determine thresholds did not result in reclassification of participants and negatively affected the discriminatory ability of the flag conditions. Given these observations it was decided that the originally selected thresholds were appropriate.

APPENDIX XVI - FMS heat maps for all subtests

FMS heat maps for all subtests

Figure A16.1 All subtests ranked according to subject number (ascending)

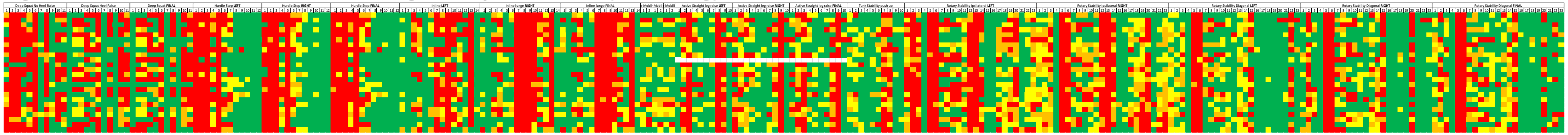


Figure A16.2 Ranked descending according to FMS final score

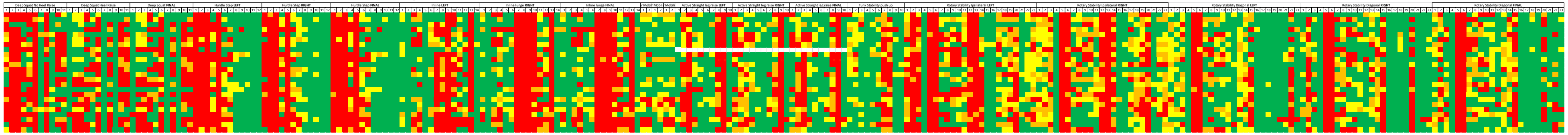


Figure A16.3 Ranked descending according to Inseason injuries (number of injuries)

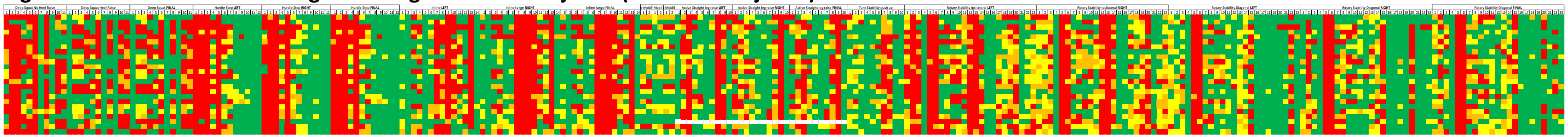
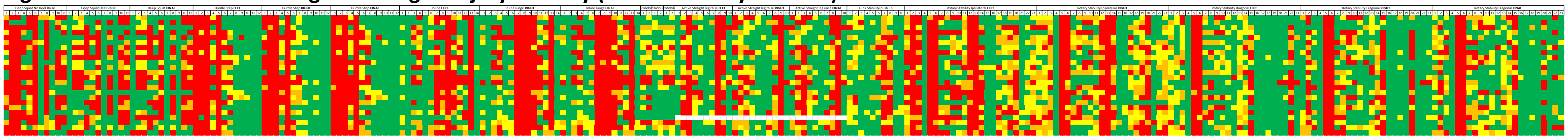


Figure A16.4 Ranked descending according to Injury severity (number of days missed)



APPENDIX XVI

FMS heat maps for subtests which inform the final score for that subtest

Figure A16.5 All Final score tests ranked according to subject number (ascending)

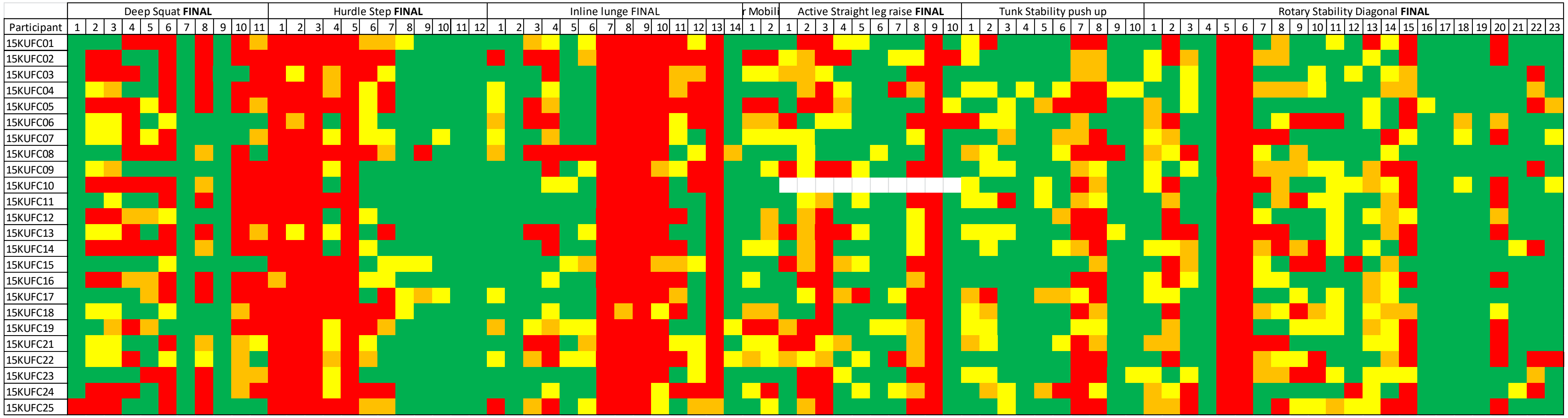


Figure A16.6 Ranked descending according to FMS final score

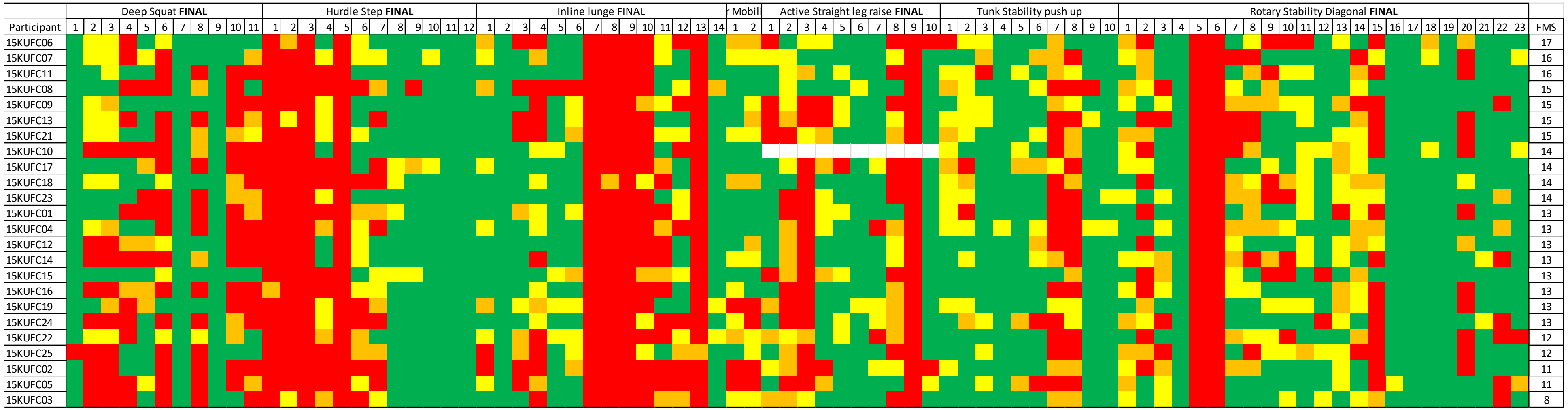


Figure A16.7 Ranked descending according to Inseason injuries (number of injuries)

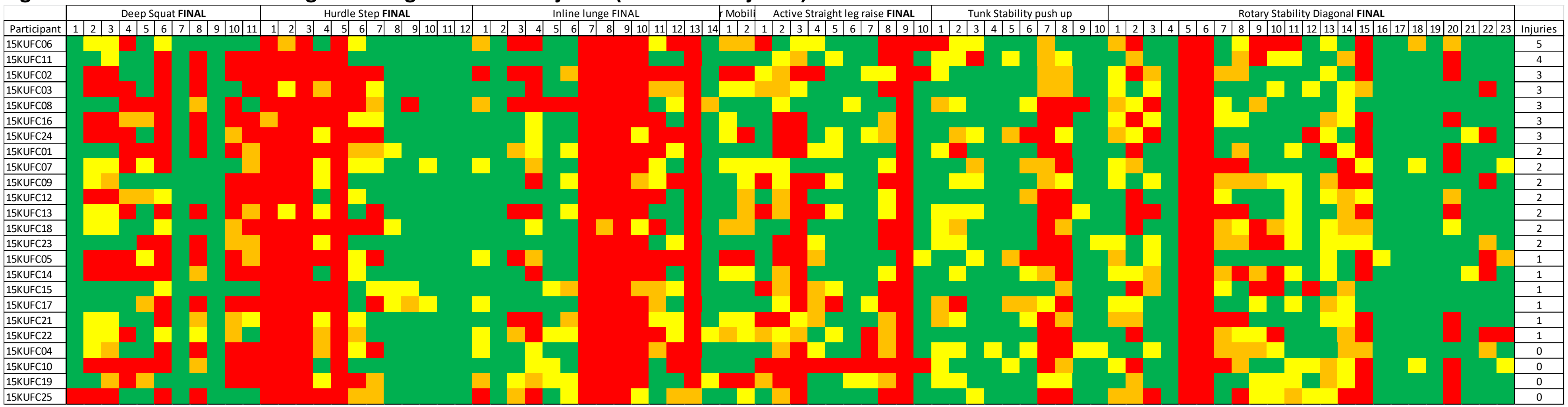
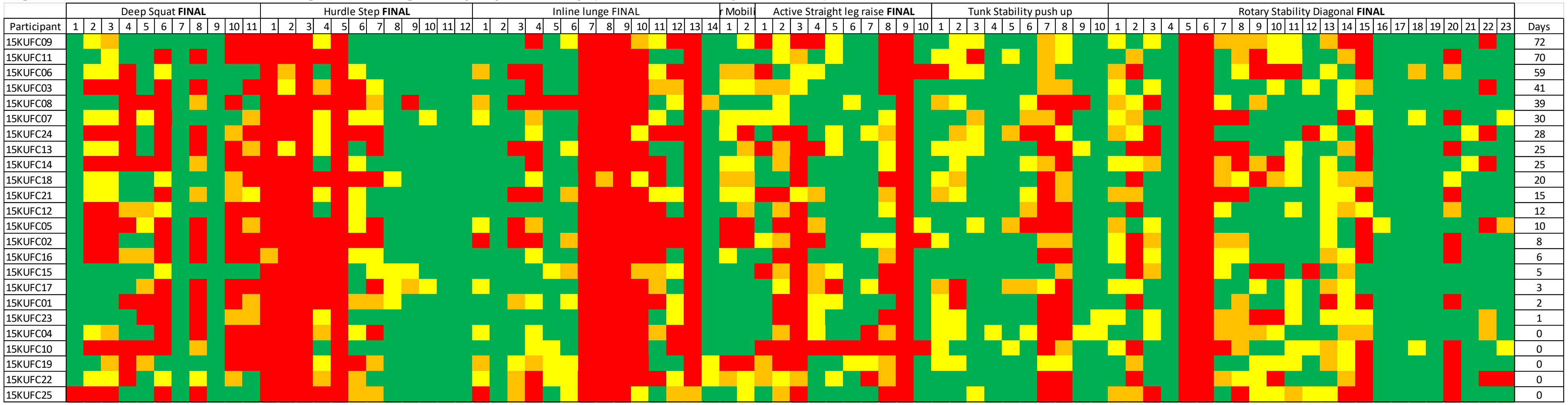


Figure A16.8 Ranked descending according to Injury severity (number of days missed)



APPENDIX XVII - Evaluation of Acute to Chronic workload

Acute to Chronic workload

The characteristics of the acute to chronic workload ratio were evaluated prior to its inclusion into the model. For illustration purposes the ratio can be presented as:

$$ACWR = \frac{\mathrm{AW}}{CW}$$

Where:
ACWR = acute to chronic workload ratio
AW = acute workload
CW = chronic workload

It was identified that the ratio could be calculated in two ways.

1. The first method (as used in our study) involves inclusion of the acute workload week value in the chronic workload week calculations i.e.

$$ACWR = \frac{\mathrm{Wn}}{\sum(\mathrm{Wn}-3\ +\ \mathrm{Wn}-2\ +\mathrm{Wn}-1\ +\ \ \mathrm{Wn})/4}$$

Where:
ACWR = acute to chronic workload ratio
Wn = work load in week n

2. The second method does not include the acute workload week value in the chronic workload week calculations i.e.

$$ACWR = \frac{\mathrm{Wn}}{\sum(\mathrm{Wn}-4\ +\ \mathrm{Wn}-3\ +\mathrm{Wn}-2\ +\ \ \mathrm{Wn}-1)/4}$$

Where:
ACWR = acute to chronic workload ratio
Wn = work load in week n

Both methods were identified as having limitations due to the way in which the ratio may be calculated. Given that the method compares the most recent week against the previous four weeks, the ratio only works when training has taken place for a minimum of four weeks. In order to overcome this, a value of one was assigned to all participants for the initial three weeks given that no prior training had taken place and any training was therefore a 100% increase in load; equivalent to a ratio of 1.

For calculation of the acute to chronic workload ratio as per the second method, if no training has taken place in weeks one to four but training takes place in week five, a value of infinity is calculated i.e.

$$ACWR = \frac{50}{0}$$

$$ACWR = \infty$$

This value is therefore of no clinical use. This problem is rectified, as in method one, by including the acute workload week values in the chronic workload week calculations. Despite this modification, a ratio of zero may still be calculated if:

i. No training takes place in the acute week

$$ACWR = \frac{0}{50}$$

$$ACWR = 0$$

ii. No training has taken place for the previous four weeks

$$ACWR = \frac{0}{0}$$

$$ACWR = 0$$

It is therefore not possible, on evaluation of the index alone, to identify which scenario would result in the observed value of a zero. This was true for both methods. Having identified these limitations, alternate methods for measuring load were investigated, namely a rolling cumulative rolling average. As stated earlier, an increase or 'spike' in training load (percentage increase larger than 30% or a ratio greater than 1.3) has been associated with an increased risk of injury (Hulin et al 2014, Hulin et al 2016, Moller et al 2017). Therefore being able to detect an increase in training load is an important characteristic of the measure. On evaluation of the different methods it was identified that both the acute to chronic workload ratio and the four week rolling average were responsive increases in load (figure A17.1, point A). However it was identified that with the four week rolling average, subsequent changes in load are masked in the rolling average calculation which may result in any further change being undetected. It was also identified that when no steady state of load is occurring; the acute to chronic workload ratio may disproportionality magnify any small increases in load (figure A17.1, point B). Given that the measure should be sensitive to fluctuations in load, the acute to chronic workload ratio was selected over the four week rolling average, as the latter masks any fluctuations once a large increase in training load has occurred. The acute to chronic workload ratio may be considered as a measure of changes in load, although the identified limitations must be taken into consideration when evaluating the results. It was therefore included as an input in the model.

Comparing the characteristics of the acute to chronic workload ratio and rolling four week average to changes in load.

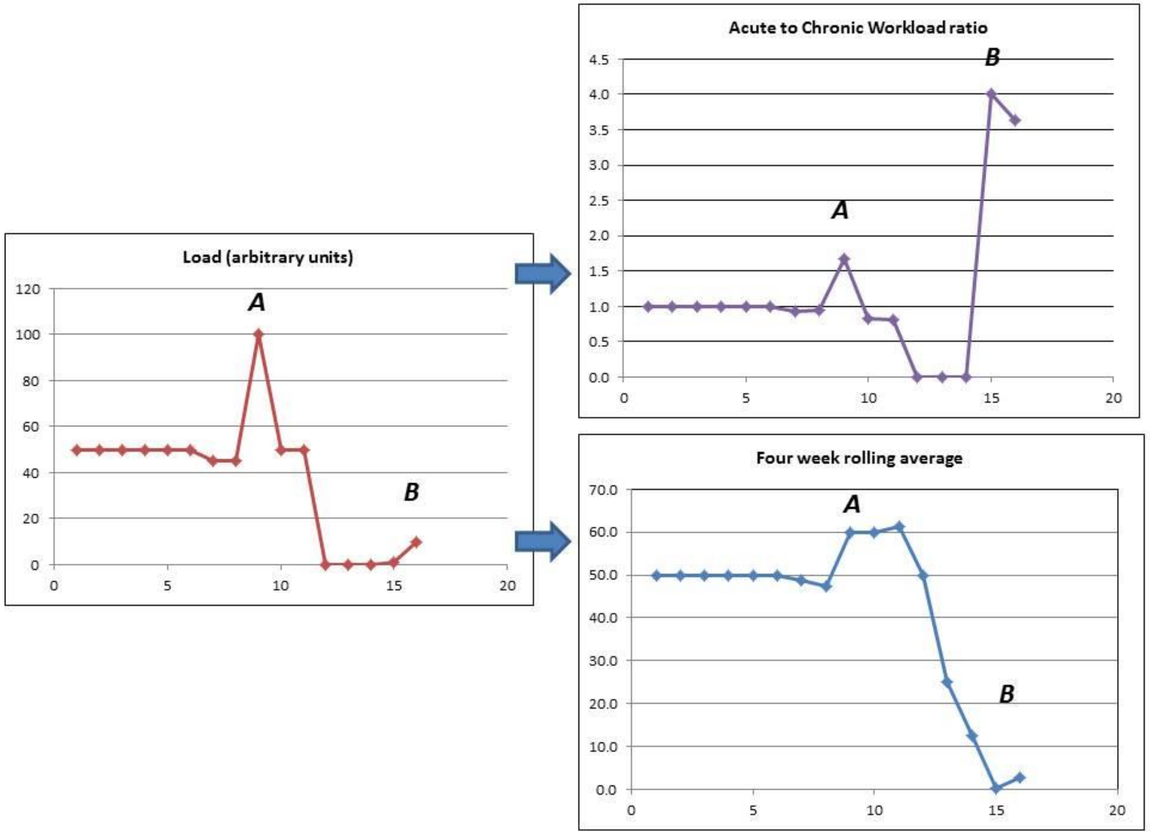
Table A17.1

Time (AU)*	Load (AU)	Acute to Chronic Workload ratio	Four week rolling average (AU)
1	50	1	50
2	50	1	50
3	50	1	50
4	50	1	50
5	50	1	50
6	50	1	50
7	45	0.9	48.8
8	45	0.9	47.5
9	100	1.7	60
10	50	0.8	60
11	50	0.8	61.3
12	0	0	50
13	0	0	25
14	0	0	12.5
15	1	4	0.3
16	10	3.6	2.8

***AU = arbitrary units**

Return

Figure A17.1



A and B reference points used in the evaluation of the acute to chronic workload ratio and rolling cumulative average

APPENDIX XVIII - Matlab script save function for all tests

MATLAB routine for saving data

```
% This script runs one of the tests on all participants and saves the
% outputs in a .csv file

% In the .m file that contains the test, the first line needs to be:
% (Here I use "Deep_squat" as an example):
%
% function output = Deep_squat(filename)
%
% The data gets loaded by calling:
% data = btk_loadc3d(filename);
%
% At the end there is a section that contains all the output names:
% var_names = {'com_maxx','com_maxy','com_maxz', ...
%
% and below that there is a section that fills in the "output" variable:
% %% Output data
% output.var_names = var_names;
% for i_var=1:length(var_names)
%     output.(var_names{i_var}) = eval(var_names{i_var});
% end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Inputs - you should only need to modify this section

% Set the test here (name of .m file, e.g. "Deep_squat"):
test_name = 'Deep_squat_no_HR';

% Set the trial names here as a cell array
all_trials = {%'Insert files to be saved'};
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% The test name will also be the name of the output file:
outfilename = [test_name '.csv'];

% open output file
fid = fopen(outfilename,'wt');

first_trial = 1; % flag that this is the first trial

for itrial=1:length(all_trials)

    % get input filename
    filename = all_trials{itrial};
    [pathstr,name,ext] = fileparts(filename);

    % run function that contains test
    eval(['output = ' test_name '(filename);']);

    % if this is the first trial, write header line
    if first_trial
```

```
        for i_var = 1:length(output.var_names)
```

```
            fprintf(fid,',%s,%s,%s',[output.var_names{i_var}
'_1'],[output.var_names{i_var} '_2'],[output.var_names{i_var} '_3']);
        end
        fprintf(fid,'\n');
        first_trial = 0; % now set flag to zero
    end

    % write trial name
    fprintf(fid,'%s',name);

    % write data
    for i_var = 1:length(output.var_names)
        fprintf(fid,',%f,%f,%f', output.(output.var_names{i_var}));
    end
    fprintf(fid,'\n');

end

% close output file
fclose(fid);
```

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APPENDIX XIX - Matlab script for Deep Squat no heel raise and heel raise tests

MATLAB routine for Deep Squat no heel raise and heel raise tests

```
function output = Deep_squat_no_HR(filename)
```

load data

```
data = btk_loadc3d(filename);
% Set thresholds
Heel_Raise_threshold = 5;

% find event markers - associatted user defined lables with data
angle_freq = data.marker_data.AngleInfo.frequency; % sampling frequency
events = data.events_data.Data.Right_Foot_Strike;

% Label markers
RHEE_start = data.marker_data.Markers.RHEE(1,3);
LHEE_start = data.marker_data.Markers.LHEE(1,3);
LTOE = data.marker_data.Markers.LTOE;
RTOE = data.marker_data.Markers.RTOE;
LHEE = data.marker_data.Markers.LHEE;
RHEE = data.marker_data.Markers.RHEE;
LFIN = data.marker_data.Markers.LFIN;
RFIN = data.marker_data.Markers.RFIN;
```

Initialize output vectors - allocates holding space

```
Rmax_knee = zeros(length(events)-1,1);
Lmax_knee = zeros(length(events)-1,1);
incl_thorax_at_max_knee = zeros (length(events)-1,1);
incl_tibia_at_max_knee = zeros (length(events)-1,1);
Tx_vs_Tb = cell(length(events)-1,1);
incl_thorax = zeros(length(events)-1,1);
max_knee_side = cell(length(events)-1,1);
indices = zeros(length(events)-1,1);
local_indices = zeros(length(events)-1,1);
Tx_vs_tib_flag = zeros(length(events)-1,1);
Tx_vs_tib_diff = zeros(length(events)-1,1);
Lmax_knee_flag = zeros(length(events)-1,1);
Rmax_knee_flag = zeros(length(events)-1,1);
RKOT = zeros(length(events)-1,1);
LKOT = zeros(length(events)-1,1);
LKOT_flag = cell(length(events)-1,1);
RKOT_flag = cell(length(events)-1,1);
RKOT_max= zeros(length(events)-1,1);
RKOT_min= zeros(length(events)-1,1);
LKOT_max= zeros(length(events)-1,1);
LKOT_min= zeros(length(events)-1,1);
LTOE_y_start= zeros(length(events)-1,1);
LHEE_y_start= zeros(length(events)-1,1);
RTOE_y_start= zeros(length(events)-1,1);
RHEE_y_start= zeros(length(events)-1,1);
L_toe_bar_flag= zeros(length(events)-1,1);
L_heel_bar_flag= zeros(length(events)-1,1);
R_toe_bar_flag= zeros(length(events)-1,1);
R_heel_bar_flag= zeros(length(events)-1,1);
LFIN_y_start= zeros(length(events)-1,1);
RFIN_y_start= zeros(length(events)-1,1);
LFIN_finish= zeros(length(events)-1,1);
RFIN_finish= zeros(length(events)-1,1);
LFIN_y_max = zeros(length(events)-1,1);
LFIN_y_min = zeros(length(events)-1,1);
RFIN_y_min = zeros(length(events)-1,1);
RFIN_y_max = zeros(length(events)-1,1);
LFIN_fin_dist_toe = zeros(length(events)-1,1);
LFIN_fin_dist_heel = zeros(length(events)-1,1);
```

```
RFIN_fin_dist_toe= zeros(length(events)-1,1);
RFIN_fin_dist_heel = zeros(length(events)-1,1);
L_diff_heel_flag = zeros (length(events)-1,1);
R_diff_heel_flag = zeros (length(events)-1,1);
L_heel_diff_max = zeros (length(events)-1,1);
R_heel_diff_max = zeros (length(events)-1,1);

% for each attempt...
for i_attempt = 1:length(events)-1
    start_attempt = round(events(i_attempt)*angle_freq+1)-
data.marker_data.First_Frame+1;
    stop_attempt = round(events(i_attempt+1)*angle_freq)-
data.marker_data.First_Frame+1;
    % find maximum knee angle
    [Rmax_knee(i_attempt),
indexR]=max(data.marker_data.Angles.RKneeAngles(start_attempt:stop_attempt,1));
    [Lmax_knee(i_attempt),
indexL]=max(data.marker_data.Angles.LKneeAngles(start_attempt:stop_attempt,1));

if Rmax_knee(i_attempt)>Lmax_knee(i_attempt)
   index = indexR;
   disp('Right');
   max_knee_side{i_attempt} = 'Right';
else
   disp('Left');
   index =  indexL;
   max_knee_side{i_attempt} = 'Left';
end

indices(i_attempt) = start_attempt+index-1;
    local_indices(i_attempt) = index;

incl_thorax
=(data.marker_data.Angles.RThoraxAngles(start_attempt:stop_attempt,1));

% FLAG ARGUMENTS
% (1) Thorax inclination angle relative to tibial inclination angle
%     Identify tibia angle
% Right tibia
    Rtibia_x = data.marker_data.Markers.RTIL(start_attempt:stop_attempt,:)-
data.marker_data.Markers.RTIO(start_attempt:stop_attempt,:);
    Rtibia_y = -(data.marker_data.Markers.RTIA(start_attempt:stop_attempt,:)-
data.marker_data.Markers.RTIO(start_attempt:stop_attempt,:));
    Rtibia_z = data.marker_data.Markers.RTIP(start_attempt:stop_attempt,:)-
data.marker_data.Markers.RTIO(start_attempt:stop_attempt,:);

    incl_tibiaR = zeros(size(Rtibia_x,1),1);
    for i_frame = 1:size(Rtibia_x,1)
        % normalize vectors
        n_tibia_x = Rtibia_x(i_frame,:)/norm(Rtibia_x(i_frame,:));
        n_tibia_y = Rtibia_y(i_frame,:)/norm(Rtibia_y(i_frame,:));
        n_tibia_z = Rtibia_z(i_frame,:)/norm(Rtibia_z(i_frame,:));

        tibia_R = [n_tibia_x' n_tibia_y' n_tibia_z'];
        [angle_x,angle_y,angle_z] = rotxyz(tibia_R);
        incl_tibiaR(i_frame) = angle_x*180/pi;
    end

% Left tibia
  Ltibia_x = data.marker_data.Markers.LTIL(start_attempt:stop_attempt,:)-
data.marker_data.Markers.LTIO(start_attempt:stop_attempt,:);
  Ltibia_y = -(data.marker_data.Markers.LTIA(start_attempt:stop_attempt,:)-
data.marker_data.Markers.LTIO(start_attempt:stop_attempt,:));
  Ltibia_z = data.marker_data.Markers.LTIP(start_attempt:stop_attempt,:)-
data.marker_data.Markers.LTIO(start_attempt:stop_attempt,:);

    incl_tibiaL = zeros(size(Ltibia_x,1),1);
```

```
    for i_frame = 1:size(Ltibia_x,1)
        % normalize vectors
        n_tibia_x = Ltibia_x(i_frame,:)/norm(Ltibia_x(i_frame,:));
        n_tibia_y = Ltibia_y(i_frame,:)/norm(Ltibia_y(i_frame,:));
        n_tibia_z = Ltibia_z(i_frame,:)/norm(Ltibia_z(i_frame,:));

        tibia_L = [n_tibia_x' n_tibia_y' n_tibia_z'];
        [angle_x,angle_y,angle_z] = rotxyz(tibia_L);
        incl_tibiaL(i_frame) = angle_x*180/pi;
    end

 if incl_tibiaL(i_attempt) > incl_tibiaR(i_attempt);
   incl_tibia = incl_tibiaL;
   disp('Left - Tibia');
else
   disp('Right - Tibia');
   incl_tibia =  incl_tibiaR;
end

% Flag condition (1)
incl_tibia_at_max_knee(i_attempt)= incl_tibia(index);
Tx_vs_tib_flag(i_attempt)=incl_thorax_at_max_knee(i_attempt)>
incl_tibia_at_max_knee(i_attempt);
if Tx_vs_tib_flag(i_attempt)>0;
   Tx_vs_tib_diff(i_attempt)=  incl_thorax_at_max_knee(i_attempt)-
incl_tibia_at_max_knee(i_attempt);
end

% (2+3) Left + Right femur angle relative to the horizontal axis
% Idenfity femur position
% Left
for i_frame = start_attempt:stop_attempt
 pointa = data.marker_data.Markers.LFEO(i_frame,:);
 pointb = data.marker_data.Markers.LFEP(i_frame,:);
 AB = pointa - pointb;
 len_AB = sqrt(sum(AB.^2));
%  Femur position relative to the global Z axis
AB_AC(i_frame) = acosd(dot(AB/len_AB,[0,0,-1]));
end

max_AB_AC(i_attempt) = max(AB_AC(start_attempt:stop_attempt));
Lmax_knee_flag(i_attempt)= max_AB_AC(i_attempt) < 90;

% Right
for i_frame = start_attempt:stop_attempt
 pointc = data.marker_data.Markers.RFEO(i_frame,:);
 pointd = data.marker_data.Markers.RFEP(i_frame,:);
 CD = pointc - pointd;
 len_CD = sqrt(sum(CD.^2));
CD_AC(i_frame) = acosd(dot(CD/len_CD,[0,0,-1]));
end

max_CD_AC(i_attempt) = max(CD_AC(start_attempt:stop_attempt));
Rmax_knee_flag(i_attempt) = max_CD_AC(i_attempt) < 90;

% (4+5) Left + Right knee position in the coronal plane relative to the
% medial and lateral borders of the foot

%     Right KJC over toes - medial border movement is -ve
 for i_frame = start_attempt:stop_attempt
    point1 = data.marker_data.Markers.RHEE(i_frame,:);
    point2 = data.marker_data.Markers.RTOE(i_frame,:);
    % Create virtual point for plane
    point3 = [point1(1)  point1(2) point1(3)+1];
    plane1 = createPlane(point1, point2, point3);
    % lateral border
    plane2 = [data.marker_data.Markers.RANK(i_frame,:) plane1(4:9)];
```

```
    norm_plane = cross(plane1(4:6),plane1(7:9));
    plane1 = [plane1(1:3)-50*norm_plane plane1(4:9)];%set medial border distance
    Rknee_pt = data.marker_data.Markers.RFEO(i_frame,:); %KJC
    d1 = distancePointPlane(Rknee_pt, plane1);
    d2 = distancePointPlane(Rknee_pt, plane2);
    if d1*d2>0
        RKOT(i_attempt) = RKOT(i_attempt) + 1;
        RKOT_max(i_attempt) = max(RKOT_max(i_attempt),((d1+d2)/2));% lateral
displacement
        RKOT_min(i_attempt) = min(RKOT_min(i_attempt),((d1+d2)/2));% medial
displacement
    end

%     Left KJC over toes - medial border movement is +ve
    point1 = data.marker_data.Markers.LHEE(i_frame,:);
    point2 = data.marker_data.Markers.LTOE(i_frame,:);
    point3 = [point1(1)  point1(2) point1(3)+1];
    plane1 = createPlane(point1, point2, point3);
    plane2 = [data.marker_data.Markers.LANK(i_frame,:) plane1(4:9)];
    norm_plane = cross(plane1(4:6),plane1(7:9));
    plane1 = [plane1(1:3)+50*norm_plane plane1(4:9)];%set medial border distance

    Lknee_pt = data.marker_data.Markers.LFEO(i_frame,:);
    d1 = distancePointPlane(Lknee_pt, plane1);
    d2 = distancePointPlane(Lknee_pt, plane2);
    if d1*d2>0
        LKOT(i_attempt) = LKOT(i_attempt) + 1;
        LKOT_max(i_attempt) = max(LKOT_max(i_attempt),((d1+d2)/2));% medial
displacement
        LKOT_min(i_attempt) = min(LKOT_min(i_attempt),((d1+d2)/2));% lateral
displacement
    end

 end

%  (6,7,8,9) Left and Right dowel position relative to the anterior and posterior
border of the foot

%  (Dowel aligned over feet) - LEFT
%find lowest z point FIN(person at the lowest)
[~,LFIN_z_min_index(i_attempt)] =
min(data.marker_data.Markers.LFIN(start_attempt:stop_attempt,3));
% maximum point of FIN between start attempt and perosn at lowest as above
[~,LFIN_z_start_index(i_attempt)] =
max(data.marker_data.Markers.LFIN(start_attempt:start_attempt+LFIN_z_min_index(i_
attempt),3));
LFIN_y_start(i_attempt) =
data.marker_data.Markers.LFIN(start_attempt+LFIN_z_start_index(i_attempt),2);

[~,RFIN_z_min_index(i_attempt)] =
min(data.marker_data.Markers.RFIN(start_attempt:stop_attempt,3));
[~,RFIN_z_start_index(i_attempt)] =
max(data.marker_data.Markers.RFIN(start_attempt:start_attempt+RFIN_z_min_index(i_
attempt),3));
RFIN_y_start(i_attempt) = data.marker_data.Markers.RFIN(start_attempt,2);

%total displacement
LFIN_finish(i_attempt) =
abs(min(data.marker_data.Markers.LFIN(start_attempt:stop_attempt,2))-
LFIN_y_start(i_attempt));
RFIN_finish(i_attempt) =
abs(min(data.marker_data.Markers.RFIN(start_attempt:stop_attempt,2))-
RFIN_y_start(i_attempt));

LTOE_y_start(i_attempt) = (LTOE(start_attempt,2))-40;
LHEE_y_start(i_attempt) = (LHEE(start_attempt,2));
LFIN_y = data.marker_data.Markers.LFIN(start_attempt:stop_attempt,2);
```

```
LFIN_y_min(i_attempt) =
min(data.marker_data.Markers.LFIN(start_attempt:stop_attempt,2));
LFIN_y_max(i_attempt) =
max(data.marker_data.Markers.LFIN(start_attempt:stop_attempt,2));

L_toe_bar_flag(i_attempt) = sum(LFIN_y < LTOE_y_start(i_attempt));
L_heel_bar_flag(i_attempt)  = sum(LFIN_y > LHEE_y_start(i_attempt));

if L_toe_bar_flag(i_attempt)>0;
   LFIN_fin_dist_toe(i_attempt) = abs(LFIN_y_min(i_attempt)-
LTOE_y_start(i_attempt));
end

if L_heel_bar_flag(i_attempt)>0
   LFIN_fin_dist_heel(i_attempt)= abs(LFIN_y_max(i_attempt)-
LHEE_y_start(i_attempt));
end

% (Dowel aligned over feet) - Right
RTOE_y_start(i_attempt) = (RTOE(start_attempt,2))-40;
RHEE_y_start(i_attempt) = (RHEE(start_attempt,2));
RFIN_y = data.marker_data.Markers.RFIN(start_attempt:stop_attempt,2);
RFIN_y_min(i_attempt) =
min(data.marker_data.Markers.RFIN(start_attempt:stop_attempt,2));
RFIN_y_max(i_attempt) =
max(data.marker_data.Markers.RFIN(start_attempt:stop_attempt,2));

R_toe_bar_flag(i_attempt) = sum(RFIN_y < RTOE_y_start(i_attempt));
R_heel_bar_flag(i_attempt)  = sum(RFIN_y > RHEE_y_start(i_attempt));

if R_toe_bar_flag(i_attempt)>0;
   RFIN_fin_dist_toe(i_attempt) = abs(RFIN_y_min(i_attempt)-
RTOE_y_start(i_attempt));
end

if R_heel_bar_flag(i_attempt)>0
   RFIN_fin_dist_heel(i_attempt)= abs(RFIN_y_max(i_attempt)-
RHEE_y_start(i_attempt));
end

% (10+11) Left heel raise relative to starting position
   % find maximum difference from start for RHEE
    R_diff_heel = data.marker_data.Markers.RHEE(start_attempt:stop_attempt,3)-
RHEE_start ;
    R_diff_heel_flag(i_attempt) = sum(R_diff_heel>Heel_Raise_threshold);
    R_heel_diff_max(i_attempt) =
max(data.marker_data.Markers.RHEE(start_attempt:stop_attempt,3))- RHEE_start;

    L_diff_heel = data.marker_data.Markers.LHEE(start_attempt:stop_attempt,3)-
LHEE_start ;
    L_diff_heel_flag(i_attempt) = sum(L_diff_heel>Heel_Raise_threshold);
    L_heel_diff_max(i_attempt) =
max(data.marker_data.Markers.LHEE(start_attempt:stop_attempt,3))- LHEE_start;
end
```

Save function rules met/not met Flag condition numbers

```
var_names = {'Tx_vs_tib_flag',...  % Rule 1.
'Lmax_knee_flag'...                % 2.
'Rmax_knee_flag'...                % 3.
'LKOT'...    % 4.
'RKOT'...    % 5.
'L_toe_bar_flag','L_heel_bar_flag'... % 6. + 7
'R_toe_bar_flag','R_heel_bar_flag'... % 8. + 9
'L_diff_heel_flag'...     % 10.
'R_diff_heel_flag'};      % 11.
```

Output data

output.var_names = var_names; for i_var=1:length(var_names) output.(var_names{i_var}) = eval(var_names{i_var}); end

Can be used for the Deep Squat heel raise test

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APPENDIX XX - Matlab script for Hurdle Step tests

MATLAB routine for Hurdle Step tests

```
function output = Hurdle_step_left(filename)
% load data
data = btk_loadc3d(filename);

% find event markers - associatted user defined lables with data
angle_freq = data.marker_data.AngleInfo.frequency; % sampling frequency
events = data.events_data.Data.Right_Foot_Strike;
target = data.events_data.Data.Left_Foot_Off;

% Set thresholds
movement_threshold_angle = 10;
movement_threshold_dist = 5;

%Label markers
RHEE_start = data.marker_data.Markers.RHEE(1,3);
LHEE_start = data.marker_data.Markers.LHEE(1,3);
```

Initialize output vectors - allocates holding space

```
indices_target = zeros(length(events)-1,1);
local_index_target =zeros(length(events)-1,1);
Tx_incl_start = zeros(length(events)-1,1);
Tx_incl_diff = zeros(length(events)-1,1);
Tx_incl_flag = zeros(length(events)-1,1);
LKOT = zeros(length(events)-1,1);
RKOT = zeros(length(events)-1,1);
AB_AC= zeros(length(events)-1,1);
LKOT_flag = cell(length(events)-1,1);
RKOT_flag = cell(length(events)-1,1);
Fin_z_flag = zeros(length(events)-1,1);
% Tx ROM - movement flags
LTx_sf_start = zeros(length(events)-1,1);
LTx_rot_start = zeros(length(events)-1,1);
RTx_sf_start =  zeros(length(events)-1,1);
RTx_rot_start = zeros(length(events)-1,1);
LTx_sf_flag = zeros(length(events)-1,1);
LTx_rot_flag= zeros(length(events)-1,1);
RTx_sf_flag = zeros(length(events)-1,1);
RTx_rot_flag= zeros(length(events)-1,1);
% Lx ROM - movement flags
Lx_flex_start = zeros(length(events)-1,1);
RLx_sf_start = zeros(length(events)-1,1);
RLx_rot_start = zeros(length(events)-1,1);
LLx_sf_start= zeros(length(events)-1,1);
LLx_rot_start = zeros(length(events)-1,1);
Lx_flex_diff_flag = zeros(length(events)-1,1);
RLx_sf_diff_flag= zeros(length(events)-1,1);
RLx_rot_diff_flag =zeros(length(events)-1,1);
attempt_frames = zeros(length(events)-1,1);
R_max_heel_to_target= zeros(length(events)-1,1);
% Heels
R_max_heel_from_target= zeros(length(events)-1,1);
L_max_heel_to_target= zeros(length(events)-1,1);
L_max_heel_from_target= zeros(length(events)-1,1);

for i_attempt = 1:length(events)-1
    start_attempt = round(events(i_attempt)*angle_freq+1)-
data.marker_data.First_Frame+1;
    stop_attempt = round(events(i_attempt+1)*angle_freq)-
data.marker_data.First_Frame+1;
    target_attempt = round(target(i_attempt)*angle_freq)-
data.marker_data.First_Frame+1;
    attempt_frames(i_attempt) = (stop_attempt-start_attempt)+1;
```

```
% Indices - At target -  at palcement of heel on floor
indices_target(i_attempt) = round(target(i_attempt)*angle_freq)-
data.marker_data.First_Frame+1;
local_index_target(i_attempt) = indices_target(i_attempt)-start_attempt+1;

% FLAG ARGUMENTS
% Flag conditions 1. + 2.
% Same as the deep squat heel raise/no heel raise KOT
%     1. Hips, knees and ankles remained aligned in the saggital plane
%     Medial border movement is -ve
 for i_frame = start_attempt:stop_attempt
    point1 = data.marker_data.Markers.RHEE(i_frame,:);
    point2 = data.marker_data.Markers.RTOE(i_frame,:);
    point3 = [point1(1)  point1(2) point1(3)+1];
    plane1 = createPlane(point1, point2, point3);
    plane2 = [data.marker_data.Markers.RANK(i_frame,:) plane1(4:9)];
    norm_plane = cross(plane1(4:6),plane1(7:9));
    plane1 = [plane1(1:3)-50*norm_plane plane1(4:9)];%set medial border distance
    Rknee_pt = data.marker_data.Markers.RFEO(i_frame,:);
    d1 = distancePointPlane(Rknee_pt, plane1);
    d2 = distancePointPlane(Rknee_pt, plane2);
    if d1*d2>0
        RKOT(i_attempt) = RKOT(i_attempt) + 1;
    end

%     Medial border movement is +ve
    point1 = data.marker_data.Markers.LHEE(i_frame,:);
    point2 = data.marker_data.Markers.LTOE(i_frame,:);
    point3 = [point1(1)  point1(2) point1(3)+1];
    plane1 = createPlane(point1, point2, point3);
    plane2 = [data.marker_data.Markers.LANK(i_frame,:) plane1(4:9)];
    norm_plane = cross(plane1(4:6),plane1(7:9));
    plane1 = [plane1(1:3)+50*norm_plane plane1(4:9)];%set medial border distance

    Lknee_pt = data.marker_data.Markers.LFEO(i_frame,:);
    d1 = distancePointPlane(Lknee_pt, plane1);
    d2 = distancePointPlane(Lknee_pt, plane2);
    if d1*d2>0
        LKOT(i_attempt) = LKOT(i_attempt) + 1;
    end

 end
    if RKOT(i_attempt)>= 1;
           disp ('Alignement Lost Right');
           RKOT_flag{i_attempt} = 'Alignment Lost Right';
     else  disp('Alignement Maintained Right');
           RKOT_flag{i_attempt} = ('Alignement Maintained Right');
    end
    if LKOT(i_attempt)>= 1;
           disp ('Alignement Lost Left');
           LKOT_flag{i_attempt} = 'Alignement Lost Left';
     else   disp('Alignement Maintained Left');
         LKOT_flag{i_attempt} = 'Alignement Maintained Left';
    end

% 3. 4. 5. Minimal to no movement in the Lumbar spine - > degrees 10
% Find starting angles for all three planes
Lx_flex_start(i_attempt) =
(data.marker_data.Angles.RSpineAngles(start_attempt,1));
LLx_sf_start(i_attempt) =
(data.marker_data.Angles.LSpineAngles(start_attempt,2));
LLx_rot_start(i_attempt) =
(data.marker_data.Angles.LSpineAngles(start_attempt,3));
RLx_sf_start(i_attempt) =
(data.marker_data.Angles.RSpineAngles(start_attempt,2));
```

```
RLx_rot_start(i_attempt) =
(data.marker_data.Angles.RSpineAngles(start_attempt,3));

% Find difference from start and check flag
Lx_flex_diff =
data.marker_data.Angles.RSpineAngles(start_attempt:stop_attempt,1)-
Lx_flex_start(i_attempt);
Lx_flex_diff_flag(i_attempt) = sum(abs(Lx_flex_diff) > movement_threshold_angle);
RLx_sf_diff = data.marker_data.Angles.RSpineAngles(start_attempt:stop_attempt,2)-
RLx_sf_start(i_attempt);
RLx_sf_diff_flag(i_attempt) = sum(abs(RLx_sf_diff) > movement_threshold_angle);
RLx_rot_diff =
data.marker_data.Angles.RSpineAngles(start_attempt:stop_attempt,3)-
RLx_rot_start(i_attempt);
RLx_rot_diff_flag(i_attempt) = sum(abs(RLx_rot_diff) > movement_threshold_angle);

% 6.7.8. Minimal to no movement in Tx Spine
Tx_incl_start(i_attempt) =
data.marker_data.Angles.RThoraxAngles(start_attempt,1);
RTx_sf_start(i_attempt) =
data.marker_data.Angles.RThoraxAngles(start_attempt,2);
RTx_rot_start(i_attempt) =
data.marker_data.Angles.RThoraxAngles(start_attempt,3);

Tx_incl_diff =
data.marker_data.Angles.RThoraxAngles(start_attempt:stop_attempt,1)-
Tx_incl_start(i_attempt);
Tx_incl_flag(i_attempt) = sum(abs(Tx_incl_diff) > movement_threshold_angle);

RTx_sf_diff =
data.marker_data.Angles.RThoraxAngles(start_attempt:stop_attempt,2)-
RTx_sf_start(i_attempt);
RTx_sf_flag(i_attempt)= sum(abs(RTx_sf_diff)> movement_threshold_angle);
RTx_rot_diff =
data.marker_data.Angles.RThoraxAngles(start_attempt:stop_attempt,3)-
RTx_rot_start(i_attempt);
RTx_rot_flag(i_attempt)= sum(abs(RTx_rot_diff)> movement_threshold_angle);

% 9. Dowel position remains parallel to the horizontal axis
% Find the angle between the left and right hand with the horizontal axis
for i_frame = start_attempt:stop_attempt
 pointa = data.marker_data.Markers.LFIN(i_frame,:);
 pointb = data.marker_data.Markers.RFIN(i_frame,:);
 pointc = [pointb(1)  pointb(2) pointa(3)];
 AB = pointa - pointb;
 AC = pointa - pointc;

len_AB = sqrt(sum(AB.^2));
len_AC = sqrt(sum(AC.^2));
AB_AC(i_frame) = acosd(len_AC/len_AB);
end
% Flag
Fin_z_flag(i_attempt) = sum(AB_AC > movement_threshold_angle);

% 10. Assessor visually assess Loss of balance

% 11. 12. If contact between foot and hurdle occurs
L_max_heel_to_target(i_attempt) =
max(data.marker_data.Markers.LHEE(start_attempt:target_attempt,3));
L_max_heel_from_target(i_attempt) =
max(data.marker_data.Markers.LHEE(target_attempt:stop_attempt,3));

end
```

Save function

```
var_names = {'LKOT','RKOT'... %rules 1-6
```

```
'Lx_flex_diff_flag',...%7
'RLx_rot_diff_flag','RLx_sf_diff_flag',...%7
'Tx_incl_flag'...%8
'RTx_rot_flag','RTx_sf_flag',...%8
'Fin_z_flag',... %9
'L_max_heel_to_target','L_max_heel_from_target'}; %10+11
```

Output data

```
output.var_names = var_names;
for i_var=1:length(var_names);
    output.(var_names{i_var}) = eval(var_names{i_var});
end
```

Can be used for Hurdle Step Right test – need to swap Left and Right

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APPENDIX XXI - Matlab script for Inline Lunge tests

MATLAB routine for Inline Lunge tests

```
function output = Inline_lunge_left(filename)
```

load data

```
data = btk_loadc3d(filename);
% Set thresholds
Heel_Raise_threshold = 5;
movement_threshold_angle = 10;
movement_threshold_angle_d = 20;
KJC_HEE_dist = 100;

% find event markers - associatted user defined lables with data
angle_freq = data.marker_data.AngleInfo.frequency; % sampling frequency
events = data.events_data.Data.Right_Foot_Strike;

% Label markers
RKJC = data.marker_data.Markers.RFEO;
LHEE = data.marker_data.Markers.LHEE;
KJC_HEE_diff = sqrt(sum((RKJC-LHEE).^2,2));
RHEE_start = data.marker_data.Markers.RHEE(1,3);
LHEE_start = data.marker_data.Markers.LHEE(1,3);
LAJC_start = data.marker_data.Markers.LTIO(1,3)+0.5;
```

Initialise output vectors - allocates holding space

```
indices = zeros(length(events)-1,1);
local_indices = zeros(length(events)-1,1);
% Flags
Cx_flex_start = zeros(length(events)-1,1);
Cx_flex_flag = zeros(length(events)-1,1);
Fin_y_flag = zeros (length(events)-1,1);
AB_AC= zeros(length(events)-1,1);
Fin_x_start = zeros(length(events)-1,1);
Tx_incl_start = zeros(length(events)-1,1);
Tx_incl_diff = zeros(length(events)-1,1);
Tx_incl_flag = zeros(length(events)-1,1);
RTx_sf_start =  zeros(length(events)-1,1);
RTx_rot_start = zeros(length(events)-1,1);
RTx_sf_flag = zeros(length(events)-1,1);
RTx_rot_flag= zeros(length(events)-1,1);
Fin_x_flag = zeros(length(events)-1,1);
RKOT = zeros(length(events)-1,1);
LKOT = zeros(length(events)-1,1);
LKOT_at_target = zeros(length(events)-1,1);
RKOT_at_target = zeros(length(events)-1,1);
min_KJC_HEE_diff =  zeros(length(events)-1,1);
KJC_HEE_diff_flag = zeros(length(events)-1,1);
Knee_board_flag = zeros(length(events)-1,1);
L_diff_heel_flag = zeros (length(events)-1,1);

for i_attempt = 1:length(events)-1
    start_attempt = round(events(i_attempt)*angle_freq+1)-
data.marker_data.First_Frame+1;
    stop_attempt = round(events(i_attempt+1)*angle_freq)-
data.marker_data.First_Frame+1;
%  Index is determined step 5

% 1. Neck flex - also satisfied by rule 3.
Cx_flex_start(i_attempt) = data.marker_data.Angles.LNeckAngles(start_attempt,1);
Cx_flex_diff = data.marker_data.Angles.LNeckAngles(start_attempt:stop_attempt,1)-
Cx_flex_start(i_attempt);
Cx_flex_flag(i_attempt) = sum(abs(Cx_flex_diff) > movement_threshold_angle);
```

```
% 2.  Dowel remains vertical - reference to origin
for i_frame = start_attempt:stop_attempt
 pointa = data.marker_data.Markers.LFIN(i_frame,:);
 pointb = data.marker_data.Markers.RFIN(i_frame,:);
 AB = pointa - pointb;
len_AB = sqrt(sum(AB.^2));

AB_AC(i_frame) = acosd(dot(AB/len_AB,[0,0,-1]));
end
% Flag
Fin_y_flag(i_attempt) = sum(AB_AC > movement_threshold_angle_d);

% 3. dowel changes more than 10 degrees froms start
Fin_x_start(i_attempt) = AB_AC(start_attempt);
Fin_x_flag(i_attempt) = sum(Fin_x_start(i_attempt > movement_threshold_angle));

% 4. 5. 6. Minimal to no movement in Tx Spine  - all directions
Tx_incl_start(i_attempt) =
data.marker_data.Angles.RThoraxAngles(start_attempt,1);
RTx_sf_start(i_attempt) =
data.marker_data.Angles.RThoraxAngles(start_attempt,2);
RTx_rot_start(i_attempt) =
data.marker_data.Angles.RThoraxAngles(start_attempt,3);

Tx_incl_diff =
data.marker_data.Angles.RThoraxAngles(start_attempt:stop_attempt,1)-
Tx_incl_start(i_attempt);
Tx_incl_flag(i_attempt) = sum(abs(Tx_incl_diff) > movement_threshold_angle);

RTx_sf_diff =
data.marker_data.Angles.RThoraxAngles(start_attempt:stop_attempt,2)-
RTx_sf_start(i_attempt);
RTx_sf_flag(i_attempt)= sum(abs(RTx_sf_diff)> movement_threshold_angle);
RTx_rot_diff =
data.marker_data.Angles.RThoraxAngles(start_attempt:stop_attempt,3)-
RTx_rot_start(i_attempt);
RTx_rot_flag(i_attempt)= sum(abs(RTx_rot_diff)> movement_threshold_angle);

% 7. 9. 10 - Same as deep squat KOT
%  Hips, knees and ankles remained aligned in the saggital plane
 for i_frame = start_attempt:stop_attempt
%     Medial border movement is +ve
    point1 = data.marker_data.Markers.LHEE(i_frame,:);
    point2 = data.marker_data.Markers.LTOE(i_frame,:);
    point3 = [point1(1)  point1(2) point1(3)+1];
    plane1 = createPlane(point1, point2, point3);
    plane2 = [data.marker_data.Markers.LANK(i_frame,:) plane1(4:9)];
    norm_plane = cross(plane1(4:6),plane1(7:9));
    plane1 = [plane1(1:3)+50*norm_plane plane1(4:9)];%set medial border distance

    Lknee_pt = data.marker_data.Markers.LFEO(i_frame,:);
    d1 = distancePointPlane(Lknee_pt, plane1);
    d2 = distancePointPlane(Lknee_pt, plane2);
    if d1*d2>0
        LKOT(i_attempt) = LKOT(i_attempt) + 1;
    end

%      Medial border movement is -ve
    point1 = data.marker_data.Markers.LHEE(i_frame,:);
    point2 = data.marker_data.Markers.LTOE(i_frame,:);
    point3 = [point1(1)  point1(2) point1(3)+1];
    plane1 = createPlane(point1, point2, point3);
    plane2 = [data.marker_data.Markers.LANK(i_frame,:) plane1(4:9)];
    norm_plane = cross(plane1(4:6),plane1(7:9));
    plane1 = [plane1(1:3)+50*norm_plane plane1(4:9)];%set medial border distance

    Rknee_pt = data.marker_data.Markers.RFEO(i_frame,:);
```

```
    d1 = distancePointPlane(Rknee_pt, plane1);
    d2 = distancePointPlane(Rknee_pt, plane2);
    if d1*d2>0
        RKOT(i_attempt) = RKOT(i_attempt) + 1;

    end
 end

% .8 10.  Determine index
[min_KJC_HEE_diff(i_attempt),index_min_KJC_HEE_diff(i_attempt)] =
min(KJC_HEE_diff(start_attempt:stop_attempt));
indices_min_KJC_HEE_diff(i_attempt) =
start_attempt+index_min_KJC_HEE_diff(i_attempt)-1;
% Also for 11. minimial distance flag
KJC_HEE_diff_flag(i_attempt) = sum(min_KJC_HEE_diff(i_attempt) > KJC_HEE_dist);

% 8. 10. - at target - Same as deep squat KOT

i_frame = indices_min_KJC_HEE_diff(i_attempt);
    point1 = data.marker_data.Markers.LHEE(i_frame,:);
    point2 = data.marker_data.Markers.LTOE(i_frame,:);
    point3 = [point1(1)  point1(2) point1(3)+1];
    plane1 = createPlane(point1, point2, point3);
    plane2 = [data.marker_data.Markers.LANK(i_frame,:) plane1(4:9)];
    norm_plane = cross(plane1(4:6),plane1(7:9));
    plane1 = [plane1(1:3)+50*norm_plane plane1(4:9)];%set medial border distance

    Lknee_pt = data.marker_data.Markers.LFEO(i_frame,:);
    d1 = distancePointPlane(Lknee_pt, plane1);
    d2 = distancePointPlane(Lknee_pt, plane2);
    if d1*d2>0
        LKOT_at_target(i_attempt) = 1;
    end

%      Medial border movement is -ve
    point1 = data.marker_data.Markers.LHEE(i_frame,:);
    point2 = data.marker_data.Markers.LTOE(i_frame,:);
    point3 = [point1(1)  point1(2) point1(3)+1];
    plane1 = createPlane(point1, point2, point3);
    plane2 = [data.marker_data.Markers.LANK(i_frame,:) plane1(4:9)];
    norm_plane = cross(plane1(4:6),plane1(7:9));
    plane1 = [plane1(1:3)+50*norm_plane plane1(4:9)];%set medial border distance

    Rknee_pt = data.marker_data.Markers.RFEO(i_frame,:);
    d1 = distancePointPlane(Rknee_pt, plane1);
    d2 = distancePointPlane(Rknee_pt, plane2);
    if d1*d2>0
        RKOT_at_target(i_attempt) = 1;

    end

%    12.
Knee_board_flag(i_attempt) = min(RKJC(start_attempt:stop_attempt,3)) >
LAJC_start;

% 13. Argument for Heel lift - Forward leg
   % find maximum difference from start for LHEE
    L_diff_heel = data.marker_data.Markers.LHEE(start_attempt:stop_attempt,3)-
LHEE_start ;
    L_diff_heel_flag(i_attempt) = sum(L_diff_heel>Heel_Raise_threshold);

end
```

Save function

```
var_names = {'Cx_flex_flag'... %1
'Fin_x_flag','Fin_y_flag'... %2 + 3
```

```
'Tx_incl_flag'...%4
'RTx_rot_flag','RTx_sf_flag'...%5 + 6
'LKOT',...%7
'LKOT_at_target'...%8
'RKOT',...%9
'RKOT_at_target'...%10
'KJC_HEE_diff_flag'...%11
'Knee_board_flag'...%12
'L_diff_heel_flag'};...%13
%14 - Loss of balance assessed visually
```

Output data

```
output.var_names = var_names;
for i_var=1:length(var_names)
    output.(var_names{i_var}) = eval(var_names{i_var});
end
```

Can also be used for Right – need to change leading foot values KOT

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APPENDIX XXII - Matlab script for Shoulder Mobility tests

MATLAB routine for Shoulder Mobility

```
function output = Shoulder_mobility_left(filename)
```

Load data

```
data = btk_loadc3d(filename);
% Labelling
angle_freq = data.marker_data.AngleInfo.frequency; % sampling frequency
events = data.events_data.Data.Right_Foot_Strike;
LFin = data.marker_data.Markers.LFIN;
RFin = data.marker_data.Markers.RFIN;
hand_diff = sqrt(sum((LFin-RFin).^2,2));

LFIN_m = data.marker_data.Markers.LFIN(:,1); %chose x as its sideways best for
this
LFIN_mvel = (size(LFIN_m));
RFIN_m = data.marker_data.Markers.RFIN(:,1);
RFIN_mvel = (size(RFIN_m));
```

Initialize output vectors

```
min_hands = zeros(length(events)-1,1);
indices_min_hands = zeros(length(events)-1,1);
index_min_hands = zeros(length(events)-1,1);

for i_attempt = 1:length(events)-1;
   start_attempt = round(events(i_attempt)*angle_freq+1)-
data.marker_data.First_Frame+1;
   stop_attempt = round(events(i_attempt+1)*angle_freq)-
data.marker_data.First_Frame+1;

%    find Minimal distance between finger markers
    [min_hands(i_attempt),index_min_hands(i_attempt)] =
min(hand_diff(start_attempt:stop_attempt));
    indices_min_hands(i_attempt) = start_attempt+index_min_hands(i_attempt)-1;

% Finger Velocity
for i_frame = 3:size(LFIN_m,1)-2
    LFIN_mvel(i_frame) = (LFIN_m(i_frame-2)-8*LFIN_m(i_frame-
1)+8*LFIN_m(i_frame+1)-LFIN_m(i_frame+2))/(12*(1/100));
    RFIN_mvel(i_frame) = (RFIN_m(i_frame-2)-8*RFIN_m(i_frame-
1)+8*RFIN_m(i_frame+1)-RFIN_m(i_frame+2))/(12*(1/100));
end

end

start_attempt = round(events(1)*angle_freq+1)-data.marker_data.First_Frame+1;
attempt_index1 = round(events(2)*angle_freq+1)-data.marker_data.First_Frame+1;
attempt_index2 = round(events(3)*angle_freq+1)-data.marker_data.First_Frame+1;
% Used to analyse smooth movements 1. 2.
figure
subplot (2,1,1)
plot(LFIN_mvel(start_attempt:end),'b');hold on;
ylim([-2000 2000])
xlabel ('frames');
ylabel(' angular velocity');
plot(attempt_index1-start_attempt+1,LFIN_mvel(attempt_index1),'r+');
plot(attempt_index2-start_attempt+1,LFIN_mvel(attempt_index2),'r+');
title('Left Hand');
subplot (2,1,2)
plot (RFIN_mvel(start_attempt:end),'b');hold on;
ylim([-2000 2000])
xlabel ('frames');
ylabel(' angular velocity');
```

```
plot(attempt_index1-start_attempt+1,RFIN_mvel(attempt_index1),'r+');
plot(attempt_index2-start_attempt+1,RFIN_mvel(attempt_index2),'r+');
title('Right Hand');
```

Save function

```
var_names = {'min_hands'}; %3
```

Output data

```
output.var_names = var_names;
for i_var=1:length(var_names)
    output.(var_names{i_var}) = eval(var_names{i_var});
end
```

Can be used for Right Shoulder Mobility test – need to swap leading arm
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APPENDIX XXIII - Matlab script for Active Straight-Leg Raise tests

MATLAB routine for Active Straight-Leg Raise

```
function output = Active_straight_leg_raise_left_1(filename)
```

load data

```
data = btk_loadc3d(filename);
%Label markers
LASI = data.marker_data.Markers.LASI;
LKNE = data.marker_data.Markers.LKNE;
LMID_THI = ((LASI+LKNE)/2);

% find event markers - associatted user defined lables with data
angle_freq = data.marker_data.AngleInfo.frequency; % sampling frequency
events = data.events_data.Data.Right_Foot_Strike;
```

Initialize outputs - allocates holding space

```
max_Lhip = zeros(length(events)-1,1);
indices = zeros(length(events)-1,1);
Lknee_x_start= zeros(length(events)-1,1);
Lknee_x_flag= zeros(length(events)-1,1);
indices_max_Lhip= zeros(length(events)-1,1);
LHEE_at_max_Lhip= zeros(length(events)-1,1);
LMID_THI_y_start= zeros(length(events)-1,1);
LKNE_y_start= zeros(length(events)-1,1);
LHEE_flag= zeros(length(events)-1,1);
Rhip_x_start= zeros(length(events)-1,1);
Rhip_x_flag= zeros(length(events)-1,1);
Rhip_y_start= zeros(length(events)-1,1);
Rhip_y_flag= zeros(length(events)-1,1);
Rhip_z_start= zeros(length(events)-1,1);
Rhip_z_flag= zeros(length(events)-1,1);
Rknee_x_start= zeros(length(events)-1,1);
Rknee_x_flag= zeros(length(events)-1,1);
Rankle_x_start= zeros(length(events)-1,1);
Rankle_x_flag= zeros(length(events)-1,1);
LFoot_y_flag= zeros(length(events)-1,1);
RFoot_y_flag= zeros(length(events)-1,1);

% for each attempt...
for i_attempt = 1:length(events)-1
    start_attempt = round(events(i_attempt)*angle_freq+1)-
data.marker_data.First_Frame+1;
    stop_attempt = round(events(i_attempt+1)*angle_freq)-
data.marker_data.First_Frame+1;

    % find maximum right hip angle for indexing
    [max_Lhip(i_attempt),
index_max_Lhip]=max(data.marker_data.Angles.LHipAngles(start_attempt:stop_attempt
,1));
    indices_max_Lhip(i_attempt) = start_attempt+index_max_Lhip-1;

    %11. Calculate scoring variable
    LHEE_at_max_Lhip(i_attempt) =
data.marker_data.Markers.LANK(indices_max_Lhip(i_attempt),2);
    LMID_THI_y_start(i_attempt) = LMID_THI(start_attempt,2);
    LKNE_y_start(i_attempt) = data.marker_data.Markers.LKNE(start_attempt,2);

    if (LHEE_at_max_Lhip(i_attempt) >  LMID_THI_y_start(i_attempt)) &&
(LHEE_at_max_Lhip(i_attempt) > LKNE_y_start(i_attempt));
        LHEE_flag(i_attempt) = 3;
    elseif LHEE_at_max_Lhip(i_attempt)> LKNE_y_start(i_attempt)
        LHEE_flag(i_attempt) = 2;
    else
```

```
        LHEE_flag(i_attempt) = 1;
    end

% 1.     Moving limb knee flexion angle
Lknee_x_diff =
data.marker_data.Angles.RKneeAngles(start_attempt:indices_max_Lhip(i_attempt),1)-
Lknee_x_start(i_attempt);
Lknee_x_flag(i_attempt) = sum(abs(Lknee_x_diff) > movement_threshold_angle);
% 2.     Moving limb ankle plantarflexion angle
Lankle_x_start(i_attempt) =
(data.marker_data.Angles.LAnkleAngles(start_attempt,1));
Lankle_x_diff =
data.marker_data.Angles.LAnkleAngles(start_attempt:stop_attempt,1)-
Lankle_x_start(i_attempt);
Lankle_x_flag(i_attempt) = sum(abs(Lankle_x_diff) > movement_threshold_angle);

% 3.     Static limb hip flexion angle
Rhip_x_start(i_attempt) = (data.marker_data.Angles.RHipAngles(start_attempt,1));
Rhip_x_diff = data.marker_data.Angles.RHipAngles(start_attempt:stop_attempt,1)-
Rhip_x_start(i_attempt);
Rhip_x_flag(i_attempt) = sum(abs(Rhip_x_diff) > movement_threshold_angle);
% 4.     Static limb hip abduction/adduction angle
Rhip_y_start(i_attempt) = (data.marker_data.Angles.RHipAngles(start_attempt,2));
Rhip_y_diff = data.marker_data.Angles.RHipAngles(start_attempt:stop_attempt,2)-
Rhip_y_start(i_attempt);
Rhip_y_flag(i_attempt) = sum(abs(Rhip_y_diff) > movement_threshold_angle);
% 5.     Static limb hip rotation angle plane
Rhip_z_start(i_attempt) = (data.marker_data.Angles.RHipAngles(start_attempt,3));
Rhip_z_diff = data.marker_data.Angles.RHipAngles(start_attempt:stop_attempt,3)-
Rhip_z_start(i_attempt);
Rhip_z_flag(i_attempt) = sum(abs(Rhip_z_diff) > movement_threshold_angle);
% 6. Static limb knee flexion angle
Rknee_x_start(i_attempt) =
(data.marker_data.Angles.RKneeAngles(start_attempt,1));
Rknee_x_diff = data.marker_data.Angles.RKneeAngles(start_attempt:stop_attempt,1)-
Rknee_x_start(i_attempt);
Rknee_x_flag(i_attempt) = sum(abs(Rknee_x_diff) > movement_threshold_angle);
% 7.     Static limb ankle plantarflexion angle
Rankle_x_start(i_attempt) =
(data.marker_data.Angles.RAnkleAngles(start_attempt,1));
Rankle_x_diff =
data.marker_data.Angles.RAnkleAngles(start_attempt:stop_attempt,1)-
Rankle_x_start(i_attempt);
Rankle_x_flag(i_attempt) = sum(abs(Rankle_x_diff) > movement_threshold_angle);

% 8.     Moving limb foot position relative to the horizontal axis
for i_frame = start_attempt:stop_attempt
 pointc = data.marker_data.Markers.RTOE(i_frame,:);
 pointd = data.marker_data.Markers.RTIO(i_frame,:);
 CD = pointd - pointc;
 len_CD = sqrt(sum(CD.^2));
CD_AC(i_frame) = acosd(dot(CD/len_CD,[0,0,-1]));
end
min_CD_AC(i_attempt) = min(CD_AC(start_attempt:start_attempt+100));
RFoot_y_flag(i_attempt) = min_CD_AC(i_attempt) > movement_threshold_angle_d;

% 9.     Static limb foot position relative to the horizontal axis
for i_frame = start_attempt:stop_attempt
 pointa = data.marker_data.Markers.LTOE(i_frame,:);
 pointb = data.marker_data.Markers.LTIO(i_frame,:);
 AB = pointb - pointa;
 len_AB = sqrt(sum(AB.^2));
AB_AC(i_frame) = acosd(dot(AB/len_AB,[0,0,-1]));
end
min_AB_AC(i_attempt) = min(AB_AC(start_attempt:start_attempt+100));
LFoot_y_flag(i_attempt) = min_AB_AC(i_attempt) > movement_threshold_angle_d;
```

```
end
```

Save function

```
var_names = {'Lknee_x_flag'...%1
'Lankle_x_flag'...%2
'Rhip_x_flag','Rhip_y_flag','Rhip_z_flag'...%3 4. 5.
'Rknee_x_flag'...%6
'Rankle_x_flag'...%7
'RFoot_y_flag'...%8
'LFoot_y_flag'...%9
'LHEE_flag'};%11
%10 Head remains on floor - assessed visually
```

Output data

```
output.var_names = var_names;
for i_var=1:length(var_names)
    output.(var_names{i_var}) = eval(var_names{i_var});
end
```

Can be used for right side – need to swap left and right for moving and static limbs

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APPENDIX XXIV - Matlab script for Trunk Stability Push-Up test

MATLAB routine for Trunk Stability Push-Up

```
function output = Trunk_stability_pushup(filename)

% load data
data = btk_loadc3d(filename);

% find event markers - associated user defined labels with data
angle_freq = data.marker_data.AngleInfo.frequency; % sampling frequency
events = data.events_data.Data.Right_Foot_Strike;
movement_threshold_angle_ext = -10;
movement_threshold_angle_tot = 10;
movement_threshold_dist = 5;
movement_threshold_angle_d = 10;
```

Initialize output vectors - allocates holding space

```
Lmin_elbow = zeros(length(events)-1,1);
Rmin_elbow = zeros(length(events)-1,1);
indices = zeros(length(events)-1,1);
local_indices = zeros(length(events)-1,1);
min_elbow_side = cell(3,1);

PELV = data.marker_data.Markers.RPSI(:,3);
PELV_vel = (size(PELV));
C7M = data.marker_data.Markers.C7(:,3);
C7M_vel = zeros(size(C7M));

% get required markers
RELB = data.marker_data.Markers.RELB;
LELB = data.marker_data.Markers.LELB;
LFIN = data.marker_data.Markers.LFIN;
RFIN = data.marker_data.Markers.RFIN;
```

Flag functions

```
RFIN_starty=zeros(length(events)-1,1);
RFIN_flag=zeros(length(events)-1,1);
LFIN_starty=zeros(length(events)-1,1);
LFIN_flag=zeros(length(events)-1,1);
% Feet
LFoot_y_flag=zeros(length(events)-1,1);
RFoot_y_flag=zeros(length(events)-1,1);
% Tx ROM - movement flags
Tx_incl_start = zeros(length(events)-1,1);
Tx_incl_flag = zeros(length(events)-1,1);
% Lx ROM - movement flags
Lx_flex_start = zeros(length(events)-1,1);
Lx_flex_diff_flag = zeros(length(events)-1,1);
% Hip
LHip_flex_start = zeros(length(events)-1,1);
LHip_flex_flag = zeros(length(events)-1,1);
RHip_flex_start = zeros(length(events)-1,1);
RHip_flex_flag = zeros(length(events)-1,1);
Rknee_start_flag= zeros(length(events)-1,1);
Lknee_start_flag= zeros(length(events)-1,1);
LKnee_flex_start = zeros(length(events)-1,1);
LKnee_flex_flag = zeros(length(events)-1,1);
RKnee_flex_start = zeros(length(events)-1,1);
RKnee_flex_flag = zeros(length(events)-1,1);
LELB_flag = zeros(length(events)-1,1);
RELB_flag =zeros(length(events)-1,1);
```

```
for i_attempt = 1:length(events)-1;
    start_attempt = round(events(i_attempt)*angle_freq+1)-
data.marker_data.First_Frame+1;
    stop_attempt = round(events(i_attempt+1)*angle_freq)-
data.marker_data.First_Frame+1;

% 1.+ 2.Hand  position remains unchanged throughout attempts
RFIN_starty(i_attempt) = RFIN(start_attempt,2);
RFINy_dist = RFIN_starty(i_attempt)- RFIN(start_attempt:stop_attempt,2);
RFIN_flag(i_attempt) = sum(abs(RFINy_dist > movement_threshold_dist));

LFIN_starty(i_attempt) = LFIN(start_attempt,2);
LFINy_dist = LFIN_starty(i_attempt)- LFIN(start_attempt:stop_attempt,2);
LFIN_flag(i_attempt) = sum(abs(LFINy_dist > movement_threshold_dist));

% 3.Thorax and pelvis start movement at the same time/ similar speed
% Find 1st derivative
for i_frame = 3:size(C7M,1)-2
    C7M_vel(i_frame) = (C7M(i_frame-2)-8*C7M(i_frame-1)+8*C7M(i_frame+1)-
C7M(i_frame+2))/(12*(1/100));
    PELV_vel(i_frame) = (PELV(i_frame-2)-8*PELV(i_frame-1)+8*PELV(i_frame+1)-
PELV(i_frame+2))/(12*(1/100));
end
% find max speed, 1/10 of max = start
C7M_vel_max(i_attempt) = max(C7M_vel(start_attempt:stop_attempt,1));
C7M_start_index(i_attempt) =
find(C7M_vel(start_attempt:stop_attempt,1)>C7M_vel_max(i_attempt)*(1/10),1,'first
');
C7M_start_indices(i_attempt) =start_attempt+C7M_start_index(i_attempt)-1;
C7M_start_local_indices(i_attempt) =  C7M_start_index(i_attempt);

% Plots the Velocity of thorax to pelvis for visual assessment
start_attempt = round(events(1)*angle_freq+1)-data.marker_data.First_Frame+1;

figure
plot(PELV_vel(start_attempt:end),'r');hold on;
plot(C7M_vel(start_attempt:end),'b');hold on;
xlabel ('frames');
ylabel ('angular velocity');
ylim([-2000 2000]);
legend ('Pelvis','C7');
plot(C7M_start_indices-start_attempt+1,C7M_vel(C7M_start_indices),'ks');
plot(C7M_start_indices-start_attempt+1-25,C7M_vel(C7M_start_indices-25),'ko');
plot(C7M_start_indices-start_attempt+1+25,C7M_vel(C7M_start_indices+25),'ko');

% 4. No lag in Lx spine
Lx_flex_start(i_attempt) = data.marker_data.Angles.RSpineAngles(start_attempt,1);
Lx_flex_diff =
data.marker_data.Angles.RSpineAngles(start_attempt:indices(i_attempt),1)-
Lx_flex_start(i_attempt);
Lx_flex_diff_flag(i_attempt) = max(Lx_flex_diff < movement_threshold_angle_ext);
% find min elbow angle (max press)
% Calculating elbow angle
% Need to do vector from the wrist joint center to the elbow and the elbow marker
to the acromion marker, elbow joint centre
LWJC_ELB = (data.marker_data.Markers.LRAO-data.marker_data.Markers.LELB);
LELB_GHJ = (data.marker_data.Markers.LELB-data.marker_data.Markers.LHUP);
% dot(A,B) = |A|*|B|*cos(angle between A,B)
len_LWJC_ELB =
sqrt(LWJC_ELB(start_attempt:stop_attempt,1).^2+LWJC_ELB(start_attempt:stop_attemp
t,2).^2+LWJC_ELB(start_attempt:stop_attempt,3).^2);
len_LELB_GHJ =
sqrt(LELB_GHJ(start_attempt:stop_attempt,1).^2+LELB_GHJ(start_attempt:stop_attemp
t,2).^2+LELB_GHJ(start_attempt:stop_attempt,3).^2);
LELB_angle =
acosd(dot(LWJC_ELB(start_attempt:stop_attempt,:)./repmat(len_LWJC_ELB,1,3),LELB_G
HJ(start_attempt:stop_attempt,:)./repmat(len_LELB_GHJ,1,3),2));
```

```
% 5. + 6.knee starts in extended position
% Find start position - compare against flag
Lknee_start_angle =
data.marker_data.Angles.LKneeAngles(start_attempt:start_attempt+100,1);
Lknee_min_angle(i_attempt) = min(Lknee_start_angle);
Lknee_start_flag(i_attempt) = Lknee_min_angle(i_attempt) > 10;

Rknee_start_angle =
data.marker_data.Angles.RKneeAngles(start_attempt:start_attempt+100,1);
Rknee_min_angle(i_attempt) = min(Rknee_start_angle);
Rknee_start_flag(i_attempt) = Rknee_min_angle(i_attempt) > 10;

%7. 8. Foot position relative to the horizontal axis
% Identify foot
for i_frame = start_attempt:stop_attempt
 pointa = data.marker_data.Markers.LTOE(i_frame,:);
 pointb = data.marker_data.Markers.LTIO(i_frame,:);
 AB = pointa - pointb;
 len_AB = sqrt(sum(AB.^2));
 %angle relative to horizontal axis
 AB_AC(i_frame) = acosd(dot(AB/len_AB,[0,0,-1]));
end

min_AB_AC(i_attempt) = min(AB_AC(start_attempt:start_attempt+100));
LFoot_y_flag(i_attempt) = min_AB_AC(i_attempt) > movement_threshold_angle_d;

for i_frame = start_attempt:stop_attempt
 pointc = data.marker_data.Markers.RTOE(i_frame,:);
 pointd = data.marker_data.Markers.RTIO(i_frame,:);
 CD = pointc - pointd;
 len_CD = sqrt(sum(CD.^2));
CD_AC(i_frame) = acosd(dot(CD/len_CD,[0,0,-1]));
end

min_CD_AC(i_attempt) = min(CD_AC(start_attempt:start_attempt+100));
RFoot_y_flag(i_attempt) = min_CD_AC(i_attempt) > movement_threshold_angle_d;

% 9. + 10. Elbow extended at end of movement

% Idenfity elbow as per appendix Right ELBOW
RWJC_ELB = (data.marker_data.Markers.RRAO-data.marker_data.Markers.RELB);
RELB_GHJ = (data.marker_data.Markers.RELB-data.marker_data.Markers.RHUP);
% dot(A,B) = |A|*|B|*cos(angle between A,B)
len_RWJC_ELB =
sqrt(RWJC_ELB(start_attempt:stop_attempt,1).^2+RWJC_ELB(start_attempt:stop_attemp
t,2).^2+RWJC_ELB(start_attempt:stop_attempt,3).^2);
len_RELB_GHJ =
sqrt(RELB_GHJ(start_attempt:stop_attempt,1).^2+RELB_GHJ(start_attempt:stop_attemp
t,2).^2+RELB_GHJ(start_attempt:stop_attempt,3).^2);
RELB_angle =
acosd(dot(RWJC_ELB(start_attempt:stop_attempt,:)./repmat(len_RWJC_ELB,1,3),RELB_G
HJ(start_attempt:stop_attempt,:)./repmat(len_RELB_GHJ,1,3),2));

   [min_LELB_angle(i_attempt), indexL]=min(LELB_angle);
   [min_RELB_angle(i_attempt), indexR]=min(RELB_angle);

if min_LELB_angle(i_attempt)>min_RELB_angle(i_attempt)
   index = indexR;
   disp('Right');
   min_elbow_side{i_attempt} = 'Right';
else
   index =  indexL;
   disp('Left');
   min_elbow_side{i_attempt} = 'Left';
end
```

```
LELB_flag(i_attempt) = min_LELB_angle(i_attempt) > 30;
RELB_flag(i_attempt)= min_RELB_angle(i_attempt) > 30;
end
```

Save function

```
var_names = {'LFIN_flag','RFIN_flag'... %1 + 2
'Lx_flex_diff_flag'... %4
'Lknee_start_flag','Rknee_start_flag'... %5+6
'LFoot_y_flag','RFoot_y_flag',... %7+8
'LELB_flag','RELB_flag'};... %9+10
```

Output data

```
output.var_names = var_names;
for i_var=1:length(var_names)
    output.(var_names{i_var}) = eval(var_names{i_var});
end
```

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APPENDIX XXV - Matlab script for Rotary Stability Unilateral repetition tests

MATLAB routine for Rotary Stability Unilateral repetition

```
function output = Rotary_stability_ips_left(filename)
```

Load data

```
data = btk_loadc3d(filename);

% Set Thresholds
KJC_HUO_dist = 190;
mvmt_start_threshold = 5;
mvt_frame_threshold = 50;
EAT = 30; % Extension angle threshold
FAT = 150; % Flexion angle threshold
movement_threshold_dist = 5;
movement_threshold_angle = 10;

% find event markers - associatted user defined lables with data
angle_freq = data.marker_data.AngleInfo.frequency; % sampling frequency
events = data.events_data.Data.Right_Foot_Strike;
target = data.events_data.Data.Left_Foot_Off;
%  Label Markers
LKJC = data.marker_data.Markers.LFEO;
LHUO = data.marker_data.Markers.LELB;

% Minimal Distance beween elbow and knee joint center Y co-ordinates
KJC_HUO_diff_ips = sqrt(sum((LKJC-LHUO).^2,2));
LHUO2 = data.marker_data.Markers.LELB(:,2);
LKJC2 = data.marker_data.Markers.LFEO(:,2);

%Stabilising limb
LFIN = data.marker_data.Markers.LFIN;
LKJC = data.marker_data.Markers.LFEO;
LTOE = data.marker_data.Markers.LTOE;
RFIN = data.marker_data.Markers.RFIN;
RKJC = data.marker_data.Markers.RFEO;
RTOE = data.marker_data.Markers.RTOE;

% Get required markers UL model
CLAV = data.marker_data.Markers.CLAV;
C7 = data.marker_data.Markers.C7;
STRN = data.marker_data.Markers.STRN;
T10 = data.marker_data.Markers.T10;
RHUP = data.marker_data.Markers.RHUP;
LHUP = data.marker_data.Markers.LHUP;
RELB = data.marker_data.Markers.RELB;
LELB = data.marker_data.Markers.LELB;
```

Initialize output vectors - allocates holding space

```
min_KJC_HUO_diff =zeros(length(events)-1,1);
GH_indices= zeros(length(events)-1,1);
KJC_HUO_diff_ips_flag= zeros(length(events)-1,1);
Lhip_start_local_indices = zeros(length(events)-1,1);
LGHz_start_local_indices = zeros(length(events)-1,1);
mvmt_start_diff_flag = zeros(length(events)-1,1);
HIP_indices = zeros(length(events)-1,1);
indices= zeros(length(events)-1,1);
RFIN_startx=zeros(length(events)-1,1);
RFIN_flag=zeros(length(events)-1,1);
RKJC_startx=zeros(length(events)-1,1);
RKJC_flag=zeros(length(events)-1,1);
RTOE_startx=zeros(length(events)-1,1);
RTOE_flag=zeros(length(events)-1,1);
RANKx_start=zeros(length(events)-1,1);
```

```
RANKx_diff_flag=zeros(length(events)-1,1);
RGHx = zeros(size(CLAV,1),1);
LGHx = zeros(size(CLAV,1),1);
RGHz = zeros(size(CLAV,1),1);
LGHz = zeros(size(CLAV,1),1);
Lhip_start = zeros(length(events)-1,1);
LGHz_start = zeros(length(events)-1,1);
LGHz_max_TT= zeros(length(events)-1,1);
LGHz_flex_flag_TT= zeros(length(events)-1,1);
LGHz_max_FT= zeros(length(events)-1,1);
LGHz_flex_flag_FT= zeros(length(events)-1,1);
LELB_angle_min_TT= zeros(length(events)-1,1);
LELB_angle_min_TT= zeros(length(events)-1,1);
LELB_angle_min_FT= zeros(length(events)-1,1);
LELB_angle_min_FT_flag= zeros(length(events)-1,1);
Lhip_minx_to_target =zeros(length(events)-1,1);
Lhip_minx_from_target =zeros(length(events)-1,1);
Lhip_ext_flag_to_target =zeros(length(events)-1,1);
Lhip_ext_flag_from_target =zeros(length(events)-1,1);
Lknee_minx_to_target =zeros(length(events)-1,1);
Lknee_minx_from_target =zeros(length(events)-1,1);
Lknee_ext_flag_to_target =zeros(length(events)-1,1);
Lknee_ext_flag_from_target =zeros(length(events)-1,1);

for i_attempt = 1:length(events)-1
    start_attempt = round(events(i_attempt)*angle_freq+1)-
data.marker_data.First_Frame+1;
    stop_attempt = round(events(i_attempt+1)*angle_freq)-
data.marker_data.First_Frame+1;
    target_attempt = round(target(i_attempt)*angle_freq)-
data.marker_data.First_Frame+1;

% 2. SHOULDER calculation for each frame in the trial
for iframe = 1:size(CLAV,1)
    [RGHx(iframe),LGHx(iframe),RGHz(iframe),LGHz(iframe)] =
hum_flex_elev(CLAV(iframe,:)',C7(iframe,:)',STRN(iframe,:)',...

T10(iframe,:)',RHUP(iframe,:)',LHUP(iframe,:)',RELB(iframe,:)',LELB(iframe,:)');
end
    % change to degrees
RGHx = unwrap(RGHx)*180/pi;
LGHx = unwrap(LGHx)*180/pi;
RGHz = unwrap(RGHz)*180/pi; % angle of elevation
LGHz = unwrap(LGHz)*180/pi; % angle of elevation

% ELBOW angle calculation
% Need to do vector from the wrist joint center to the elbow and the elbow marker
to the acromion marker, elbow joint center
LWJC_ELB = (data.marker_data.Markers.LRAO-data.marker_data.Markers.LELB);
LELB_GHJ = (data.marker_data.Markers.LELB-data.marker_data.Markers.LHUP);
% dot(A,B) = |A|*|B|*cos(angle between A,B)
len_LWJC_ELB =
sqrt(LWJC_ELB(start_attempt:stop_attempt,1).^2+LWJC_ELB(start_attempt:stop_attemp
t,2).^2+LWJC_ELB(start_attempt:stop_attempt,3).^2);
len_LELB_GHJ =
sqrt(LELB_GHJ(start_attempt:stop_attempt,1).^2+LELB_GHJ(start_attempt:stop_attemp
t,2).^2+LELB_GHJ(start_attempt:stop_attempt,3).^2);
LELB_angle =
acosd(dot(LWJC_ELB(start_attempt:stop_attempt,:)./repmat(len_LWJC_ELB,1,3),LELB_G
HJ(start_attempt:stop_attempt,:)./repmat(len_LELB_GHJ,1,3),2));

% RIGHT_ELBOW
RWJC_ELB = (data.marker_data.Markers.RRAO-data.marker_data.Markers.RELB);
RELB_GHJ = (data.marker_data.Markers.RELB-data.marker_data.Markers.RHUP);
% dot(A,B) = |A|*|B|*cos(angle between A,B)
```

```
len_RWJC_ELB =
sqrt(RWJC_ELB(start_attempt:stop_attempt,1).^2+RWJC_ELB(start_attempt:stop_attemp
t,2).^2+RWJC_ELB(start_attempt:stop_attempt,3).^2);
len_RELB_GHJ =
sqrt(RELB_GHJ(start_attempt:stop_attempt,1).^2+RELB_GHJ(start_attempt:stop_attemp
t,2).^2+RELB_GHJ(start_attempt:stop_attempt,3).^2);
RELB_angle =
acosd(dot(RWJC_ELB(start_attempt:stop_attempt,:)./repmat(len_RWJC_ELB,1,3),RELB_G
HJ(start_attempt:stop_attempt,:)./repmat(len_RELB_GHJ,1,3),2));

% Flags
% 1.     Stabilising limb  - Thumb -  maintains contact with board
RFIN_startx(i_attempt) = RFIN(start_attempt,1);
RFINx_dist = RFIN_startx(i_attempt)- RFIN(start_attempt:stop_attempt,1);
RFIN_flag(i_attempt) = sum(abs(RFINx_dist > movement_threshold_dist));
% 2.     Stabilising limb -  Knee -  maintains contact with board
RKJC_startx(i_attempt) = RKJC(start_attempt,1);
RKJCx_dist = RKJC_startx(i_attempt)- RKJC(start_attempt:stop_attempt,1);
RKJC_flag(i_attempt) = sum(abs(RKJCx_dist > movement_threshold_dist));
% 3.     Stabilising limb - Toe -  maintains contact with board
RTOE_startx(i_attempt) = RTOE(start_attempt,1);
RTOEx_dist =RTOE_startx(i_attempt)- RTOE(start_attempt:stop_attempt,1);
RTOE_flag(i_attempt) = sum(abs(RTOEx_dist > movement_threshold_dist));
% 4.     Stabilising limb - ankle angle remains unchanged throughout attempts
RANKx_start(i_attempt) = data.marker_data.Angles.RAnkleAngles(start_attempt,1);
RANKx_diff = data.marker_data.Angles.RAnkleAngles(start_attempt:stop_attempt,1) -
RANKx_start(i_attempt);
RANKx_diff_flag (i_attempt) = sum(abs(RANKx_diff(i_attempt) >
movement_threshold_angle));

% 5.     Stabilising limb  - foot position perpendicular to the horizontal axis
at start of attempts
for i_frame = start_attempt:stop_attempt
 pointc = data.marker_data.Markers.RTOE(i_frame,:);
 pointd = data.marker_data.Markers.RTIO(i_frame,:);
 CD = pointc - pointd;
 len_CD = sqrt(sum(CD.^2));
CD_AC(i_frame) = acosd(dot(CD/len_CD,[0,0,-1]));
end
min_CD_AC(i_attempt) = min(CD_AC(start_attempt:start_attempt+100));
RFoot_y_flag(i_attempt) = min_CD_AC(i_attempt) > movement_threshold_angle;

% 6.     Moving limb - foot position perpendicular to the horizontal axis at
start of attempts
for i_frame = start_attempt:stop_attempt
 pointa = data.marker_data.Markers.LTOE(i_frame,:);
 pointb = data.marker_data.Markers.LTIO(i_frame,:);
 AB = pointa - pointb;
 len_AB = sqrt(sum(AB.^2));
AB_AC(i_frame) = acosd(dot(AB/len_AB,[0,0,-1]));
end
min_AB_AC(i_attempt) = min(AB_AC(start_attempt:start_attempt+100));
LFoot_y_flag(i_attempt) = min_AB_AC(i_attempt) > movement_threshold_angle;

% 11.    Ipsilateral upper and lower limb movement starts simultaneously
LGHz_start(i_attempt) = LGHz(start_attempt);
LGHz_start_diff = abs(LGHz(start_attempt:target_attempt)-LGHz_start(i_attempt));
GH_index = find(LGHz_start_diff > mvmt_start_threshold,1,'first');
GH_indices(i_attempt) = start_attempt+GH_index-1;

Lhip_start(i_attempt) = data.marker_data.Angles.LHipAngles(start_attempt,1);
Lhip_start_diff =
abs(data.marker_data.Angles.LHipAngles(start_attempt:target_attempt,1)-
Lhip_start(i_attempt));
HIP_index = find(Lhip_start_diff > mvmt_start_threshold,1,'first');
HIP_indices(i_attempt) = start_attempt+HIP_index-1;
```

```
mvmt_start_diff(i_attempt) = abs(GH_indices(i_attempt)-HIP_indices(i_attempt));
mvmt_start_diff_flag(i_attempt) = mvmt_start_diff(i_attempt) >
mvt_frame_threshold;

% 7.+ 8. Shoulder angle – 90 degrees relative to the torso at start of attempts
LGHz_start(i_attempt)=LGHz(start_attempt,1);
LGHz_start_flag(i_attempt)= (LGHz_start(i_attempt)<80) |
(LGHz_start(i_attempt)>100);

RGHz_start(i_attempt)=RGHz(start_attempt,1);
RGHz_start_flag(i_attempt)= (RGHz_start(i_attempt)<80) |
(RGHz_start(i_attempt)>100);

% 9.+ 10.Stabilising limb - Hip angle – 90 degrees relative to the torso at start
of attempts
% Identify torso angle at the start
Tx_x_start(i_attempt) = data.marker_data.Angles.LThoraxAngles(start_attempt,1);
for i_frame = start_attempt:stop_attempt
LFEPz = data.marker_data.Markers.LFEP(i_frame,3);
LFEOz = data.marker_data.Markers.LFEO(i_frame,3);
LFEPy = data.marker_data.Markers.LFEP(i_frame,2);
LFEOy = data.marker_data.Markers.LFEO(i_frame,2);
LFE_angle(i_frame) = atan((LFEPz-LFEOz)/(LFEPy-LFEOy))*180/pi;
end

for i_frame = start_attempt:stop_attempt
RFEPz = data.marker_data.Markers.RFEP(i_frame,3);
RFEOz = data.marker_data.Markers.RFEO(i_frame,3);
RFEPy = data.marker_data.Markers.RFEP(i_frame,2);
RFEOy = data.marker_data.Markers.RFEO(i_frame,2);
RFE_angle(i_frame) = atan((RFEPz-RFEOz)/(RFEPy-RFEOy))*180/pi;
end
% Hip angle at start of attempt
Lhip_start(i_attempt) = LFE_angle(start_attempt);
Rhip_start(i_attempt) = RFE_angle(start_attempt);
% Subtract according to the sine convention used
Lhip_start_angle(i_attempt) = 90-LFE_angle(start_attempt);
Rhip_start_angle(i_attempt) = 90-RFE_angle(start_attempt);
% Angle relative to the torso
Tx_calc(i_attempt) = Tx_x_start(i_attempt);
Lflag_angle(i_attempt) = 180 -Tx_calc(i_attempt)-Lhip_start_angle(i_attempt);
Rflag_angle(i_attempt) = 180 -Tx_calc(i_attempt)-Rhip_start_angle(i_attempt);
% Flag
Rhip_start_flag(i_attempt)= (Rflag_angle(i_attempt)<80) |
(Rflag_angle(i_attempt)>100);
Lhip_start_flag(i_attempt)= (Lflag_angle(i_attempt)<80) |
(Lflag_angle(i_attempt)>100);

% Set index for target
[min_KJC_HUO_diff(i_attempt),index] =
min(KJC_HUO_diff_ips(start_attempt:stop_attempt));
indices(i_attempt) = start_attempt+index-1;

% 12.    Moving arm stays in line over board
LHUO_startx(i_attempt) = LHUO(start_attempt,1);
LHUO_x = LHUO(start_attempt:stop_attempt,1);
LHUO_OB_flag(i_attempt) = sum(LHUO_x > LHUO_startx(i_attempt));
% 13.    Moving leg stays in line over board
LKJC_startx(i_attempt) = LKJC(start_attempt,1);
LKJC_x = LKJC(start_attempt:stop_attempt,1);
LKJC_OB_flag(i_attempt) = sum(LKJC_x > LKJC_startx(i_attempt));

% Shoulder - LEFT ANGLE OF ELEVATION = GHz
% 14. 20. Moving limb – Shoulder joint – achieves “full” elevation at end of
movement
LGHz_max_TT(i_attempt)= max(LGHz(start_attempt:target_attempt,:));
LGHz_flex_flag_TT(i_attempt) = LGHz_max_TT(i_attempt)< FAT;
```

```
LGHz_max_FT(i_attempt)= max(LGHz(target_attempt:stop_attempt,:));
LGHz_flex_flag_FT(i_attempt) = LGHz_max_FT(i_attempt)< FAT;
% 15. 21.Moving limb - Elbow joint - achieves "full" extension at end of movement
LELB_angle_min_TT(i_attempt) = min(LELB_angle(1:target_attempt-
start_attempt+1,:));
LELB_angle_min_TT_flag(i_attempt) = LELB_angle_min_TT(i_attempt) > EAT;
LELB_angle_min_FT(i_attempt) = min(LELB_angle(target_attempt-
start_attempt+1:end,:));
LELB_angle_min_FT_flag(i_attempt) = LELB_angle_min_FT(i_attempt) > EAT;
% 16. 22. Moving limb - Hip joint - achieves "full" extension at end of movement
Lhip_minx_to_target(i_attempt)=
min(data.marker_data.Angles.LHipAngles(start_attempt:target_attempt,1));
Lhip_ext_flag_to_target(i_attempt) = Lhip_minx_to_target(i_attempt)> EAT;
Lhip_minx_from_target(i_attempt) =
min(data.marker_data.Angles.LHipAngles(target_attempt:stop_attempt,1));
Lhip_ext_flag_from_target(i_attempt) = Lhip_minx_from_target(i_attempt)> EAT;
% 17.23. Moving limb - Knee joint - achieves "full" extension at end of movement
Lknee_minx_to_target(i_attempt)=
min(data.marker_data.Angles.LKneeAngles(start_attempt:target_attempt,1));
Lknee_ext_flag_to_target(i_attempt) = Lknee_minx_to_target(i_attempt)> EAT;
Lknee_minx_from_target(i_attempt) =
min(data.marker_data.Angles.LKneeAngles(target_attempt:stop_attempt,1));
Lknee_ext_flag_from_target(i_attempt) = Lknee_minx_from_target(i_attempt)> EAT;

%18. Moving limbs - % elbow and knee touch over the board
AKJC_HUO_diff_ips2(i_attempt) = min(abs(LHUO2(start_attempt:stop_attempt) -
LKJC2(start_attempt:stop_attempt)));
KJC_HUO_diff_ips_flag(i_attempt) = AKJC_HUO_diff_ips2(i_attempt) > KJC_HUO_dist;
end
```

Save function

```
var_names = {'RFIN_flag'... %1
'RKJC_flag'... %2
'RTOE_flag'... %3
'RANKx_diff_flag'...%4
'LFoot_y_flag','RFoot_y_flag'... %5+6
'RGHz_start_flag','LGHz_start_flag'...%7+8
'Lhip_start_flag','Rhip_start_flag'...%9+10
'mvmt_start_diff_flag'...%11
'LHUO_OB_flag','LKJC_OB_flag'... %12 +13.
'LGHz_flex_flag_TT','LELB_angle_min_TT_flag'...%14 + 15
'Lhip_ext_flag_to_target','Lknee_ext_flag_to_target'...%16+17
'KJC_HUO_diff_ips_flag'... %18
'LGHz_flex_flag_FT','LELB_angle_min_FT_flag'... %19 + 20
'Lhip_ext_flag_from_target','Lknee_ext_flag_from_target'};%21+22
% 19.   No contact of moving limbs with floor  - assessed visually
```

Output data

```
output.var_names = var_names;
for i_var=1:length(var_names)
    output.(var_names{i_var}) = eval(var_names{i_var});
end
```

Can also be used for right – need to swap static/stabilising limbs and moving limbs
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APPENDIX XXVI - Matlab script for Rotary Stability Diagonal repetition tests

MATLAB routine for Rotary Stability Diagonal repetition

```
function output = Rotary_stability_cont_left(filename)
```

load data

```
data = btk_loadc3d(filename);

KJC_HUO_dist = 190;
mvmt_start_threshold = 5;
mvt_frame_threshold = 50;
EAT = 30; % Extension angle threshold
FAT = 150; % Flexion angle threshold
movement_threshold_dist = 5;
movement_threshold_angle = 10;

% find event markers - associatted user defined lables with data
angle_freq = data.marker_data.AngleInfo.frequency; % sampling frequency
events = data.events_data.Data.Right_Foot_Strike;
target = data.events_data.Data.Left_Foot_Off;

% left shoulder to right knee
LHUO = data.marker_data.Markers.LELB;
RKJC = data.marker_data.Markers.RFEO;
KJC_HUO_diff_ips = sqrt(sum((RKJC-LHUO).^2,2));
LHUO1 = data.marker_data.Markers.LELB(:,1);
RKJC1 = data.marker_data.Markers.RFEO(:,1);
LHUO2 = data.marker_data.Markers.LELB(:,2);
RKJC2 = data.marker_data.Markers.RFEO(:,2);

%Label Markers
LFIN = data.marker_data.Markers.LFIN;
LKJC = data.marker_data.Markers.LFEO;
LTOE = data.marker_data.Markers.LTOE;
RFIN = data.marker_data.Markers.RFIN;
RKJC = data.marker_data.Markers.RFEO;
RTOE = data.marker_data.Markers.RTOE;

% Get required markers UL model
CLAV = data.marker_data.Markers.CLAV;
C7 = data.marker_data.Markers.C7;
STRN = data.marker_data.Markers.STRN;
T10 = data.marker_data.Markers.T10;
RHUP = data.marker_data.Markers.RHUP;
LHUP = data.marker_data.Markers.LHUP;
RELB = data.marker_data.Markers.RELB;
LELB = data.marker_data.Markers.LELB;
```

Initialise output vectors - allocates holding space

```
min_KJC_HUO_diff =zeros(length(events)-1,1);
GH_indices= zeros(length(events)-1,1);
KJC_HUO_diff_ips_flag= zeros(length(events)-1,1);
Rhip_start_local_indices = zeros(length(events)-1,1);
LGHz_start_local_indices = zeros(length(events)-1,1);
mvmt_start_diff_flag = zeros(length(events)-1,1);
HIP_indices = zeros(length(events)-1,1);
indices= zeros(length(events)-1,1);
AKJC_HUO_diff_ips1= zeros(length(events)-1,1);
AKJC_HUO_diff_ips2= zeros(length(events)-1,1);
LHUO_startx= zeros(length(events)-1,1);
LHUO_TOB= zeros(length(events)-1,1);
LHUO_TOB_flag= zeros(length(events)-1,1);
RKJC_startx= zeros(length(events)-1,1);
RKJC_TOB= zeros(length(events)-1,1);
```

```
RKJC_TOB_flag= zeros(length(events)-1,1);
mvmt_start_diff= zeros(length(events)-1,1);
RGHx = zeros(size(CLAV,1),1);
LGHx = zeros(size(CLAV,1),1);
RGHz = zeros(size(CLAV,1),1);
LGHz = zeros(size(CLAV,1),1);
Rhip_start = zeros(length(events)-1,1);
LGHz_start = zeros(length(events)-1,1);
LGHz_max_TT= zeros(length(events)-1,1);
LGHz_flex_flag_TT= zeros(length(events)-1,1);
LGHz_max_FT= zeros(length(events)-1,1);
LGHz_flex_flag_FT= zeros(length(events)-1,1);
LELB_angle_min_TT= zeros(length(events)-1,1);
LELB_angle_min_TT= zeros(length(events)-1,1);
LELB_angle_min_FT= zeros(length(events)-1,1);
LELB_angle_min_FT_flag= zeros(length(events)-1,1);
Rhip_minx_to_target =zeros(length(events)-1,1);
Rhip_minx_from_target =zeros(length(events)-1,1);
Rhip_ext_flag_to_target =zeros(length(events)-1,1);
Rhip_ext_flag_from_target =zeros(length(events)-1,1);
Rknee_minx_to_target =zeros(length(events)-1,1);
Rknee_minx_from_target =zeros(length(events)-1,1);
Rknee_ext_flag_to_target =zeros(length(events)-1,1);
Rknee_ext_flag_from_target =zeros(length(events)-1,1);
RFIN_startx=zeros(length(events)-1,1);
RFIN_flag=zeros(length(events)-1,1);
LKJC_startx=zeros(length(events)-1,1);
LKJC_flag=zeros(length(events)-1,1);
LTOE_startx=zeros(length(events)-1,1);
LTOE_flag=zeros(length(events)-1,1);
LANKx_start=zeros(length(events)-1,1);
LANKx_diff_flag=zeros(length(events)-1,1);

for i_attempt = 1:length(events)-1
    start_attempt = round(events(i_attempt)*angle_freq+1)-
data.marker_data.First_Frame+1;
    stop_attempt = round(events(i_attempt+1)*angle_freq)-
data.marker_data.First_Frame+1;
    target_attempt = round(target(i_attempt)*angle_freq)-
data.marker_data.First_Frame+1;

% SHOULDER calculation for each frame in the trial
for iframe = 1:size(CLAV,1)
    [RGHx(iframe),LGHx(iframe),RGHz(iframe),LGHz(iframe)] =
hum_flex_elev(CLAV(iframe,:)',C7(iframe,:)',STRN(iframe,:)',...

T10(iframe,:)',RHUP(iframe,:)',LHUP(iframe,:)',RELB(iframe,:)',LELB(iframe,:)');
end
    % change to degrees
RGHx = unwrap(RGHx)*180/pi;
LGHx = unwrap(LGHx)*180/pi;
RGHz = unwrap(RGHz)*180/pi; % angle of elevation
LGHz = unwrap(LGHz)*180/pi; % angle of elevation

% ELBOW angle calculation
% Need to do vector from the wrist joint center to the elbow and the elbow marker
to the acromion marker, elbow joint center
LWJC_ELB = (data.marker_data.Markers.LRAO-data.marker_data.Markers.LELB);
LELB_GHJ = (data.marker_data.Markers.LELB-data.marker_data.Markers.LHUP);
% dot(A,B) = |A|*|B|*cos(angle between A,B)
len_LWJC_ELB =
sqrt(LWJC_ELB(start_attempt:stop_attempt,1).^2+LWJC_ELB(start_attempt:stop_attemp
t,2).^2+LWJC_ELB(start_attempt:stop_attempt,3).^2);
len_LELB_GHJ =
sqrt(LELB_GHJ(start_attempt:stop_attempt,1).^2+LELB_GHJ(start_attempt:stop_attemp
t,2).^2+LELB_GHJ(start_attempt:stop_attempt,3).^2);
```

```
LELB_angle =
acosd(dot(LWJC_ELB(start_attempt:stop_attempt,:)./repmat(len_LWJC_ELB,1,3),LELB_G
HJ(start_attempt:stop_attempt,:)./repmat(len_LELB_GHJ,1,3),2));

% RIGHT_ELBOW
RWJC_ELB = (data.marker_data.Markers.RRAO-data.marker_data.Markers.RELB);
RELB_GHJ = (data.marker_data.Markers.RELB-data.marker_data.Markers.RHUP);
% dot(A,B) = |A|*|B|*cos(angle between A,B)
len_RWJC_ELB =
sqrt(RWJC_ELB(start_attempt:stop_attempt,1).^2+RWJC_ELB(start_attempt:stop_attemp
t,2).^2+RWJC_ELB(start_attempt:stop_attempt,3).^2);
len_RELB_GHJ =
sqrt(RELB_GHJ(start_attempt:stop_attempt,1).^2+RELB_GHJ(start_attempt:stop_attemp
t,2).^2+RELB_GHJ(start_attempt:stop_attempt,3).^2);
RELB_angle =
acosd(dot(RWJC_ELB(start_attempt:stop_attempt,:)./repmat(len_RWJC_ELB,1,3),RELB_G
HJ(start_attempt:stop_attempt,:)./repmat(len_RELB_GHJ,1,3),2));

% 1.Stabilising limb  - Thumb -  maintains contact with board
RFIN_startx(i_attempt) = RFIN(start_attempt,1);
RFINx_dist = RFIN_startx(i_attempt)- RFIN(start_attempt:stop_attempt,1);
RFIN_flag(i_attempt) = sum(abs(RFINx_dist > movement_threshold_dist));
% 2.Stabilising limb -  Knee -  maintains contact with board
LKJC_startx(i_attempt) = LKJC(start_attempt,1);
LKJCx_dist = LKJC_startx(i_attempt)- LKJC(start_attempt:stop_attempt,1);
LKJC_flag(i_attempt) = sum(abs(LKJCx_dist > movement_threshold_dist));
% 3.Stabilising limb - Toe -  maintains contact with board
LTOE_startx(i_attempt) = LTOE(start_attempt,1);
LTOEx_dist =LTOE_startx(i_attempt)- LTOE(start_attempt:stop_attempt,1);
LTOE_flag(i_attempt) = sum(abs(LTOEx_dist > movement_threshold_dist));
% 4.Stabilising limb - ankle angle remains unchanged throughout attempts
LANKx_start(i_attempt) = data.marker_data.Angles.LAnkleAngles(start_attempt,1);
LANKx_diff = data.marker_data.Angles.LAnkleAngles(start_attempt:stop_attempt,1) -
LANKx_start(i_attempt);
LANKx_diff_flag (i_attempt) = sum(abs(LANKx_diff(i_attempt) >
movement_threshold_angle));


% 5.Stabilising limb  - foot position perpendicular to the horizontal axis at
start of attempts
for i_frame = start_attempt:stop_attempt
 pointa = data.marker_data.Markers.LTOE(i_frame,:);
 pointb = data.marker_data.Markers.LTIO(i_frame,:);
 AB = pointa - pointb;
 len_AB = sqrt(sum(AB.^2));
AB_AC(i_frame) = acosd(dot(AB/len_AB,[0,0,-1]));
end
min_AB_AC(i_attempt) = min(AB_AC(start_attempt:start_attempt+100));
LFoot_y_flag(i_attempt) = min_AB_AC(i_attempt) > movement_threshold_angle;

% 6.Moving limb - foot position perpendicular to the horizontal axis at start of
attempts
for i_frame = start_attempt:stop_attempt
 pointc = data.marker_data.Markers.RTOE(i_frame,:);
 pointd = data.marker_data.Markers.RTIO(i_frame,:);
 CD = pointc - pointd;
 len_CD = sqrt(sum(CD.^2));
CD_AC(i_frame) = acosd(dot(CD/len_CD,[0,0,-1]));
end
min_CD_AC(i_attempt) = min(CD_AC(start_attempt:start_attempt+100));
RFoot_y_flag(i_attempt) = min_CD_AC(i_attempt) > movement_threshold_angle;

% 11.Contralateral upper and lower limb movement starts simultaneously
LGHz_start(i_attempt) = LGHz(start_attempt);
LGHz_start_diff = abs(LGHz(start_attempt:target_attempt)-LGHz_start(i_attempt));
GH_index = find(LGHz_start_diff > mvmt_start_threshold,1,'first');
GH_indices(i_attempt) = start_attempt+GH_index-1;
```

```
Rhip_start(i_attempt) = data.marker_data.Angles.RHipAngles(start_attempt,1);
Rhip_start_diff =
abs(data.marker_data.Angles.RHipAngles(start_attempt:target_attempt,1)-
Rhip_start(i_attempt));
HIP_index = find(Rhip_start_diff > mvmt_start_threshold,1,'first');
HIP_indices(i_attempt) = start_attempt+HIP_index-1;

%  FLAG
mvmt_start_diff(i_attempt) = abs(GH_indices(i_attempt)-HIP_indices(i_attempt));
mvmt_start_diff_flag(i_attempt) = mvmt_start_diff(i_attempt) >
mvt_frame_threshold;

% 7+8. Shoulder angle - 90 degrees relative to the torso at start of attempts
LGHz_start(i_attempt)=LGHz(start_attempt,1);
LGHz_start_flag(i_attempt)= (LGHz_start(i_attempt)<80) |
(LGHz_start(i_attempt)>100);

RGHz_start(i_attempt)=RGHz(start_attempt,1);
RGHz_start_flag(i_attempt)= (RGHz_start(i_attempt)<80) |
(RGHz_start(i_attempt)>100);

% Identify thorax angle at start
Tx_x_start(i_attempt) = data.marker_data.Angles.LThoraxAngles(start_attempt,1);

% 9+10. Hip angle - 90 degrees relative to the torso at start of attempts
for i_frame = start_attempt:stop_attempt
LFEPz = data.marker_data.Markers.LFEP(i_frame,3);
LFEOz = data.marker_data.Markers.LFEO(i_frame,3);
LFEPy = data.marker_data.Markers.LFEP(i_frame,2);
LFEOy = data.marker_data.Markers.LFEO(i_frame,2);
LFE_angle(i_frame) = atan((LFEPz-LFEOz)/(LFEPy-LFEOy))*180/pi;
end

for i_frame = start_attempt:stop_attempt
RFEPz = data.marker_data.Markers.RFEP(i_frame,3);
RFEOz = data.marker_data.Markers.RFEO(i_frame,3);
RFEPy = data.marker_data.Markers.RFEP(i_frame,2);
RFEOy = data.marker_data.Markers.RFEO(i_frame,2);
RFE_angle(i_frame) = atan((RFEPz-RFEOz)/(RFEPy-RFEOy))*180/pi;
end
% Hip angle at start of attempt
Lhip_start(i_attempt) = LFE_angle(start_attempt);
Rhip_start(i_attempt) = RFE_angle(start_attempt);
% Subtract according to the sine convention used
Lhip_start_angle(i_attempt) = 90-LFE_angle(start_attempt);
Rhip_start_angle(i_attempt) = 90-RFE_angle(start_attempt);
% Angle relative to the torso
Tx_calc(i_attempt) = Tx_x_start(i_attempt);
Lflag_angle(i_attempt) = 180 -Tx_calc(i_attempt)-Lhip_start_angle(i_attempt);
Rflag_angle(i_attempt) = 180 -Tx_calc(i_attempt)-Rhip_start_angle(i_attempt);
% Flag
Rhip_start_flag(i_attempt)= (Rflag_angle(i_attempt)<80) |
(Rflag_angle(i_attempt)>100);
Lhip_start_flag(i_attempt)= (Lflag_angle(i_attempt)<80) |
(Lflag_angle(i_attempt)>100);

% Set index for target
[min_KJC_HUO_diff(i_attempt),index] =
min(KJC_HUO_diff_ips(start_attempt:stop_attempt));
indices(i_attempt) = start_attempt+index-1;
% 12.Elbow and knee touch over the board
AKJC_HUO_diff_ips1(i_attempt) = min(abs(LHUO1(start_attempt:stop_attempt) -
RKJC1(start_attempt:stop_attempt)));
AKJC_HUO_diff_ips2(i_attempt) = min(abs(LHUO2(start_attempt:stop_attempt) -
RKJC2(start_attempt:stop_attempt)));
```

```
if (AKJC_HUO_diff_ips1(i_attempt)< KJC_HUO_dist) & (AKJC_HUO_diff_ips2 <
KJC_HUO_dist);
    KJC_HUO_diff_ips_flag(i_attempt) = 0;
else KJC_HUO_diff_ips_flag(i_attempt) = 1;
end

% 13.   Moving limbs - knee over board
RKJC_startx(i_attempt) = RKJC(start_attempt,1);
RKJC_TOB (i_attempt) = RKJC(index,1);
RKJC_TOB_flag(i_attempt) =  RKJC_TOB(i_attempt)> RKJC_startx(i_attempt);
% 14.Moving limbs - elbow over board (in order to touch knee)
LHUO_startx(i_attempt) = LHUO(start_attempt,1);
LHUO_TOB (i_attempt) = LHUO(index,1);
LHUO_TOB_flag(i_attempt) =  LHUO_TOB(i_attempt)< LHUO_startx(i_attempt);

% 15.+20 Moving limb - Hip joint - achieves "full" extension at end of movement
Rhip_minx_to_target(i_attempt)=
min(data.marker_data.Angles.RHipAngles(start_attempt:target_attempt,1));
Rhip_ext_flag_to_target(i_attempt) = Rhip_minx_to_target(i_attempt)> EAT;
Rhip_minx_from_target(i_attempt) =
min(data.marker_data.Angles.RHipAngles(target_attempt:stop_attempt,1));
Rhip_ext_flag_from_target(i_attempt) = Rhip_minx_from_target(i_attempt)> EAT;
% 16.+21 Moving limb - Knee joint - achieves "full" extension at end of movement
Rknee_minx_to_target(i_attempt)=
min(data.marker_data.Angles.RKneeAngles(start_attempt:target_attempt,1));
Rknee_ext_flag_to_target(i_attempt) = Rknee_minx_to_target(i_attempt)> EAT;
Rknee_minx_from_target(i_attempt) =
min(data.marker_data.Angles.RKneeAngles(target_attempt:stop_attempt,1));
Rknee_ext_flag_from_target(i_attempt) = Rknee_minx_from_target(i_attempt)> EAT;
% 17.+ 22 Moving limb - Shoulder joint - achieves "full" elevation at end of
movement
LGHz_max_TT(i_attempt)= max(LGHz(start_attempt:target_attempt,:));
LGHz_flex_flag_TT(i_attempt) = LGHz_max_TT(i_attempt)< FAT;
LGHz_max_FT(i_attempt)= max(LGHz(target_attempt:stop_attempt,:));
LGHz_flex_flag_FT(i_attempt) = LGHz_max_FT(i_attempt)< FAT;
% 18.+ 23 Moving limb - Elbow joint - achieves "full" extension at end of
movement
LELB_angle_min_TT(i_attempt) = min(LELB_angle(1:target_attempt-
start_attempt+1,:));
LELB_angle_min_TT_flag(i_attempt) = LELB_angle_min_TT(i_attempt) > EAT;
LELB_angle_min_FT(i_attempt) = min(LELB_angle(target_attempt-
start_attempt+1:end,:));
LELB_angle_min_FT_flag(i_attempt) = LELB_angle_min_FT(i_attempt) > EAT;
end
```

Save function

```
var_names = {'RFIN_flag'... %1
'LKJC_flag'... %2
'LTOE_flag'... %3
'LANKx_diff_flag'...%4
'LFoot_y_flag','RFoot_y_flag'... %5+6
'RGHz_start_flag','LGHz_start_flag'... %7+8
'Lhip_start_flag','Rhip_start_flag'... %9+10
'mvmt_start_diff_flag'... %11
'KJC_HUO_diff_ips_flag','RKJC_TOB_flag','LHUO_TOB_flag'... %12+13+14
'LGHz_flex_flag_TT','LGHz_flex_flag_FT'... %15+20
'LELB_angle_min_TT_flag','LELB_angle_min_FT_flag'... %16+21
'Rhip_ext_flag_to_target','Rhip_ext_flag_from_target'...%17 + 22
'Rknee_ext_flag_to_target','Rknee_ext_flag_from_target'}; %18 + 23

% 19 No contact of moving limbs with floor - assessed visually
```

Output data

```
output.var_names = var_names;
for i_var=1:length(var_names)
```

```
    output.(var_names{i_var}) = eval(var_names{i_var});
end
```

Can be used for Right – need to swap left and right / stabilising/moving limb

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