Developing a non-invasive method for *in vivo* monitoring of forearm flexor tendon excursions during rehabilitation following surgical tendon repair

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MPhil
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ABSTRACT

Background: An injury to the wrist and hand can impact different anatomical structures. Any damage or cut to the flexor tendons can leave a devastating impact if not treated well and can therefore compromise our daily physical activities. Surgery and rehabilitation are two factors contributing to recovery post flexor tendon repair.

Method: A comprehensive literature search was conducted identifying the pertinent factors that can contribute towards tendon recovery. The methodology of the study focuses on measurement of flexor tendon excursion of flexor pollicis longus, flexor digitorum superficialis (index, middle, ring and little finger), flexor carpi ulnaris and flexor carpi radialis tendons on healthy volunteers. The measurements were carried out twice on the same subjects on two different days. The tendon excursions were viewed under diagnostic 2D ultrasound, in three positions- finger flexion to 90 degree, whilst making a fist and on gripping JAMAR at 5 kgf.

Results: The ultrasound images of the tendons showed anatomical variability. Variability was also noted in the distance from the wrist crease to the muscle tendon junction at rest. The tendon excursions varied in all the participants and showed higher values on gripping JAMAR at 5kgf (49.03N). It also showed that the maximal tendon excursion per degree of movement was noticed in FDS(I) followed by FCU and FDS(M) tendons. With the use of JAMAR, it showed a maximal tendon excursion per Newton load of force in FPL followed by FDS(M) and FDS(R) tendons.

Conclusion: The developed method and data would assist in planning a rehabilitation regime for the patients post flexor tendon repair. Future research is required to implement this experimental protocol in patients with flexor tendon repair.

Keywords: Tendon injuries, hand/wrist/forearm, sutures, surgery, treatment/rehabilitation/therapy, zone.

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Contents

<u>List of figures</u>:

List of Tables

CHAPTER 1

1. Introduction

The wrist and hand play an important role in activities of daily living by enabling both gross and powerful movements (e.g. power grip), and intricate and finely controlled movements (e.g. threading a needle) (Griffin et al, 2012; Lui and Zhan 2013). The ability to adapt between these two extremes of performance can be explained by structures such as skeletal, muscular, tendon and ligament of the wrist and hand. The wrist and hand are interconnected in specific ways with the strong integration between the sensory and motor representation of the wrist and hand in the central nervous system (Westling and Johansson, 1984). Any disruption to these musculoskeletal interaction and/or the sensory motor system can compromise the efficient working of the wrist and hand and may lead to a significant interruption in activities of daily living. Mild to moderate or acute reversible injuries (e.g. a muscle strain) have no long term impact on ADL as the recovery is complete and last a short period of time. However, in case of more severe or complex injuries (e.g. a crush injury, glass cut and machinery injuries involving motor and sensory structures) where the musculoskeletal integrity is broken and/or the sensory motor system is interrupted, the disruption to ADL can be permanent and life changing. In people who have such complex injuries the long term impact on ADL can be minimized if the surgical and therapeutic management is effective and evidence informed (Tan et al, 2007).

The wrist and hand is most commonly used limb segment therefore is at risk of injury. The injuries can vary from simple injuries that recover fully following a conservative management and with little intervention to complex injuries (e.g. burns, mechanical crush injuries, glass cut injuries) that require complex interventional management possibly involving a combination of surgery and rehabilitation (Lindqvist, 2010). Complex injuries can involve more than one anatomical structures such as arteries, nerves, muscles, bones and tendons (Darlis et al, 2004; Jong et al, 2014). The range of injuries are very wide and variable and for the purpose of this thesis the main focus will be made on the injuries that mainly affect the flexor tendons.

The traditional management of such flexor tendon injuries involves a combination of surgery and rehabilitation (e.g. splints and exercise). In order to identify an effective evidence based recommendation for the management of flexor tendon injuries there is a need to:

(a) Have a comprehensive understanding of the anatomical structures of wrist and hand (Chapter 2)

(b) Understand the nature of tendon injuries and their recovery process (Chapter 3 and 4)

(c) Review the literature to identify best clinical practice (surgical and rehabilitation) (Chapter 4)

(d) Identify methods to optimise clinical practice (Chapter 5 and 6).

CHAPTER 2

1 Anatomical structures of wrist and hand

1.1 Skeletal structures

The hand comprises of 19 bones which includes 14 phalanges and 5 metacarpal bones (thumb and 4 fingers). The wrist is formed by the 8 carpal bones, radius and ulna (Tubiana, 1998; Lui and Zhan 2013). The joints of the thumb include a carpometacarpal joint (CMCJ), metacarpophalengeal joint (MCPJ) and interphalengeal joint (IPJ). The joints of each of the 4 fingers consists of metacarpophalengeal joint (MCPJ), proximal interphalengeal joint (PIPJ) and distal interphalengeal joint (DIPJ) (Clarkson, 2000; Nordin and Frankel, 2001; Tyldesley, 2002; Reese and Bandy, 2010; Levangie and Norkin, 2011; Snell, 2012).

The carpal bones in the wrist are of different shapes and sizes. There are two rows of carpal bones- a proximal row: scaphoid, lunate, triquetrum, pisiform; and a distal row: trapezium, trapezoid, capitate, hamate (fig:4) (Papp, 2007). The articulation between the distal side of the trapezium (carpal bone) and first metacarpal base forms the CMCJ (fig: 1). One side of the articular surface of this joint is concave and other is convex hence CMCJ is identified as a saddle joint. The radiocarpal joint or the wrist joint is biaxial and ellipsoid (fig:5). It is formed by the articulation of distal end of radius, triangular articular disc with the triquetrium, scaphoid and lunate. The mid carpal joint is formed by the proximal and distal row of carpal bones (Taylor and Schwarz, 1970; Hentz and Chase, 2001; Tyldesley, 2002; McCullough, 2006; Nordin and Frankel, 2001; Snell, 2012).

The anatomical movements of the 4 fingers (index, middle, ring and little) are flexion, extension, abduction and adduction. The primary movements of the thumb are- flexion, extension, abduction, adduction and opposition (Neumann and Bielefeld, 2003; Lin et al, 2011). The thumb, primarily by its ability to work in opposition, is essential to perform most daily activities that involve grasp, pick and pinch.

The active movements at the radiocarpal joint are flexion, extension, radial deviation (abduction) and ulnar deviation (adduction). All the carpal bones contribute to various wrist and hand movements.

Trauma to these carpal bones can contribute to instability and restrict the joint range of movements in wrist and may contribute to poor performance in grasps (Moojen and Bos, 2002).

The carpal bones are interconnected by the different ligaments and these act as a stabilizer of the wrist joint. Injury to the proximal carpal row, distal carpal row, radiocarpal or midcarpal joints can result in wrist instability. Trauma to the wrist can also result in the derangement of the bones leading to an alteration of kinematics and carpal instability (Khan et al, 2012).

Any traumatic injury to the radiocarpal joint can either affect the distal end of radius and/or ulna, the proximal carpal bones (particularly- triquetrium, scaphoid, lunate) or the distal radio-ulnar joint (Bilos et al, 1977). Joint instability, a painful and stiff wrist or osteoarthritis are some of the complications which may follow after a traumatic injury to the radiocarpal joint (Anderson et al, 2005; Erhart et al, 2012).

There are 3 arches in our hand- distal transverse, longitudinal and oblique which allows the hand to grasp objects of different shapes and sizes (fig:2). The longitudinal arch extends from the wrist crease to the second and third metacarpal, the distal transverse arch forms a concave curvature formed at the metacarpal heads of the four fingers (index, middle, ring, little) and the oblique arch is the concavity formed by the opposable thumb with the four fingers (index, middle, ring, little). A concave postural base is formed in the palm by these three arches and is maintained by the intrinsic musculature (Sangole and Levin, 2007). Human grasps have been classified into power and precision grasp based on the object, shape, size and finger postures (fig:3). The contribution of all the thumb, fingers and palm is crucial in power grasp for better stability. In precision grasp, the degree of contact between the object and finger is less (Kang and Ikeuchi, 1992). Loss of function in any of the fingers can either result in weakness or non-performance of grasps.

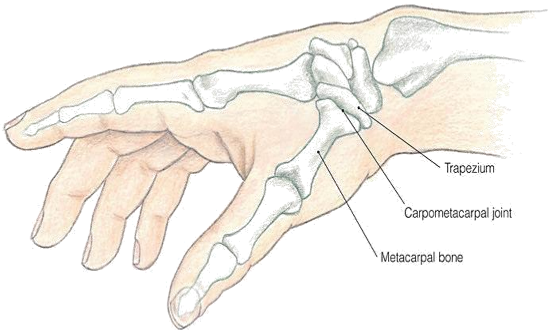


Figure 1: The carpometacarpal joint is a saddle joint and its articulation allows for the versatility of movement that allows thumb to come in opposition.

Adapted from: http://www.onehealth.co.uk/orthopaedics-procedures-osteoarthritis-thumb

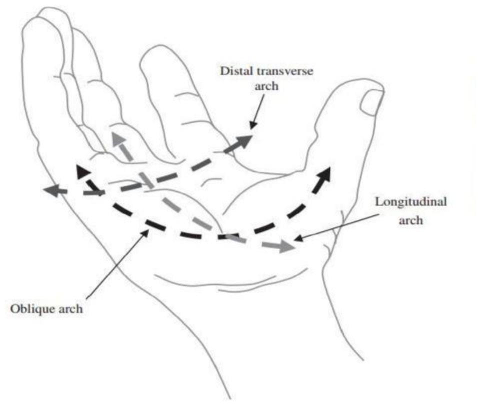


Figure 2: This figure illustrates the arches of the hand: distal transverse, longitudinal and oblique. It allows the hand to grasp objects of different shapes and sizes.

Adaptedfrom:https://www.oxfordshire.gov.uk/cms/sites/default/files/folders/documents/childreneducationandfamilies/educationandlearning/specialeducationalneeds/SEND/HandArchDevelopment.pdf

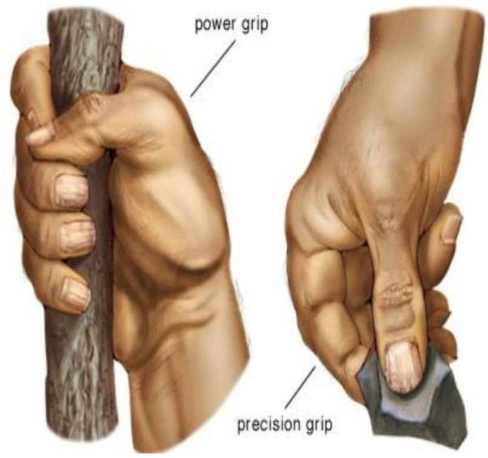


Figure 3: This figure illustrates the human grasps- power grip and precision grip based on the object, shape, size and finger postures.

Adapted from: https://www.britannica.com/science/human-muscle-system/images-videos/A-fully-opposable-thumb-gives-the-human-hand-its-unique/73005

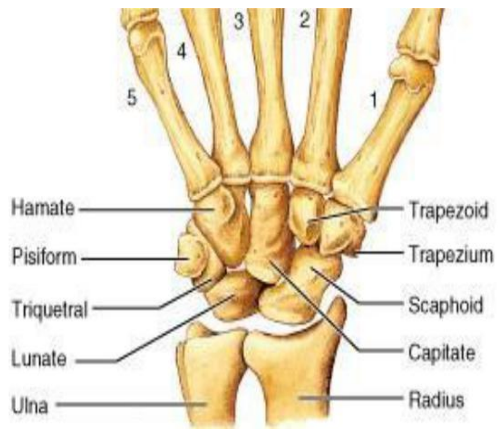


Figure 4:This figure illustrates Proximal row carpal bones: scaphoid, lunate, triquetrum, pisiform. Distal row carpal bones: trapezium, trapezoid, capitate, hamate.

Adapted from: http://www.anatomy-diagram.info/wrist-boneanatomy/

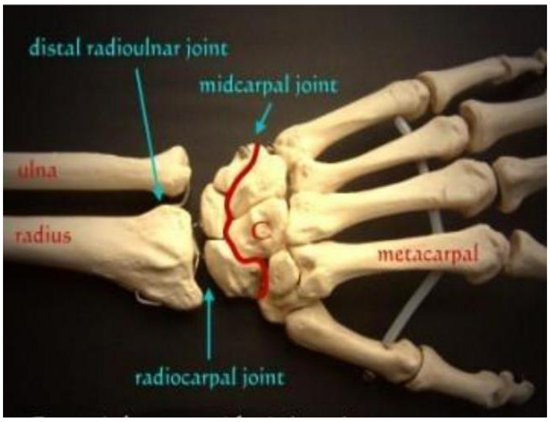


Figure 5: This figure illustrates that the radiocarpal joint or the wrist joint is biaxial and ellipsoid. The mid carpal joint is formed by the proximal and distal row of carpal bones.

Adapted from:
http://www.primehealthchannel.com/radiocarpal-joint.html

1.2 Ligaments & Pulleys

Ligaments and pulleys are important musculoskeletal structures that contributes to stability during movement, control and contributes in flexor mechanism of wrist and hand. Ligaments are fibrous band of tissues that join the bones together and offer stability during joint motion. Ligaments are located in the volar and dorsal surface of the wrist and are described as extrinsic (connects carpal bones to radius, ulna and metacarpal bones) and intrinsic (connect the individual carpal bones) (Connell et al, 2001; Weintraub, 2003). The ligaments of the wrist and hand are listed in the table below:

Joint	Palmar/Dorsal	Ligament
Radiocarpal joint	Palmar	Radioscaphocapitate (RSC), Long radiolunate (LRL) or radiolunotriquetral, Short radiolunate (SRL), Radioscapholunate(RSL)
	Dorsal	Dorsal radiocarpal (Dorsal RC)
Midcarpal joint	Palmar	Scapho-trapezium-trapezoid (STT) Scaphocapitate (SC) Capitate trapezium (CTm) Triquetrocapitate (TC) Triquetrohamate (TH) Palmar scaphotriquetral (Palmar ST)
	Dorsal	Dorsal intercarpal (DIC) Dorsal scaphotriquetral (Dorsal ST)

Ulnocarpal joint		Ulnolunate (UL), Ulnocapitate (UC), Ulnotriquetral (UT)
Distal radioulnar joint		Triangular fibrocartilage complex (TFCC) Distal radioulnar (DRU) Palmar radioulnar (PRU) Meniscus homologue (MH)
Intrinsic or intra-articular or interosseous ligaments		
Proximal carpal row		Scapholunate interosseous (SLI) Lunotriquetral interosseous (LTI)
Distal carpal row		Trapeziotrapezoid (TT) Trapeziocapitate (TC) Capitohamate (CH)
MCPJ		Palmar ligament Medial collateral ligament Lateral collateral ligament Deep transverse metacarpal ligament
IPJ		Palmar ligament Medial and lateral collateral lig
Distal carpal row		Trapeziotrapezoid (TT) Trapeziocapitate (TC) Capitohamate (CH)
MCPJ		Palmar ligament Medial collateral ligament Lateral collateral ligament Deep transverse metacarpal Ligament
IPJ		Palmar ligament Medial and lateral collateral lig

Table 1:This table lists the joints of the wrist and hand and the ligaments attached to it (Apergis, 2013)

The ulnar collateral and radial collateral ligament provides stability to the MCP, PIP and DIP joint (Madan et al, 2014) Injury to the PIP joint can cause dislocation, fractures or damage the collateral ligament. Collateral ligament injury occurs due to the axial loading and forceful dorsiflexion (Rettig, 2004; Lee and Healy, 2005). The ulnar and radial collateral ligaments are commonly susceptible to injuries with the ulnar ligament having more injuries (Berger and Weiss, 2004; Dickson and Evans, 2013). This injury results in restricted range of movement, poor pinch and grip strength of the thumb (Doyle and Botte, 2003; Venus and Chester, 2012).

In the digits, the flexor tendons pass through fibrous rings called pulleys which direct the tendons keeping them close to the phalanges, thereby facilitating the flexion of the digits (Tubiana et al, 1998). There are eight pulleys at different locations from MCP to the distal phalanx. There are five annular pulleys (A1-over MCPJ, A2-over proximal phalanx, A3- pulley over PIP, A4-over middle phalanx, A5-over DIPJ) and three cruciate pulleys (C1, C2, C3) (fig: 6). Annular pulleys keep the flexor tendons constrained so that tendons are able to glide smoothly in flexion, extension and contribute to mechanical efficiency. Excessive loading or direct injuries can rupture the pulleys thus, resulting in bowstringing of the tendons (fig:7) (Brand et al, 1975; Uchiyama et al, 1995; Doyle, 2006). Intricate annular pulleys (A2 and A4) are important in preventing bowstringing of the tendons thus maintaining the essential biomechanics of flexion (Dona and Walsh, 2006; Lehfeldt et al, 2008). The degree of tendon bowstringing is controlled by A3 pulley and also holds the tendons close to the phalanges (Schoffl and Schoffl, 2006). Bowstringing can result in poor grip strength, inability to perform fine motor tasks, loss of proper finger flexion and stiffness in the joints.

Cruciate pulleys have two crossing bands, they provide additional stability and flexibility to the tendon sheaths (Fig:6). During finger flexion, the cruciate pulleys are constricted and allow the annular pulleys to move together (Seiler, 2002; Lowrie and Lees, 2013). The constriction also helps to prevent any impingement on the underlying tendon (Katzman, 1999). The pulley system for the thumb consists of one oblique pulley centered over proximal phalanx and two annular pulleys (A1-over MP joint, A2-over IP joint) (Warwick et al, 2009). The oblique pulley facilitates full excursion and prevents bowstringing of the flexor pollicis longus and is considered as the most important pulley of the thumb. (fig:8) (Bayat et al, 2002).

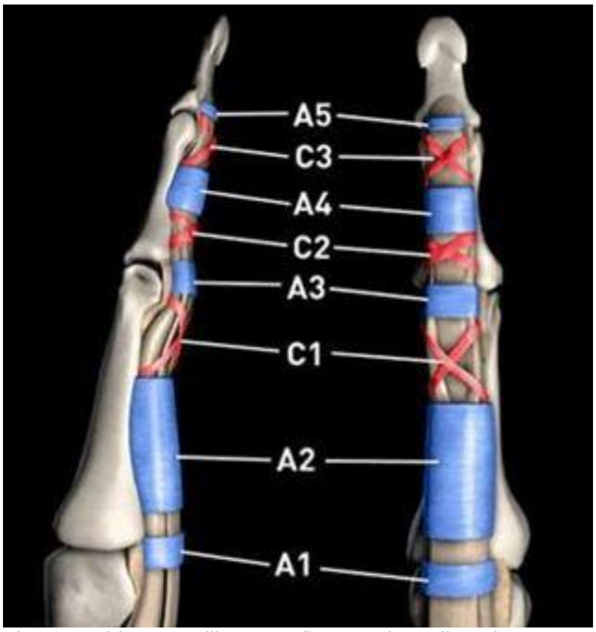


Figure 6: This Image illustrates five annular pulleys (A1-over MCPJ, A2-over proximal phalanx, A3- pulley over PIP, A4-over middle phalanx, A5-over DIPJ) and three cruciate pulleys (C1, C2, C3)

Adapted from:

http://radAdapted from.us/pulley-lesion-of-the-fingers/

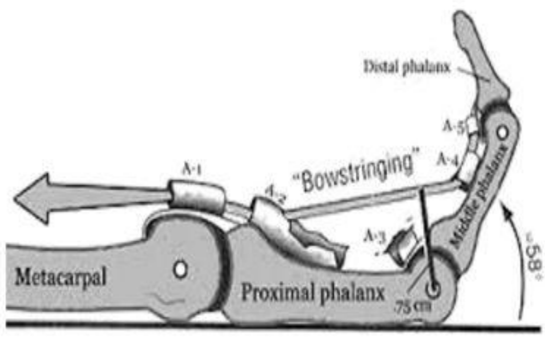


Figure 7: This image illustrates that excessive loading or direct injuries can rupture the pulleys (A3) thus, resulting in bowstringing of the tendon.

Adaptedfrom:**http://www.massagetoday.com/mpacms/mt/article.php?id=1429**

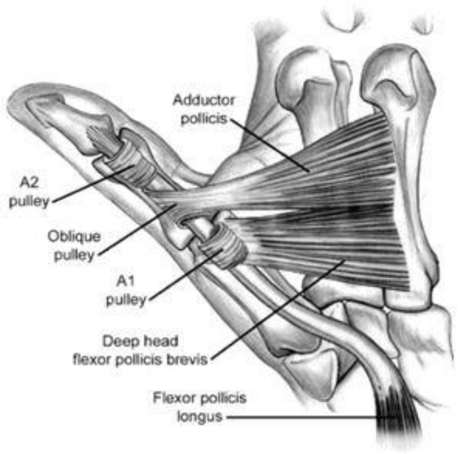


Figure 8:This image iilustrates A1, A2 and oblique pulley of the thumb. It facilitates full excursion and prevents bowstringing of the flexor pollicis longus.

Adapted from: **http://boneandspine.com/flexor-tendon-pulley-system-of-hand/**

1.3 Retinaculum & synovial sheath

The retinaculum is a strong fibrous band surrounding the tendons that act to stabilize and hold them in place. At the wrist there are two types of retinaculum- flexor (transverse carpal ligament or anterior annular ligament) at the palmar side and extensor at the dorsal side (fig: 9,10). The flexor tendons and median nerve passes under the flexor retinaculum to the pisiform and hook of the hamate. It passes laterally to tubercles of scaphoid and trapezium. The extensor retinaculum extends obliquely at the back of the wrist and attaches laterally to the anterior border of radius, medially to the triquetral and pisiform bones (Tubiana et al, 1998; Doyle, 2006; Drake, 2009).

The synovial sheath is a layer that envelops the tendons. There are two synovial sheaths present around the digital flexor tendons- one surrounds flexor digitorum superficialis and flexor digitorum profundus and a second surrounds flexor pollicis longus. Extensions of these sheaths arise from the flexor retinaculum to middle of the metacarpal bones around the index, middle, ring and little finger tendons (Drake, 2009; Snell, 2012). Synovial sheaths can be affected by rheumatoid arthritis. In addition, an infection in the synovial sheath leads to tenosynovitis (inflammation of the sheath), thus such circumstances therefore have the potential to impair the functions of hand (Jacob, 2007).

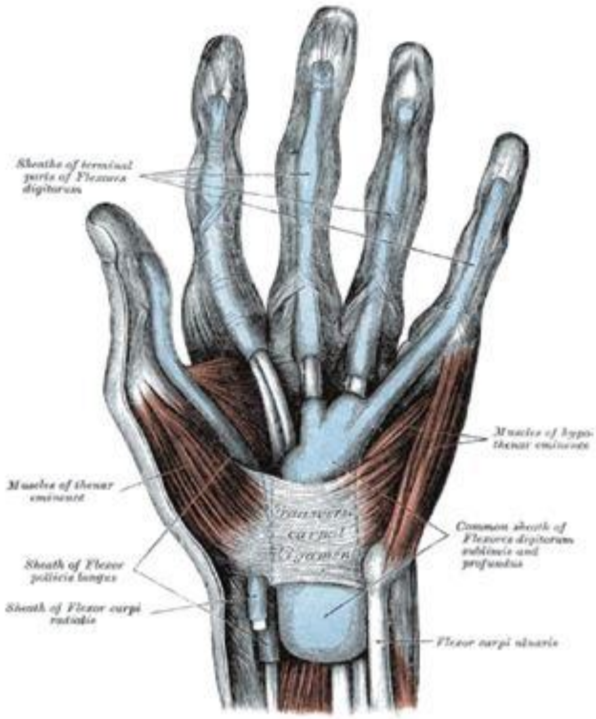


Figure 9: This image illustrates the flexor retinaculum (transverse carpal ligament or anterior annular ligament) which is at the palmar side of the hand.

Adapted from: **https://en.wikipedia.org/wiki/Flexor_retinaculum_of_the_hand**

Figure 10: This image illustrates the extensor retinaculum which is at the dorsal side of the hand.

Adapted from: **https://en.wikipedia.org/wiki/Extensor_retinaculum_of_the_hand**

1.4 Muscles

Muscles that act to produce flexion of the wrist are: flexor carpi radialis, flexor carpi ulnaris and palmaris longus (when present). Muscles flexing the digits which also assist in wrist flexion are flexor digitorum superficialis, flexor pollicis longus, flexor digitorum profundus (fig:11). Muscles that extend the wrist are: extensor carpi ulnaris, extensor carpi radialislongus and brevis, extensor digitorum, extensor indicis, extensor digiti minimi, extensor pollicis longus and brevis (fig:12) (Chaurasia, 2004; Drake2009; Snell, 2012; Taylor and Schwarz, 1970; Zatsiorsky and Prilutsky, 2012).

The thin and elongated lumbricals originate from the FDP and insert in the extensor expansion of the extensor digitorum. They are formed of unipennate (index and middle finger) or bipennate (ring and little finger) muscles (Dell and Sforzo, 2005). The primary function of the lumbricals is extension of PIP, DIP joint with flexion at MCP joint. Hand injury can compromise the intrinsic muscles resulting in difficulty to perform fine motor functions. The combination of index finger and thumb pinching is carried out by the lumbricals. The absence of these small muscles would result in nail to nail contact (Kamper et al, 2002; Joshi et al, 2005; Bilge et al, 2007; Sawant et al, 2012; Burlakoti et al, 2013; Wang and Chung et al, 2014).

The interrosei are group of small muscles located between the metacarpals. There are both palmar (volar) and dorsal interossei. The function of dorsal and palmar interossei is abduction and adduction of the digits at the MCP joint respectively (Morrison and Hill, 2011; Hosapatna et al, 2013). Damage to the intrinsic muscles can compromise the full joint range of motion in the fingers and can hinder the grip performance (Dell and Sforzo, 2005). During a tendon injury both lumbricals and interossei can be injured thus affecting the hand function.

The hand function is a combination of movements performed by both intrinsic and extrinsic muscles, bones and tendons. The interrosei and lumbricals are intricately related to both flexor and extensor tendons, therefore the risk of their being affected is high after a tendon injury.

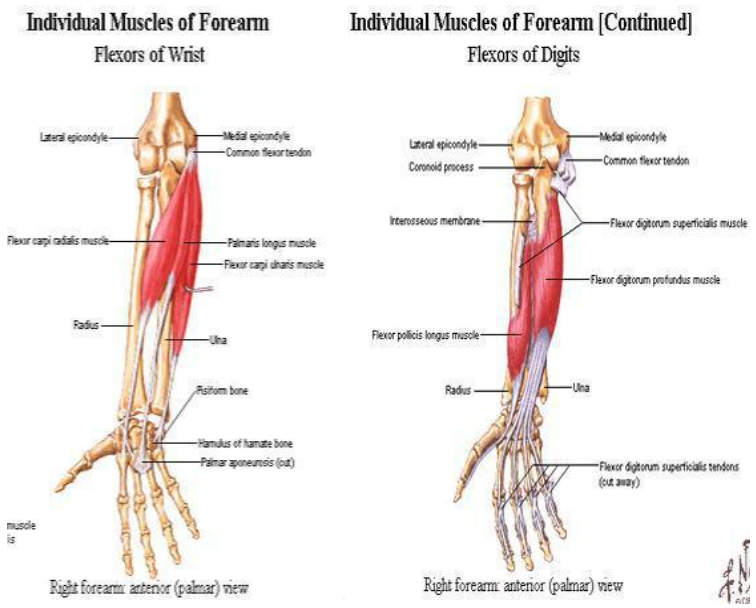


Figure 11: This image illustrates the different flexor muscles of wrist & fingers (palmar view).

Adapted from: **https://www.netterimages.com/flexors-of-wrist-and-digits-labeled-cleland-2e-general-anatomy-frank-h-netter-50697.html**

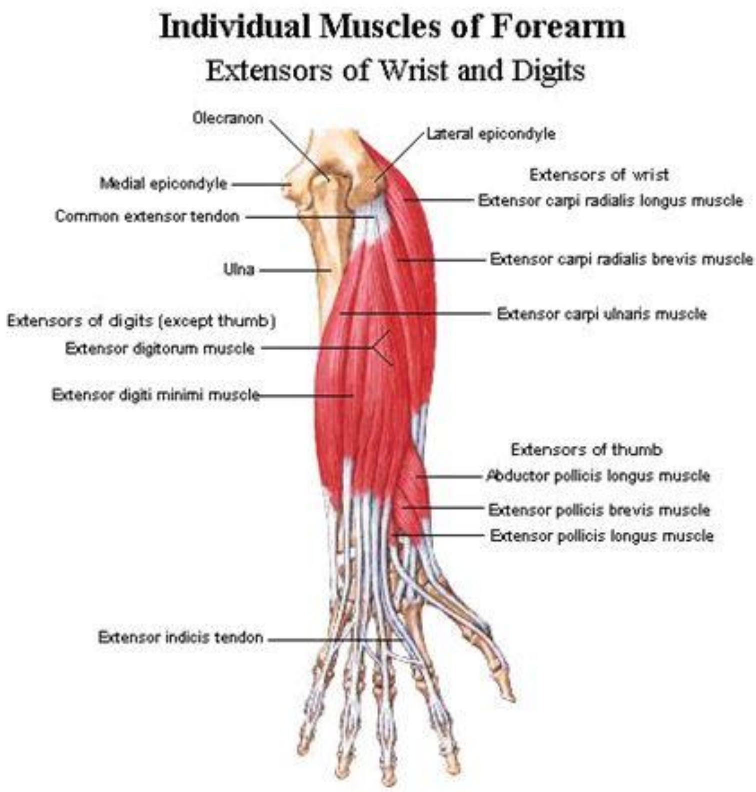


Figure 12: This image illustrates the different extensor muscles of wrist & digits

Adapted from: **https://web.duke.edu/anatomy/Lab12/Lab12.html**

1.5 Tendons

Tendons connect muscles to bone which allows the force generated to be transmitted from the muscle to the bone (Weintraub, 2003). They are composed of a bundle of collagen fibres (collagen fibres are formed from a collection of collagen fibrils) (Sharma and Maffulli, 2006; Graffin et al, 2012). Tendons are mostly composed of type I collagen fibres. Type II collagen fibres are found at the osteotendinous junction. Ligaments consist of 9-12% of type III collagen fibres (James et al, 2008; Lin et al, 2004; Franchi, 2006). The blood supply to the tendons at the musculotendinous junction, osteotendinous junction is via the synovial sheath.

The flexor tendons that act at the wrist and hand cross some regions like the wrist, carpal tunnel, fibrous flexor sheath and metacarpophalengeal joints (fig 13). The digital flexor tendons fan out in the palm towards their respective digits after passing through the carpal tunnel. The origin and insertion of the flexor muscles and its tendons is important to know in order to understand the tendon anatomy.

The flexor digitorum superficialis muscle originates from the medial epicondyle of the humerus (common flexor origin) and 4 tendons arise in the wrist region. These 4 tendons further divides into two terminal slips and inserts at the medial and lateral side of the proximal phalanx of 4 fingers (index, middle, ring, and little). The flexor digitorum superficialis tendon acts to move the proximal interphalangeal joint. Any injury to this tendon can disrupt PIP joint movement and compromising activity involving fine and gross grasp (Tubiana et al, 1998; Doyle, 2006).

The flexor digitorum profundus muscle originates from upper three quarters of the medial and anterior surfaces of the ulna. The muscle runs down the forearm deep to the superficialis muscle and 4 tendons arise at the wrist region and attaches to the base of distal phalanges of the finger. Any injury to this tendon can compromise the DIP joint function resulting in disruption of the finger tip movements, fine motor skills and regular ADL (Tubiana et al, 1998; Chaurasia, 2004; Doyle, 2006; Drake et al, 2009).

The primary function of flexor pollicis longus tendon is flexion of the interphalangeal joint of the thumb and secondary function is to assist in carpometacarpal and metacarpophalangeal joint flexion. Any injury to this tendon can affect the functional use of the thumb like gripping and pinching (Ozturk et al, 2004).

The function of flexor carpi ulnaris (FCU) and flexor carpi radialis (FCR) tendon is adduction (ulnar deviation) and abduction (radial deviation) of the wrist respectively (Bruin et al, 2011). In addition, both the tendons help in wrist flexion. Injury to FCR tendon is associated with distal radius fracture, scaphoid fractures and other serious hand trauma such as crush injuries (Hepper and Boyer, 2011).

The extensor tendons are: extensor carpi radialis brevis, extensor pollicis brevis and extensor carpi radialis longus (fig 14). They run under the extensor retinaculum to the hand passing through five fibro osseous and one fibrous tunnel. The extensor retinaculum consists of supratendinous, infratendinous layer and is a wide fibrous band which also prevents the bowstringing of the extensor tendons (Doyle, 2006).

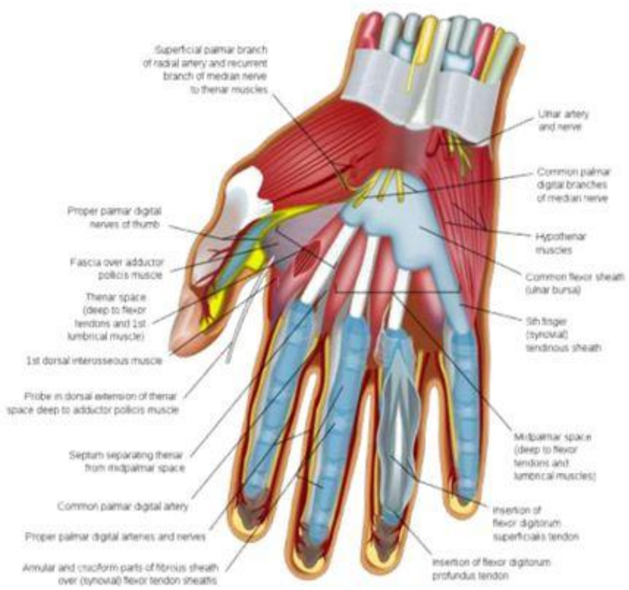


Figure 13:This image illustrates various flexor tendons, flexor sheath, nerves & arteries of hand.

Adapted from: **http://dla-by411.blogspot.co.uk/2011_02_01_archive.html**

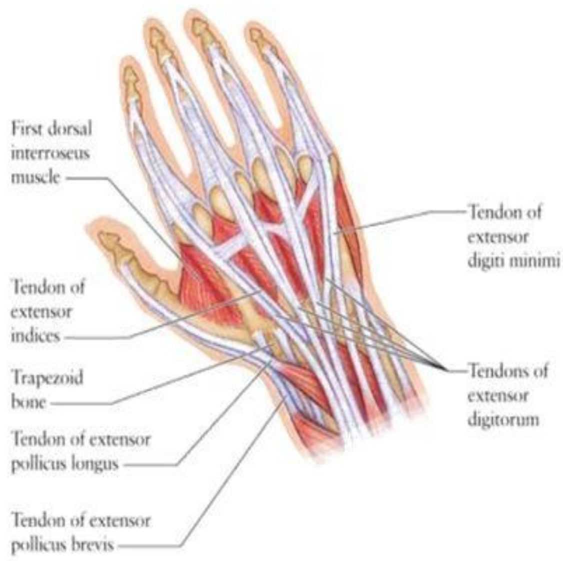


Figure 14:This image illustrates the extensor tendons of hand.

Adapted from: **http://anatomyproartifex.blogspot.co.uk/2011/06/dorsal-hand-dorsal-foots-fraternal-twin.html**

1.6 Arteries

The forearm, hand and wrist are supplied by the ulnar and radial arteries. The ulnar artery runs under the flexor carpi ulnaris lateral to ulnar nerve at the wrist. It enters the hand to the transverse carpal ligament through the Guyon’s canal. The ulnar canal/tunnel or the Guyon's canal/tunnel is in the palmar side of the wrist which allows the passage of ulnar artery and ulnar nerve into the hand. The radial artery runs between brachioradialis and flexor carpi radialis. The palmar carpal branch arises near the lower border of the pronator quadratus and runs medially to the flexor tendons. The superficial palmar branch arises just before the radial artery leaves the forearm and enters through the thenar eminence (Hentz and Chase, 2001; Tyldesley, 2002; Snell, 2012; Arachchi et al, 2013).

1.7 Nerves

The nerve to the wrist and hand is supplied by median, ulnar and radial nerve. The median nerve passes deep through the flexor retinaculum, enters the palm through the carpal tunnel and provides a nerve supply to the thenar muscles and first two lumbricals. Laterally the ulnar nerve runs between flexor digitorum profundus and superficialis and enters the palm superficial to the flexor retinaculum.

The radial nerve has two branches, one passes through the posterior part of the forearm (deep branch) and other runs under the brachioradialis muscle which passes through the anatomical snuff box (Chaurasia, 2004; Drake, 2009; Snell, 2012).

Nerves and blood vessels can be injured in many circumstances and are often a consequence of trauma. A delayed management post nerve laceration might result in long term sensory and motor deficits (Luczak et al, 2011). Both the intrinsic and extrinsic muscles require blood supply to function (Bilge et al, 2007). Any disruption in the nerve supply can affect the sensory input provided by the nerves. The combination of motor and sensory mechanism in the hand results in the proper functioning of the hand and thus this relationship is interdependent. The consequence of injury disrupting the motor and sensory mechanism can be long term if not effectively managed. Glass cut or crush injuries to the hand affects structures like muscles, nerves, tendons and bones. A nerve reconstruction might be required when the extent of damage is vast (Ray and Mackinnon, 2011; Boyd et al, 2011). Although the function of the structures are well explained, the interactions between these structures are less studied in the literatures. This understanding of the interactions is important inorder to predict the impact of an injury and also see the response to rehabilitation.

CHAPTER: 3

2 Tendon injuries:

Complex injuries to the wrist and hand is common and unless appropriately managed (either conservatively or surgically), can lead to impairment, activity limitation and exclusion from participation. There are various types of injuries affecting the structures of wrist and hand. One of the common type of injury is glass cut injury which can be either minor or major depending on the extent of injury (either layer of skin or internal structures). Severe injuries can damage the arteries or blood vessels and can result in major loss of blood (Hentz and Chase, 2001; Beasley, 2003; Bancroft, 2013; Raza et al, 2014). Glass cut injures not only causes trauma to the tendon but also the surrounding structures such as tissues, muscles, bones, nerves or arteries which might result in motor or sensory loss in wrist and hand (Griffin et al, 2012; Cheung et al, 2013). Sports injuries, biting injuries (animal or self) can also damage the underlying structures of hand and wrist (Bancroft, 2013; Carlson et al, 2013).

Animal bites can be dangerous as the chances of infections are high along with the damage of the internal structures like muscles, bones, nerves, ligaments and tendons (Cheah and Chong, 2011). Similarly, human bites can occur during fights, children or people with learning and mental disabilities where the teeth might break into the skin and affect the internal structures. Bacterial infections like streptococci and Staphylococcus aureus etc. are common in human bites. It is worthwhile to mention that the extent of damage to the structures surrounding the tendons can depend on the anatomical variability.

The shape of the tendons can be round or flat like ribbons and when healthy, they appear white and consists of fibroelastic texture. The tendon is composed of tenoblasts (immature tendon cells and are spindle shaped) and tenocytes lying within the extracellular matrix. The tenoblast gets elongated and transforms into tenocytes. The tenoblasts and tenocytes consists of 90-95% of cellular elements of the tendons. Chondrocytes, synovial cells and vascular cells consists of the remaining 5-10% of the cellular elements of the tendon (Sharma and Maffulli, 2006).

The biological healing mechanism of tendons falls under categories like intrinsic and extrinsic healing. Intrinsic healing helps in the proliferation of the fibroblasts, epitenon and endotenon cells within the tendon. In extrinsic healing depends on migration of fibroblasts and inflammatory cells from periphery of the injury to effect repair of the tendon (Maffulli et al, 2004; Walsh, 2006). After an injury to the tendon fibres, it needs to well-formed in order to restore the functions. The biological tendon healing mechanism involves the following three stages:

Inflammatory phase: After an injury to the tendon, clot formation takes place. Molecules such as platelets, neutoplils, erythrocytes, macrophages and growth factors like platelet-derived growth factors (PDGF), transforming growth factor beta (TGF beta) and insulin like growth factors (IGF) are released and moved towards the site of the wound. The extrinsic cells (neutrophils, macrophages) and intrinsic cells (endotenon, epitenon) engulf the necrotic debris by the process of phagocytosis.

Proliferative phase: The fibroblasts synthesises the extracellular matrix and its components like collagen, proteoglycans, glycoseminoglycans which is followed by granular tissue formation, collagen deposition and neurovascularisation. At the end of this stage, the injured tissue consists of large amount of extracellular matrix components, water and cells.

Remodelling phase: In this phase, there is decrease in cellular and vascular content of the callus tissue and increase in collagen fibres (type I). The collagen fibres are dense, organised and forms a well oriented matrix (approximately 8 weeks after injury) (James et al, 2008; Franchi, 2006; Maffulli et al, 2004; Walsh, 2006).

There are five flexor tendon zones in hand based on regions of potential tendon injury (Fig 15). Zone I, extends from tip of the finger to the middle of the middle phalanx contains only flexor digitorum profundus (FDP). Injury to this zone can disrupt FDP tendon function and causes the inability to flex the DIP joint. The pulleys such as A4, C3 and A5 are present in this zone, therefore these can also be damaged. Zone II, extends from middle of middle phalanx to the distal palmar crease and contains both flexor digitorum profundus and flexor digitorum superficialis. Injury to this zone involves both FDP and FDS tendons and disrupts the flexion of DIP and PIP joint. The interweaving of the FDP and FDS tendons, multiple pulleys (A1, A2, A3, A4, C1, C2) in this zone increases the complexities thereby this can impact upon the ultimate outcome compromising the results (Kotwal and Ansari, 2012). Zone II is often referred to also called as ‘No Man’s Land’ due to its relatively poor results after a tendon repair (Frontera et al, 2008). Zone III, extends from distal palmar crease to the distal edge of flexor carpal ligament. In addition to flexor tendon injuries, the lumbrical muscles (index, middle, ring, little) are also likely to be injured which originates from the radial side of the FDP tendon in the centre of the palm. The lumbricals contribute to interphalangeal joint extension and assists in MCP flexion (Doyle and Botte, 2003; Jebson and Kasdan, 2006). Zone IV is under the carpal ligament and here injuries are rare. Zone V extends from the proximal border of the transverse carpal ligament to the musculotendinous junctions of the flexor tendon. Within this zone, there is a potential for injury to the wrist flexors, finger flexors, nerves (median/ulnar), vessles and arteries (radial/ulnar) (Doyle, 2006; Kisner and Colby, 2007). Due to the presence of many structures in this region post-surgery adhesions and scars can occur, thus resulting in poor outcome post tendon repair (Bircan et al, 2005).

Flexor tendons of the thumb are flexor pollicis longus which flexes the IP, MCP and CMC joints whilst flexor pollicis brevis flexes the thumb towards the palm (Tang et al, 2012). There are three

zones to describe the flexor tendon injuries in the thumb. Zone 1 runs from the tip of the thumb to the interphalengeal joint crease and contain oblique and A2 pulleys, Zone 2 extends from the MCP joint crease to the IP joint crease and beneath the thenar muscles is the zone 3. Most tendon injuries occurs in the IP crease, near the flexor pollicis longus insertion (palmer surface of the distal phalynx of the thumb). In zone 2 injuries, both thenar muscles and flexor pollicis longus muscle are affected (Jebson and Kasdan, 2006).

The extensor tendons are located on the back of the hand and fingers and are relatively superficial and they assist in extending the wrist and fingers. The causes of injury are cut, broken bones, lacerations, crush injury and arthritis. Two common deformities after an extensor tendon injury are mallet finger injury and boutonniere deformity (Rettig, 2004; Doyle, 2006; Wolfe et al, 2011).

The extensor mechanism of the digits can be significantly affected following extensor tendon injury. As extensor tendons sits more superficially than the flexor tendons hence this type of injuries are more common (Frontera et al, 2008). Extensor tendon zones are described as occurring between zones I to VIII (fig:16). Injury to zone I (also called mallet deformity) can be caused due to the sudden forced hyperextension of the extended DIP joint and mostly affects long, ring and little finger. Zone II injuries are more commonly due to crush and laceration injuries. Zone III injuries can occur due to forced flexion of an extended PIP joint and damage to the neurovascular structures. Zone IV injuries are less common, however they show signs of adhesions due to the intricate positioning of the tendon and bone in this region, thereby affecting the movement of the finger. Zone V rests over the MCP joints and is considered as a common area for extensor tendon injuries. It occurs mostly when the joint is in flexion and common causes are lacerations, bites and joint dislocations. Location of Zone VI is over the metacarpals and clinical presentation is similar to zone V injuries. Complete lacerations at the level of Zone VII are rare due to the extensor retinaculum which covers the tendons. Zone VIII can involve multiple tendon injuries since it is located at the level of distal forearm (Doyle, 2006; Kisner and Colby, 2007; Frontera et al, 2008).

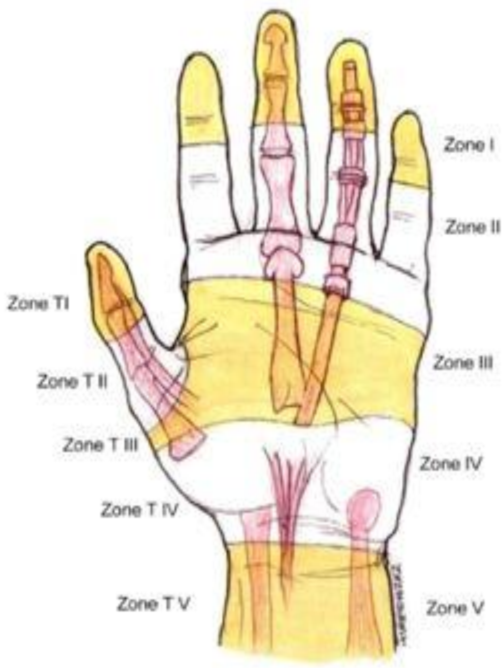


Figure 15:This image illustrates the flexor tendon zones of hand (zone I-V)

Adapted from: **http://emedicine.medscape.com/article/1245236-overview#a3**

Figure 16: This image illustrates the extensor tendon zones of hand (zone I-VIII)

Adapted from: **http://www.boneandjoint.org.uk/content/focus/extensor-tendon-injury**

CHAPTER: 4

3 Literature review:

Divided flexor tendons cannot heal without surgery as the two ends needs to be surgically attached. If the surgery is delayed for more than 3 weeks, it is called secondary repair and complications like proximal tendon end swelling, tendon shortening and muscle fibrosis might arise before the repair (Elliot, 2011; Tang, 2006). The main objective of the surgery is to connect the divided tendons without compromising flexor tendon gliding, finger and thumb functions.

Following surgery, rehabilitation is very important to promote full joint range of movement, prevent adhesions, scar tissue formation and stiffness around the surgical site (Frueh et al, 2014). An appropriate rehabilitation regime has to be followed based on the surgery, tendons and other structures involved in the repair process. Inability to comply with an appropriate rehabilitation program can lead to complications such as opening of the surgical site and rupture of the sutured tendons. A clear understanding on the structures injured during the trauma, type of surgical method and type of suture material used is very important to plan an effective rehabilitation program post tendon repair.

A comprehensive understanding on the factors that can lead to better recovery in a patient’s health is pivotal as this might help to avoid needless health care costs and early return to work. There are many studies around the rehabilitation after tendon repair. However, surgeons and therapists are still confronted with functional impairment which has adverse effects on patients’ activities and participation. For an optimal treatment plan, it is essential to explore the factors that can accelerate the healing process and promote tendon recovery which depends on the types of injuries. For example, crushing injuries may be complex due to the involvement of many structures like nerves, tendons and joints (Bircan et al, 2005). A firm grasp and understanding on the prime factors contributing towards tendon recovery is imperative to suitably execute the treatment in any clinical practice.

In this chapter an extensive literature search is attempted to extract data on the possible factors contributing towards flexor tendon recovery, which could be highly beneficial towards critically understanding the recovery process and the best possible treatment plan.

This literature review will predominantly attempt to focus on the pertinent factors that can perhaps contribute towards tendon recovery. A literature search was conducted within: CINAHL, MEDLINE, AMED, SPORTDISCUS, PSYCINFO and COCHRANE databases. The search terms are presented in table 3. The inclusion and exclusion criteria, key words and detailed descriptions of the search strategy are presented below:

Inclusion criteria	Exclusion criteria
English language Papers	Animal studies
Any study design	Non-English papers (where translation was not possible)
Cadaveric studies	Case report
Original articles with clinical outcomes	
Papers with flexor tendon injury/repair/sutures/surgery/outcomes measures/rehabilitation	

Table 2:Inclusion and exclusion criteria

Search	Key words
1	Tendon injuries (MeSH)
2	Hand OR wrist OR forearm
3	1 OR 2
4	Sutures (MeSH)
5	Surger*
6	4 OR 5
7	Treat* OR rehabili* OR therap*
8	Zone*
9	3 AND 6 AND 7 AND 8

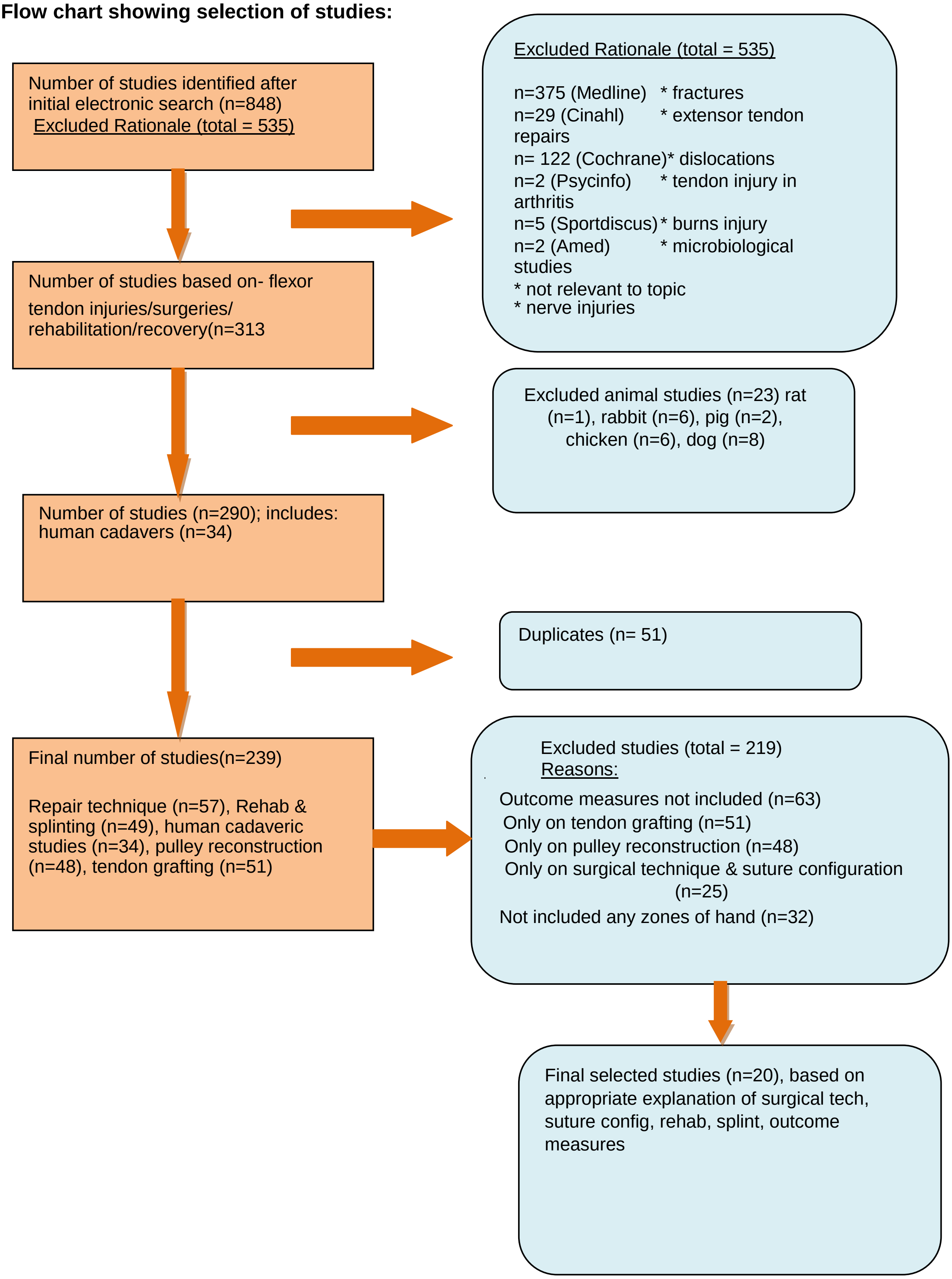
Table 3:**Search terms and key words**

The search was conducted in all the above mentioned databases without any limitations and the results brought a large number of studies as illustrated below. Following this a flowchart is made showing the selection of studies.

Database	Total no. of studies
MEDLINE	625
CINAHL	64
COHRANE	134
PSYCINFO	8
SPORTDISCUS	9
AMED	8
Total Studies:	**848**

Table 4: Database and number of studies

Flow chart showing selection of studies:



The preliminary impression from the review suggests that there are 13 prospective studies (includes 1 RCT) and 7 retrospective studies. The studies have reported a lot of confounding factors hence it is difficult to draw specific conclusions. In these circumstances, the review findings will be structured in the following way:

a) Identify the factors that contribute to recovery in patients after a surgical repair of the flexor tendon.

b) Provide a narrative study of the results with a focus on the rehabilitation process.

The two factors that contributes to the recovery post tendon repair are surgery and rehabilitation which will be discussed below.

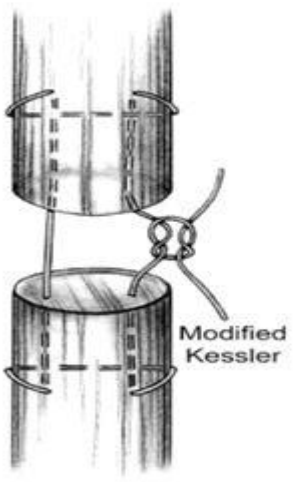
3.1 Surgery

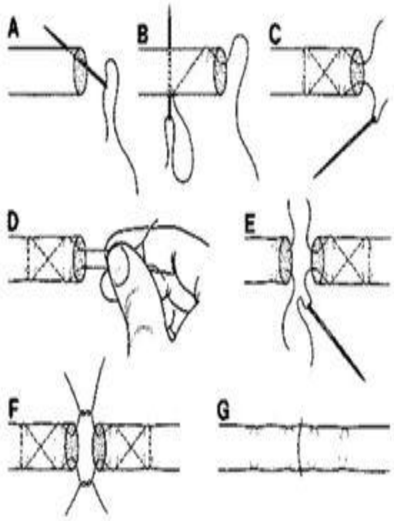
3.1.1 Surgical method

There are variety of surgical techniques in use however, the optimal type of repair remains elusive. Modified Kessler, Figure of Eight, Tang, Tsuage, Lim/Tsai, Mantero, Adelaide, Strickland, Kessler, Becker, modified Becker, Bunnell, modified Bunnell, Mason-Allen, Savage, Sandow, Silva, Lee and author's individually preferred techniques are some of the surgical methods used to repair flexor tendons (appendix 1). Some of the surgical methods used in the selected papers are discussed below:

a) Modified Kessler method:

The modified Kessler method (appendix 1, fig: 17) was used in - Caulfield et al (2008), Hung et al (2005), Kitsis et al (1998), Kitis et al (2009), Navali et al (2013), Bal et al (2011), Chan and Fung (2006), Orkar et al (2011), Bircan et al (2005), Moieman and Elliot (2000) and Orhun et al's (1999) studies. This was used in combination of different suture configurations.





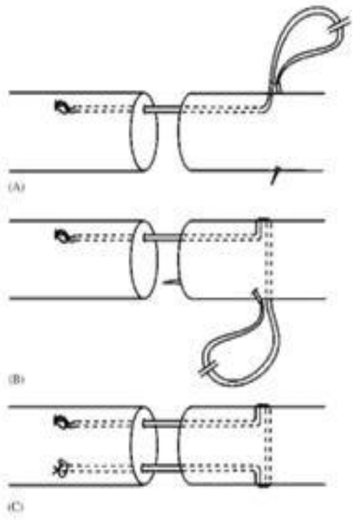


Figure 17: This image illustrates the suture technique of Modified Kessler method.

Adapted from: **http://plasticsurgerykey.com/tendon-injuries-and-tendonitis/**

Figure 18: This image illustrates the suture technique of Figure of eight method.

Adapted from: **http://murtagh.fhost.com.au/html/practice_tips/9780070158986_001_ch07.htm**

Figure 19: This image illustrates the suture technique Tang's method.

Adapted from: **http://rlbatesmd.blogspot.co.uk/2008/07/flexor-tendon-repair_10.html**

The suture is started from one end allowing the suture material to be placed in the cut ends. The suture material is inserted from one cut end of the volar lateral side of the tendon. Following this, the suture runs in a transverse plane across the tendon. The exit of the suture is on the opposite side of the volar lateral surface of the tendon. This procedure is repeated on the opposite side of the tendon and the knots are tightened gradually and gently until the tendon ends are close to each other. Following this a continuous epitendinous suture is used to even out the frayed ends (Kulkarni, 2008).

b) Figure of eight*:*

The figure of eight (appendix 1, fig: 18) was used in - Al-Qattan 2011 (involving zone II study), Al-Qattan 2011 (involving zone III study), Al-Qattan and Al-Turaiki 2009.

The above image shows the technique of the figure of eight suture. It starts from A, where the needle is inserted from one end leaving the thread outside the cut end. B and C show how a figure of eight shape is created. Following this in D the ends of the suture are pulled. Similar procedure is followed in E and a knot is made at F. The suture is gently pulled so that the tendon ends are approximated (G).

c) Tang’s technique:

A combination of author's own technique and Tang's technique was used in Hatanaka et al, 2002 study.

The technique above is called modified Tang’s method of tendon repair using four strands. In A, the suture passes from one end of the tendon longitudinally to the other cut end. The needle is then inserted to the lateral side of the tendon and passes in a transverse plane (B). Following this, the needle is inserted back to the tendon and continues longitudinally to the end of the original tendon stump. This completes the second longitudinal suture (C) (Tang and CAO, 2005).

d) Adelaide repair:

This repair was used in Sandow and McMahon (2011) study (Fig 20).

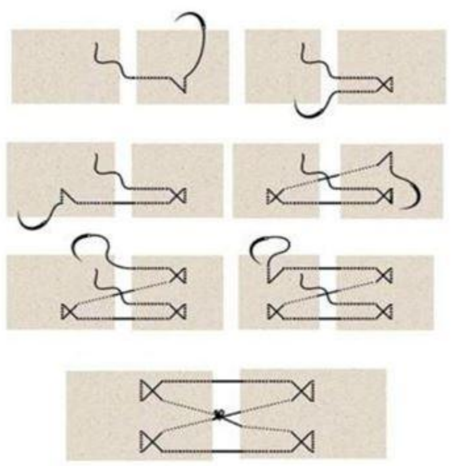


Figure 20: This image illustrates the suture technique of Adelaide method.

Adapted from:**http://jhs.sagepub.com/content/early/2013/06/19/1753193413492914.abstract**

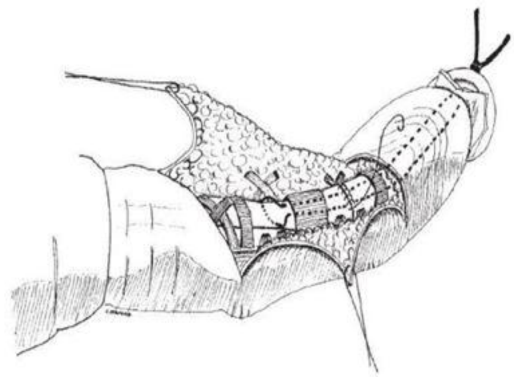


Figure 21: This image illustrates the suture technique of Mantero method.

Adapted from: **http://jhs.sagepub.com/content/24/2/148.abstract**

An insertion is made in the tendon with the needle and passed through the loop. It is then locked and comes out through the outer part of the tendon. The suture is then passed back through the tendon at the site of transection and then inserted to the other cut end of the tendon. The above process is repeated again and the two ends of the suture are tied together to make a knot.

e) Mantero technique:

This technique was used in Guinard et al, 1999, Schaller and Baer, 2010 studies (Fig 21).

The entry of the suture into the tendon is through the pulp tip. Following this, the suture is secured by an omega shaped loop which is located away from the tendon laceration (at least 1 cm), after exposure by opening the digital sheath above the A4 pulley. The dashed line is the core suture and it has to be placed in a mid-dorsal region to reduce disturbance of tendon vascularization. Finally an end to end running suture is made to secure the tendon ends.

3.1.2 Suture material

Suture material is an important aspect during wound closure. An ideal suture material should have a good tensile strength, security of the knot, non-allergenic and sterile properties (Tan et al, 2003; Lamky, 2013; Wu and Tang, 2014). Out of these properties, the important one is to maintain its tensile properties until tendon repair has achieved adequate strength and with minimal tissue response (Viinikainen et al, 2008). The suture materials used for tendon repairs are- stainless steel, ethibond, ethilon, prolene, fibre wire, supramid, barbed suture, PDS, Maxon. The table below presents the advantages and disadvantages of different suture materials (Wu and Tang, 2014).

Suture material	Advantages	Disadvantages
Stainless steel	stiffness and tensile strength is high	handling and kinking-poor
Ethibond	handling is easy with high tensile strength	Poor knot holding
Ethilon	Easy handling	Less strength
Prolene	Good knot holding capacity	Less strength
Fibre Wire	stiffness and tensile strength is high	Poor knot holding
Supramid	Easy handling	Less strength
Barbed suture	Increased suture tendon interaction; knotless	Poor tissue handling
PDS	Absorbable	Tensile strength of suture gets poor over time
Maxon	Absorbable	Tensile strength of suture gets poor over time

Table 5:This tables lists the advantages and disadvantages of various suture materials

Some of the common suture materials used in the selected studies are- polyester, nylon, prolene, ethilon and polydioxane.

a) Polyester: A non absorbable suture material made from polyethylene terephthalate.
b) Nylon: It is derived from hexamethylenediamine and adipic acid. It is classed as non-absorbable suture material and can be either monofilament or multifilament.
c) Prolene: This suture material is made of polypropylene and is monofilament in nature.
c) Ethilon: It is a polymer of nylon and is non absorbable suture in nature.
d) Polydioxane: It is monofilament, absorbable in nature and is composed of polymer of paradioxanone (Tan et al, 2003) (appendix:2).

3.1.3 Suture thickness and strands

The numerical digits such as 2/0, 3/0, 4/0, 5/0 and 6/0 are used to signify suture thickness. A smaller digit corresponds to thicker suture material and larger digits to thinner suture material (Labana et al, 2001). Furthermore, sutures can be monofilament or multifilament based on the strand material (Lamky, 2013). It is suggested that, multifilament suture material is better than the monofilament as the former helps in preventing breakage (Navali et al, 2008; Hatanaka et al, 2002; Hoffmann et al, 2008). Multifilament suture material exhibits good mechanical properties, however it can interfere in the process of healing and gliding of the tendon (Caulfield et la, 2008). Due to the presence of multiple filaments, the tissues surrounding the tendons can be damaged. This can result in adhesion and scar tissue formation, thus compromising the healing process (Navali et al, 2013). Some examples of multiple stranded sutures are- 2-strand, 4-strand, 6-strand and 8-strand suture (Wu and Tang, 2014).

3.1.4 Core suture and circumferential suture

The ‘core suture’ is the principal suture used for tendon repair (Savage, 2013). The important properties of an ideal core suture that influences the tendon repair strength are- good and easy handling of the material on soft tissues, durability of the material, strength of the material used, placement of the suture, number of strands and suture configuration (Seiler, 2001). Although core suture is the principal suture in tendon repair, however one of its shortcoming is gap formation at the tendon ends. This can be corrected by circumferential suture which ensures that the tendon ends meet laterally (Savage, 2013; Rawson, 2013). The reduced gap formation in the suture site and tensile strength is thus increased with the use of circumferential suture. The load sharing between the core and circumferential suture is crucial. If the core suture breaks, the distribution of the load between two sutures will be unequal thus leading to ruptures or poor tensile strength Savage, 2013). The different techniques used in circumferential suture are- Simple locking, Simple, Cross stitch, Lembart, Lin-Lock, Halstead (Rawson et al, 2013).

3.1.5 Knots

The knots in a tendon repair is considered as an important factor influencing the strength of the repair. The knots are considered as the weakest points in the suture site and the tendon ruptures usually takes place at the knots. A single knot technique is better than more knots at the surgical site. In single knots, all the strands carry equal amount of load whereas in more number of knots there can be uneven loading of the strands thus leading to high risk of ruptures (Wu and Tang 2014). The surgeon's knot (double twist) with four throws is considered as an effective way to hold sutures (Savage, 2013).

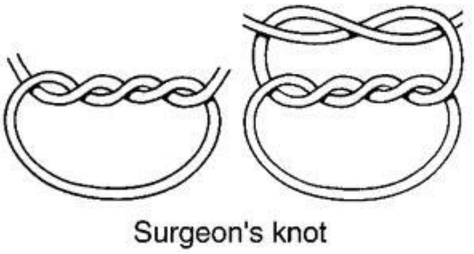


Figure 22: This image illustrates the 'Surgeon's knot' which is double twist with four throws and is considered as an effective way to hold sutures

Adapted from: **http://emedicine.medscape.com/article/1980819-technique**

3.1.6 Anchoring

Suture anchoring is another influential factor in strengthening tendon repair. Ineffective anchor points runs the risk of unwinding the strands thus leading to a poor repair. There are three anchoring methods- non grasping, grasping and locking. Non-grasping is looped around the small portion of the epitenon and grasping has suture loop which surrounds the epitenon and fibers. Locking method of anchoring creates a tight and closed loop and is considered as a better anchoring method (Wada et al, 2000; Rawson et al, 2013; Savage, 2013)

The section below describes the different surgical methods and suture configurations used in the selected research papers. Following the description, two tables are presented with surgical method, number of repairs, number of ruptures, mean rupture rate and 95% confidence interval of proportion (Table 6). Table 7 presents with the core, circumferential suture, rupture rate, zones involved and 95% CI of proportion.

a) Modified Kessler method:

In a study by Kitsis et al, 1998, all the five zones were included and the number of repairs were 339. The material and configuration of the suture used in this study was multistrand 4/0 braided polyester as core and 5/0 nylon as circumferential suture. Another study by, Kitis et al (2009) conducted on 263 digits using 2 stranded 4/0 nylon as core suture and 6/0 nylon as a circumferential suture.

Hung et al, 2005 included 46 digits in his study with a majority of zone 2 injuries. The core suture used was 2-strand modified Kessler with 4/0 nylon and 6/0 nylon as circumferential suture. The number of suture strands has not been reported in this study. This study included zones 1, 2, 3 and 5.

Caulfield et al, 2008 conducted a retrospective review to assess the safety and efficacy of use of appropriate absorbable core sutures for in zone 1 to 4 with 576 repairs and majority of injuries occurring in zone 2. The samples were divided into absorbable group and non-absorbable suture group. A 4-strand core suture was used along with a 6/0 circumferential suture. Along with some major and minor infections, a total of 8 ruptures were noted in both the groups of which 6 were in absorbable suture group and 2 in non-absorbable suture group.

Navali et al, 2013 (60 repairs in zone 2) used 4/0 prolene and Chan and Fung, 2006 (31 digits) used 4/0, 6/0 ethilion suture configurations. Chan and Fung used 6/0 nylon peripheral epitendinous running stitches, Navali et al used epitendinous 6-0 monofilament prolene in a running circumferential configuration.

Bal et al, 2010 included zones 2, 5 in 78 digits and used 3/0, 5/0 prolene which resulted in 3 ruptures (zone2=2, zone5=1). Orkar et al, 2011 included zones 1, 2 in 168 digits and used 3/0 prolene as the suture configuration. In addition, circumferential suture and horizontal mattress suture was used for FDP and FDS tendon respectively. It resulted in 15 ruptures (zone 1=3, in index finger and zone 2=12, in little finger) with the mean rupture rate of 8.3%. A less satisfactory outcome was seen in few studies in zone 2 little finger injuries when compared with other fingers (Gault, 1987; May et al, 1992;

Karlander et al, 1993; Dowd et al, 2006). As the natural resting position of the little finger is more flexed than rest of the fingers, therefore when a patient mobilizes poorly, the little finger is likely to be more severely contracted. Secondly, the tendon sheath of the little finger is smaller than the other fingers, therefore, after a suture the accommodation of the bulge of repair can be difficult thus resulting in poor results (Orkar et al, 2011; Moriya et al, 2015).

SURGERY	Paper ID	Type of study	Number of repairs	Number of ruptures	Proportion	Mean Rupture rate	95%CI of proportion
	Caulfield et al	Retrospective	576	8	0.014	1.4%	0.7-2.7%
	Hung et al	Prospective	46	3	0.065	6.5%	2.2-17.5%
	Kitsis et al	Prospective	339	6	0.018	1.8%	0.8-3.8%
	Kitis et al	Prospective	263	1	0.004	0.4%	0.1-11.4%
MODIFIED	Navali et al	RCT	60	2	0.033	3.3%	0.9-11.4%
KESSLER	Bal et al	Prospective	78	3	0.038	3.8%	1.3-10.7%
	Chan and Fung	Retrospective	31	1	0.032	3.2%	0.6-16.2%
	Orkar et al	Retrospective	168	15	0.083	8.3%	5.1-13.3%
	Bircan et al	Prospective	69	2	0.029	2.9%	0.8-10%
	Moieman and Elliot	Prospective	168	4	0.024	2.4%	0.9-6%
	Orhun et al	Prospective	9	0	0	0.0%	0-29.9%
FIGURE	Al-Qattan	Retrospective	42	0	0	0.0%	0-8.4%
OF EIGHT	Al-Qattan	Retrospective	36	0	0	0.0%	0-9.6%
	Al-Qattan and Al-Turaiki	Prospective	50	1	0.02	2.0%	0.4-10.5%
OTHER	Hatanaka et al	Prospective	14	1	0.071	7.1%	1.3-31.5%
TECHNIQUES	Hoffmann et al	Prospective	77	4	0.052	5.2%	2-12.6%
	Scheider et al	Retrospective	62	2	0.032	3.2%	0.9-1%
	Guinard et al	Prospective	24	1	0.042	4.2%	0.7-20.2%
	Schaller and Baer	Prospective	73	not given			
	Sandow and McMahon	Retrospective	73	3	0.041	4.1%	1.4-11.4%

Table 6: This table lists the number of repairs, ruptures, mean rupture rate and 95% confidence interval of all the selected studies.

The mean rupture rate of studies using modified Kessler technique varied from 0.0%-8.3% and the 95% CI of proportion was 0.018-0.032%. Zone 2 resulted in more ruptures compared to the other zones. Kitsis et al's study used multistrand sutures, which could have been a factor that compromised with the healing and caused adhesions, suggesting the cause of the higher rupture rates. This study also reported higher infections which could also be associated with the fact that, zone 5 was involved. Zone 5 consists of nerves (ulnar and median), arteries (radial and ulnar), vessels and other muscular structures therefore, the likelihood of the risk of steep growth of infection persists in zone 5 injury (Sabine and Morris, 2006). Common problems associated with post zone 5 injury is poor grip strength, loss of sensations in the fingers, diminished movement in the wrist along with scar tissue formation and reduced tendon gliding (Jaquet et al, 2004). The higher rupture rate in Hung et al's study compared to Kitis et al, can be due to involvement of more than one zone of injury. Despite the considerable difference in the sample sizes of the two studies, majority of the ruptures occurred in smaller sample group. Caulfield et al's study used absorbable and non-absorbable suture. Higher rupture rate in the absorbable suture group of can sometimes result in infections, slow healing, adhesions and ultimately resulting in poorer tensile strength (Lamky,2013). More number of strands increases the tensile strength however it also negatively affects the gliding resistance (Navali et al, 2008; Hatanaka et al, 2002; Hoffmann et al, 2008). Although some suture configurations provide higher tensile strengths, it can sometimes adversely affect the work of flexion, tendon manipulation and eventually affecting the final outcome (Navali et al, 2006).

b) Figure of eight:

Another set of research papers used ‘figure of eight’ (appendix: 3) technique in their studies. Al-Qattan 2011 conducted two individual studies on zone 2 (36 digits) and zone 3 (42 digits) respectively. Both the studies showed 0% mean rupture rate. The suture material is not mentioned in the latter study but in the zone 2 study 3 figure of eight core suture was used. No ruptures were noted in both the studies, however complications were seen in two digits in the zone 3 study. Another study by Al-Qattan and Al-Turaiki, 2009 on 50 digits (zone 2) used figure of eight technique with 3/0 and 5/0 polypropylene to repair both FDP and FDS tendons. The mean rupture rate of studies using figure of eight technique varied from 0.0%-2.0% and the 95% CI of proportion was -0.007-0.023%.

c) Other techniques:

Apart for modified Kessler and figure of eight methods, other techniques were also incorporated in some selected studies such as Tang's, Mantero's, author's technique and Adelaide repair (appendix: 3). Guinard et al, 1999 (24 digits, zone 1) and Schaller and Baer, 2010 (73 digits in zone 1,2) used Mantero technique with 2/0 monofilament nylon and 3/0 polypropylene suture configurations respectively. The former used 6/0 polydioxanone running suture and later used 6/0 polypropylene continuous epitendinous suture. Complications and ruptures are not mentioned in Schaller and Baer's study whereas Guinard et al's study reported 4 complications along with 1 rupture which was due to the infection. A careful consideration of factors such as infections, fibrosis, cicatrix, overcrowding etc. is important in order to avoid adhesions and therefore not compromising the results (Kotwal and Ansari, 2012).

Another surgical technique used is Adelaide repair by Sandow and McMahon's (2011) study on 73 digits with zone 1 and 2 injuries. The suture configuration used was with 5/0 or 6/0 nylon continuous epitendionus suture. Hatanaka et al, 2002 used a small sample size of 6 patients (7 digits) in zone 2 injuries and the sutures were repaired using author's and Tang technique with 4/0 nylon and 6/0 polypropylene monofilament suture. Complications were not mentioned in this study, however 1 rupture was reported in the middle finger within 6 weeks of repair.

Similarly Hoffmann et al, 2008 conducted studies on zone 2 injuries (77 digits) and used Lim/Tsai technique (appendix:1) along with 2 strand modified Kessler method and 4/0 monofilament steel suture (flexor digitorum profundus). Schneider et al, 1997 conducted study on zone 2 injuries (37 digits) using 4/0 monofilament steel suture (flexor digitorum profundus), 4/0 Dacron (flexor digitorum superficialis) and 6/0 nylon circumferential running suture (appendix:3). The mean rupture rate of the studies using other techniques was 3.2-7.1% and the 95% CI of proportion was 0.014-0.054%.

The higher mean rupture rate (7.1%) in Hatanaka et al's study can be due to the use of monofilament suture which has lesser tensile strength than the multifilament suture. In addition, two different techniques of surgery were used to repair flexor digitorum superficialis and flexor digitorum profundus. Surgical technique plays an important role in terminating tendon adhesions and ruptures. The ruptures in Hoffmann et al's study can be due to either complications like infection or the use of fewer stranded surgical technique. Although Schneider et al's study did not mention any complications, the reasons behind the 2 ruptures could be due to the use of different suture material for flexor digitorum profundus and flexor digitorum superficialis.

As the papers have not individually discussed about the factors contributing to the repair, hence a table is presented below summarizing the results.

Papers	**Core suture**	**Circumferential Suture**	**Mean rupture rate & Zones**	**95%CI of proportion**
		MODIFIED KESSLER		
Bircan et al, 2005	**N/A**	**N/A**	2.9% Zone 5 (FDP-index, FDS-middle	2.25-3.88%
Moieman and Elliot, 2000	3/0 or 4/0 polypropylene		2.4% Zone 1	
Orhun et al, 1999	4/0 monofilament sutures	6/0 monofilament Nylon	0.0% Zone 2	
Chan and Fung, 2006	2 strands 4/0 ethilion	6/0 nylon	3.2% Zone 2 FDS	
Caulfield et al 2008	Absorbable suture group: Polytrymethylene 3/0 Non absorbable suture group: 3/0 polypropylene, 3/0 ethibond, 3/0 nylon	Absorbable: 6/0 Polytrymethylene and 6/0 PDS Non absorbable: polypropylene, 6/0 nylon, 6/0 braided polyester	1.4% FDP (zone 2: 7, zone 1: 1)	
Hung et al 2005	2-strand core Suture with 4/0 nylon	6/0 nylon	6.5% (Zone 2: 2, Zone 3: 1)	
Kitsis et al 1998	4/0 ethibond	5/0 ethibond	1.8%(zone 1: 0; Zone 2: 5, Zone 3: 0, zone 4: 0, zone 5: 1)	
Kitis et al 2009	2-strand core suture of 4/0 nylon	6/0 nylon	0.4% Zone 2	
Navali et al 2008	2-strand or 4-strand modified Strickland techniques. Depending on tendon size, all repairs were performed with a 4-0 or 5-0 Prolene suture FDS: in 50% cases, modified Kessler technique	6-0 monofilament Prolene	3.3% Zone 2	

	using 4-0 or 5-0 Prolene			.
Bal et al 2011	3.0 and 5.0 prolene	N/A	3.8% (zone 2: 2, zone5:1)	
Orkar et al 2011	3-0 or 4-0 Prolene (depending on the size of the tendon)	N/A	8.3% zone 2: 12 zone 1: 1	
FIGURE OF EIGHT				
Al-Qattan 2011	N/A	N/A	0.0%	0.02-4.28%
Al-Qattan 2011	N/A	N/A	0.0%	
Al-Qattan and Al-Turaiki, 2009	3/0 and 5/0 polypropylene to repair both FDP and FDS		2.0% Zone 2	
OTHER TECHNIQUES				
Guinard et al, 1999	MANTERO's technique 2/0 monofilament nylon	6/0 polydioxanone	4.2% Zone 1	1.71-6.01 %
Schaller and Baer, 2010	MANTERO's technique 3/0 polypropylene	6/0 polypropylene	N/A	
Hatanaka et al 2002	AUTHOR'S technique & TANG'S technique	4/0 nylon and 6/0 polypropylene monofilament suture	7.1% Zone 2	
Sandow and McMahon's (2011)	ADELAIDE repair	5/0 or 6/0 nylon	4.1% zone 1: 1, zone 2: 2	
Hoffmann et al, 2008	Lim/Tsai technique along with 2 strand modified Kessler method and 4/0 monofilament steel suture	N/A	5.2% zone 2	
Schneider et al, 1977	4/0 monofilament steel suture (flexor digitorum profundus), 4/0 Dacron (flexor digitorum superficialis)	6/0 nylon	3.2% Zone 2	

Table 7: This table lists the core suture, circumferential suture, mean rupture rate, zones and 95% CI of proportion.

(N/A*- not mentioned in papers)

The core sutures used in the selected studies varied from sizes 3/0-5/0 and circumferential sutures from 4/0-6/0. The studies that involved multiple zones (Caulfield et al, 2008; Hun et al, 2005; Kitsis et al, 1998; Bal et al, 2011; Orkar et al, 2011; Schaller and Baer, 2010) had shown increased ruptures in zone 2 compared to rest of the zones. Based on the above table (table: 7) considering only the surgical technique and rupture rate, Figure of Eight has shown fewer ruptures rates (0.0%-2.0%). However the studies which used this technique involved 1 prospective, 2 retrospective studies and the experiment was conducted by the same authors. Therefore more research is needed in this area. The majority of studies using modified Kessler technique were prospective (8 studies), retrospective (3 studies) resulted in mean rupture rate of 0.0%-8.3%. The studies which used other surgical technique such as- Mantero, Adelaide repair, Lim/Tsai, Tang and author's own technique showed a mean rupture rate of 3.2%-7.1%.

Of the various techniques discussed, only the modified Kessler method with a modification of Tajima, Tsuge technique and circumferential suture technique have been mechanically tested in vitro using a fresh frozen human cadaveric model (Ion et al,1997; Labana et al, 2001). Many of the other techniques, including the Kessler technique, Savage, Tajima, Tsuge been tested on animal models (Winters et al, 1997; Piskin et al, 2007; Renner et al, 2015; Wichelhaus et al, 2016;) and these are not reviewed within this thesis.

Labana et al (2001) and Ion et al (1997) have tested the strength of a tendon repair using load testing device with the tendon held in a specialist clamp. Whilst in Labana et al (2001), the tendons were tested almost immediately after suturing. In Ion et al (1997), the samples were frozen after suturing and then defrosted again before testing. As a result of this, it is possible that the strength of the technique may be underestimated as the process of freezing leads to crystallisation of the fluid content within the tendons and this can therefore reduce the mechanical strength of the material **(**Arnout et al, 2013**)**.

Ion et al (1997) showed that circumferential suture could hold a maximum load of 56.04 N (using 5/0 multifilament steel), 32.29 N (using 5/0 polypropylene) and Kessler technique with Tajima modification could hold 24.03 N (using 4/0 polydioxanone).

Labana et al (2001) used Kessler technique with Tajima modification (using 4/0 nylon) could hold a maximum load of 31.8 N, 4-strand modified Tsuge (using 4/0 Supramid) and 6- strand Tsuge (using 4/0 Supramid) could hold loads of in 48.4 N and 64.2 N respectively. A surgical technique using more number of strands (6-strand) in the repair was significantly stronger in than few strands (2 or 4-

strands). The results from Labana et al's study suggests that the force occurring in the finger flexor tendon on passive finger mobilization is 8.9 N load, unresisted active mobilization of the finger is 34.4 N load, grasp is 62.9 N load.

All of these loads are higher than the loads needed to mobilise the unloaded limb, however, it is still not clear from the existing literature what the in vivo load across the surgical site will be. In order to have a greater understanding new methods of measurement are needed and until then there is a need to depend on clinical judgement of the surgeon who is able to indicate the maximum displacement (or loading) that can be allowed during rehabilitation. However, this displacement information still will not tell us as to what the maximum load on the surgical site will occur. Further research is needed to develop such in-vivo techniques.

3.2 Rehabilitation

The main objective of the rehabilitation is to obtain maximum tendon glide and restoration of hand function (Elliot, 2002; Rrecaj et al, 2014). The flexor tendons are enclosed inside a sheath which holds the tendon and glides during a movement, resulting tendon glide. Tendon excursion is the maximum amount of tendon gliding, which is the distance travelled by a tendon upon movement of a joint (W ehbe, 1987). Tendon gliding is enhanced by factors, such as mobilization and negatively altered by adhesions. (Mikkawy et al, 2013). Whilst, researchers clearly acknowledge that the increased tendon excursion will improve the functional results, it is yet, not fully explained how to determine the exact excursion of the tendon (Navali et al, 2008; Sharma and Maffulli, 2006; Evans, 2004). In this section the rehabilitation will be divided in two sub sections-mobilization protocols and splinting.

3.2.1 Mobilization protocols

Early mobilization of the tendon speeds up the recovery process by activating the collagen fibres which are abundantly present in the tendons (James et al, 2008; Franchi et al, 2006). It also encourages healing and attenuates the adhesions. However, sometimes it might also lead to rupture if not performed with caution.

There has been a significant advancement in the early post-operative mobilization of digits and clinical justification on the prevention of adhesions however the appropriate mobilization technique remains unclear (Khanna et al, 2009). The commonly used rehabilitation protocol are early passive mobilization, early active mobilization, early active-passive mobilization, Kleinert protocol, Duran protocol and combination of Kleinert and Duran protocol (Chesney et al, 2011; Stephanie et al, 2015; Ewald 2015).

The selected papers have not extensively discussed about the rehabilitation protocols therefore in the next section, the protocols used in the research papers will be individually discussed. Following this, a tables is presented focusing on the rehabilitation protocol used in the papers, the mean rupture rate and 95% CI of proportion (table 8).

(a) Modified Kleinert protocol: This protocol is used for 0-6 weeks in the following way:

0-4 weeks: A dorsal splint is applied with wrist and MCP joints in flexion and IP joints in extension. An elastic traction from fingernail through palmer pulley to volar forearm is applied with a velcro strap. It also allows night release of elastic traction, and splinting IP joints in full extension. An hourly active extension and passive flexion is also added.

4-6 weeks: The splint is discontinued and a wrist cuff with elastic traction is applied. A night splint is also applied to prevent flexion contracture. Exercises such as active wrist and finger flexion is commenced.

6 weeks: Blocking exercises and progressive resisted exercises are started on the 6th week.

In the original Kleinert protocol, the elastic traction is from the fingernail to a point proximal to the wrist. This gives minimal DIP flexion (Fig: 24).

The modified Kleinert protocol has a palmar pulley and it redirects the elastic traction to the distal palmar crease, thus attaining maximal DIP flexion (Fig: 23).

Figure 23: This image illustrates the modified Kleinert splint, which has a palmar pulley and it redirects the elastic traction to the distal palmar crease, thus attaining maximal DIP flexion.

Adapted from:http://www.slideshare.net/MohammedAljodah/hand-rehabilitation-after-flexor-tendon-repair-55186598

Figure 24:This image illustrates the original Kleinert splint, which has the elastic traction from the fingernail to a point proximal to the wrist. This gives minimal DIP flexion.

Adapted from:**://www.slideshare.net/MohammedAljodah/hand-rehabilitation-after-flexor-tendon-repair-55186598**

(b) Duran protocol: This protocol is used for 0-7.5 weeks in the following way:

0-3 days: A dorsal protective splint with wrist in 20 deg flexion, MCP joints in 50 deg flexion and IP joints in full extension is applied.

0-4.5 weeks: An hourly exercises within the splint is commenced. This includes 10 repetitions of passive DIP extension with PIP and MCP flexion. In addition, 10 repetitions of passive PIP extension with MCP and DIP joint flexion is also done.

4.5-5.5 weeks: The splint is replaced by wrist cuff with elastic flexion traction from fingernail to cuff. Active extension and passive flexion is also continued.

5.5 weeks: The wrist cuff here is discontinued and blocking, fisting exercises are started

7.5 weeks: Resistive exercises (light) with putty is started and splinting is added to correct any joint or extrinsic flexor tightness.

(c) Modified Duran protocol: A dorsal protective splint with MCP: 40-50 degrees, wrist: 20 deg flexion, IP: extension (Fig: 25) is used. A passive individual and composite flexion and extension exercises is commenced. An active composite extension exercises (manually blocking the MP in greater flexion for more complete active IP extension) and tenodesis exercises (in therapy only) is also used.

Figure 25: This image illustrates the dorsal protective splint used for modified Duran protocol.

Adapted from: **https://quizlet.com/142902855/nbcot-splints-uses-and-diagnoses-flash-cards/**

(d) Early active mobilization protocol: The research papers have used this protocol in different variations.

0-4 weeks: Individual passive flexion of each finger to the palm is carried out. Following this, active flexion of all fingers to the palm and active extension to the hood of the splint.

week 4 to 8: The above exercises are continued and exercises focusing on improving wrist stiffness, specifically radioulnar glide and radiocarpal stiffness is also carried out.

week 8: The return to light work, driving and increase to heavier activities up to 4 to 5 kgf can be carried out at week 8.

week 12: Involves return to heavy work.

week 14: Finally this week can involve full contact sports.

Controlled active mobilization protocol: The active extension of the intephalangeal joints within the splint is carried out. The active flexion of all the fingers to about two thirds of the way in the arc of flexion is done and following this, with the use of the contralateral hand the flexion arc is completed passively. The resistive exercises are started at week 6.

Papers		Mean rupture rate & Zones	95% CI of proportion
Modified Duran			
Orhun et al,1999		0.0% , zone 1: 2	0-29.9%
Kleinert/modified Kleinert Protocol			
Kitsis et al,1998		1.8% (zone 1: 0; zone 2: 5, Zone 3: 0, zone 4: 0, zone 5:1)	0.84-2.82%
Kitis et al, 2009		0.4%, zone 2	
Navali et al, 2008		3.3%, zone 2	
Bal et al 2011		3.8%, (zone 2: 2, zone 5: 1)	
Combined regimen of controlled motion			
Moieman and Elliot, 2000		2.4%, zone 1	2.65-6.58%
Orkar et al, 2011		8.3% (zone 2: 12, zone 1: 1)	
Al-Qattan, 2011		0.0%	
Al-Qattan, 2011		0.0%	
Al-Qattan and Al-Turaiki, 2009		2.0%, zone 2	
Early active mobilization			
Guinard et al,1999		4.2%, zone 1	1.14-3.2%
Schaller and Baer, 2010		Not given	
Hatanaka et al, 2002		7.1%, zone 2	
Sandow and McMahon's, 2011		4.1%, zone 1,2	
Caulfield et al, 2008		1.4%, FDP (zone 2: 7, zone 1: 1)	
Hung et al, 2005		6.5%, (zone 2: 2, zone 3: 1)	
Combination of Kleinert and Duran technique			
Hoffmann et al, 2008		5.2%, zone 2	1.67 -7.44%
Bircan et al, 2005		2.9%, zone 5 (FDP-index, FDS- middle)	
Type of rehabilitation protocol not mentioned			
Schneider et al, 1977		3.2%	**0.9-1%**

Table 8: This table lists the different studies with the summary of rupture rates and different rehabilitation protocols.

The summary of the rehabilitation protocols used in the selected papers and the mean rupture rates is described in the table above. This table shows that Kleinert protocol was used in Kitsis et al 1998 and modified Kleinert protocol was used in Navali et al 2008, Kitis et al 2009 and Bal et al 2011 studies. In addition to modified Kleinert protocol, Kitis et al, also used passive mobilization and active flexion extension exercises (5th week). Exercises such as active finger flexion/extension, making a fist, isolated FDS, FDP exercises, passive movements of MCP, PIP, DIP, active movements of all joints (shoulder, elbow, wrist, thumb) were also incorporated.

In addition to Kleinert protocol Bal et al, 2011 introduced isolated tendon gliding, tenodesis exercises (appendix 4) after 3-6 weeks (after the removal of splint) and resisted, blocking exercises in 6-8 weeks. The flexion of the wrist causes tension in the extensor tendons therefore the digits are in extension, whereas in extension of the wrist, the flexor tendons are tensed which results in flexion of the fingers. This is called tenodesis mobilization and the movement of wrist flexion and extension helps to reduce joint stiffness, oedema and proximal gliding of the flexor tendons (Mikkawy et al, 2013). The passive physiological gliding of the flexor tendons is enhanced by the tenodesis mobilization (Navali et al, 2008). This study started mobilization on same day or within 3rd post operative day.

All the studies which used Kleinert/modified Kleinert protocol showed a mean rupture rate between 0.4%-3.8% and the 95% CI of proportion was 0.002-0.015%.

Chan and Fung, 2006 used Kleinert regimen and a combined regimen of controlled motion. After 3-5 weeks, splint was removed and active ROM exercise was initiated. Following this, active finger flexion along with resistance was introduced (5-7th week) along with blocking exercises. The rehabilitation was started on 1st post operative day. The mean rupture rate of this study was 3.2%.

A combined regimen of Kleinert and Duran techniques were used in Bircan et al, 2005 and Hoffmann et al, 2008 studies. The papers have not mentioned how both the protocols were combined. Bircan et al started mobilization on 2nd or 3rd post operative day. Following Kleinert and Duran techniques, controlled active mobilization, place-hold exercises, active flexor tendon gliding exercises, isolated blocking exercises and resisted exercises (8th week) were used. In Hoffmann et al's 2008 study the rehabilitation program was divided into Lim/Tsai group (Kleinert Duran regimen, place-hold exercises and active mobilization) and modified Kessler group (Kleinert and Duran regimen only). The studies using this protocol showed a mean rupture rate between 2.9-3.2% and the 95% CI of proportion was 0.009-0.073%.

Early active mobilization was used in, Caulfield et al, 2008, Hung et al, 2005, Guinard et al, 1999, Scaller and Baer, 2010, Hatanaka et al, 2002, Sandow and McMahon, 2011. Caulfield et al used individual passive flexion followed by active flexion and extension exercise for 4 weeks. Mobilization was started on 3rd post operative day in Hung et al's study. Following active flexion and extension exercises, tenodesis mobilization and in selected cases electrical stimulation was also used. After 6th week resisted exercises were added. The rehabilitation program for this study was started in 3rd post operative day. Guinard et al, used early active mobilization from day 1 and after the removal of splint (4 weeks) full range of movement of the digits was allowed without resistance. Resistance exercise was introduced after 45 days. In Scaller and Baer's study, early active mobilization was introduced from day 1. Hatanaka et al, introduced passive flexion and extension exercise inside the splint followed by active flexion and extension exercise. Sandow and McMahon's introduced active mobilization program within 12 hours of surgery. Patients actively flexed the fingers and sometimes the other hand was used to assist in completing the range of movement. The studies using this protocol showed a mean rupture rate between 1.4-7.1% and the 95% CI of proportion was 0.010-0.029%.

Early active mobilization has shown to decrease tendon adhesions, increase tensile strength and tendon gliding (Mikkawy et al, 2013; Nasab et al, 2013). Active flexion of fingers results in more tendon excursion than passive finger flexion (Moriya et al, 2015). Loading to the flexor tendons during the active finger flexion helps in improving tensile strength. In addition, early active mobilization is also associated with less flexion contractures and better IP joint motion (Mikkawy et al, 2013; Frueh et al, 2014). The science behind the early active mobilization does not explain the higher rupture rates that is seen in the selected studies. The rehabilitation protocol alone does not decide the patient outcome. Factors such as surgical technique, surgeon's expertise, suture strands and patient compliance are some of the other factors that plays a role in deciding the outcome post flexor tendon repair (Chesney et al, 2011).

Modified Duran technique (appendix 5) was used in Orhun et al's study, 4 days after the operation, and the rehabilitation program was introduced in 4th week after the removal of the splint. This study showed a mean rupture rate of 0.0%.

Controlled active mobilization (CAM) regime was used in Orkar et al 2011 and Moieman and Elliot 2000. In Al-Qattan 2011 study (involving zone 2), Al-Qattan 2011 study (involving zone 3) and Al-

Qattan and Turaiki 2009, the rehabilitation protocol was same. Active flexion and extension exercises were performed inside the splint till the splint was removed (4th week). Resistance exercises were started at 6th week. Both the Al-Qattan studies used figure of eight techniques and had nil ruptures. Similar technique was used in Al-Qattan and Turaiki's study involving zone 2 injuries and resulted in 1 rupture. Orkar et al's study reported 15 ruptures, of which majority of them were in little finger (12 ruptures; 10- zone 2, 2- zone 1) followed by index finger (3 ruptures; 2- zone 2, 1- zone 1). The selected studies using controlled active mobilization showed mean rupture rate of 0.0% - 8.3% and 95% CI of proportion from 0.025-0.062%. It should be noted that the mean rupture rate in one of the studies (Orkar et al, 2011) using this protocol was high (8.3%) compared to rest of the studies.

Schneider et al, 1977 started exercises 3 weeks after the removal of dorsal plaster splint. The type of rehabilitation protocol is not reported in this study. It used TAM to evaluate the results and showed a mean rupture rate of 3.2%. Although the names of the rehabilitation protocol are different, there are similarities in the exercises such as- active flexion/extension, passive-flexion/extension exercises, resisted exercises, isolated tendon gliding exercises, blocking exercises, tenodesis mobilization. The resisted exercises used in the studies were started after the 6th week post tendon repair and after the removal of the splint. Few of the studies have mentioned resisted exercises, blocking exercises and tenodesis mobilization. On comparison, there was no difference in the mean rupture rate of the studies which used the aforementioned exercises and the studies which did not include the exercises.

Papers	Post operative mobilization	Rupture rate
Kitsis et al 1998	1st post op day	1.8%
Kitis et al 2009	1st post op day	0.4%
Navali et al 2008	1st post op day	3.3%
Chan and Fung, 2006	1st post op day	3.2%
Moieman and Elliot, 2000	1st post op day	2.4%
Orkar et al 2011	1st post op day	8.3%
Al-Qattan 2011	1st post op day	0.0%
Al-Qattan 2011	1st post op day	0.0%
Al-Qattan and Al-Turaiki, 2009	1st post op day	2.0%
Guinard et al, 1999	1st post op day	4.2%
Schaller and Baer, 2010	1st post op day	
Hatanaka et al, 2002	1st post op day	7.1%

Sandow and McMahon's (2011)	1st post op day	4.1%
Caulfield et al 2008	1st post op day	1.4%
Hoffmann et al, 2008	1st post op day	5.2%
Bal et al 2011	1st-3rd post op day	3.8%
Bircan et al, 2005	2nd or 3rd post op day	2.9%
Hung et al, 2005	3rd post op day	6.5%
Orhun et al, 1999	4th post op day	0.0%
Schneider et al, 1977	3 weeks after surgery	3.2%

Table 9: This table lists different papers, early/late start of mobilization and rupture rate

Most of the ruptures were noted in zone 2 irrespective of the type of rehabilitation protocol used. There seemed to be no relation between rupture rate and early/late start of mobilization (Table:10). Rehabilitation started either on first post operative day or after few days (3-4 days), both resulted in ruptures. In one of the studies (Orhun et al, 1999) the rehabilitation program was started 4 days after the repair and did not result in any ruptures. Schneider et al's (1977) study started exercises 3 weeks after the removal of the splint and resulted in 2 ruptures, whereas Hoffmann et al's (2008) study started rehabilitation program on first post operative day and resulted in 4 ruptures.

3.2.2 Splinting

Splinting is an important aspect of tendon recovery process. It maintains the wrist and digits at a specific angle. Immobilization, early passive or early active mobilization plays an important role in rehabilitation of patients post flexor tendon repair (Hundozi et al, 2013). Most ruptures occur within the first 3 weeks hence splinting after tendon repair is recommended (Bilal et al, 2014).

The splints used in the selected studies are dorsal plaster splint, Kleinert splint, dorsal blocking splint (fig:26) and neutral splint (fig:27) worn for about 4-6 weeks.

Figure 26: This image illustrates dorsal blocking splint used in the studies.

Adapted from: https://www.ncmedical.com/item_1093.html

Figure 27: This image illustrates neutral splint used in the studies.

Adapted from: http://www.alimed.com/alimed-deluxe-wrist-neutral-splint.html

Most studies have a different outlook on the position of the wrist and fingers during the splinting phase (Elliot and Amadio, 2015). The selected studies which provided details about the splinting regime are discussed below:

Papers	Wrist angle	MCP angle	Mean rupture rate
Orhun et al, 1999	30 degree flexion	Varied from 45-60 degree flexion	0.0%-4.2%
Bircan et al, 2005			
Chan and Fung, 2006			
Guinard et al, 1999			
Al-Qattan 2011	neutral position	Varied from 30-90 degree flexion	0.0%-2.0%
Al-Qattan 2011			
Al-Qattan and Al-Turaiki, 2009			
Caulfield et al 2008			
Kitis et al 2009	20 degree flexion	N/A	0.4%
Hatanaka et al, 2002		20 degree flexion	7.1%
Bal et al 2011	45 degree flexion	Varied from 30-80 degree flexion	3.8%
Hung et al, 2005	40 degree flexion		6.5%
Sandow and McMahon's (2011)	20 degrees of extension		4.1%
Hoffmann et al, 2008	30 degrees short of maximal flexion	Extension	5.2%

Table 10: This table lists the wrist, MCP angle and rupture rate used in different papers.

The studies with wrist in neutral position had a mean rupture rate of 0.0%-2.0%, with wrist in 30 degrees of flexion resulted in 0.0%-4.2% and two studies with 20 degrees wrist flexion showed 0.4% and 7.1% as the mean rupture rate. Hung et al, Bal et al, Hoffmann et al and Sandow and McMahon had a mean rupture rate of 6.5%, 3.8%, 5.2% and 4.1% respectively.

The IP joints in all the studies were rested in extension. The resting angle of the MCP joints varied in most of the studies (from 20 - 90 degrees). Bircan et al, placed MCP joints- 50-60 degrees of flexion, Guinard et al- 60 degrees, Chan and Fung- 45 degrees, Caulfield et al- 70-90 degrees, Hung et al- 90 degrees and on 3rd post of day 70 deg of MCP flexion, Kitis et al- 50 degrees, Bal et al, Al-Qattan (involving zone 3 study), Al-Qattan and Turaiki, Al-Qattan (involving zone 2 study)- 30 degrees, Hatanaka et al- 20 degrees, Sandow and McMahon's - 80 degrees. In Hoffmann et al's study the MCP and IP joints were placed in extension.

The studies with wrist in neutral position and 30 degrees of flexion have shown decreased rupture rates compared to the rest of the studies. The MCP joint angles varied in most of the studies ranging from 20 degrees to 90 degrees which makes the comparison difficult.

Some of the selected studies have chosen passive flexion by the use of rubber band and active extension of fingers (Kleinert splint). The recent studies have reported that the use of rubber band for passive finger flexion is not much in use. The constant placement of the hand in the Kleinert splint might reduce the PIP joint extension, as PIP joints are passively flexed with the rubber band (Elliot, 2002; Moriya et al, 2015). However there are some recent studies which still favors this technique (Bal et al, 2010; Farzad et al, 2014; Bilal et al, 2014). This type of rehabilitation shows that the tissues surrounding the tendons heal better, decrease adhesions, improves tendon excursion and promotes intrinsic healing (Al-Qattan, 2011). The reasons of the ruptures can vary from the choice of suture technique and splinting to the rehabilitation protocol.

Based on the outcomes from selected papers, splinting angle for the wrist varies from neutral to 20-40 degree of wrist flexion. Similarly the angle of MCP joint also varies from 20-90 degrees of flexion. This variability in the angles makes it difficult to narrow down to an optimal angle for wrist and MCP flexion with regards to splinting post flexor tendon repair. Although physiotherapy and splinting are very important post tendon repair, for better results, however the appropriate angle of the wrist still remains inconclusive (Rrecaj et al, 2014; Elliot and Amadio, 2015).

4 Conclusion

A clear conclusion from the literature review suggests that zone 2 is more prone to ruptures post flexor tendon repair irrespective of diverse surgical techniques and rehabilitation protocols. The chosen studies did not show a relationship between rupture rate and early/late start of mobilization. Differences in surgical technique, rehabilitation protocols and splinting regime makes the comparison of results across studies complex in nature. The significance of all the mentioned research findings for clinical practice lies in the understanding that not one factor alone is adequate for recovery after tendon repair.

Review of the literature suggests that mobilization after a flexor tendon repair contributes towards the recovery process. There are different rehabilitation protocols used in various hospital set ups. The main objective of the rehabilitation protocols is to mobilize the fingers, improve gliding, tendon excursion and decrease adhesions. Inappropriate mobilization can either lead to tendon ruptures or adhesions resulting in poor tendon gliding. It is important for the therapist to know how much force a repaired tendon can take, or how much is the tendon actually moving. In addition, it is important to understand the basic anatomy and excursion of flexor tendons in the hand to plan an effective rehabilitation program. This cannot be visible whilst mobilizing the fingers and can only be found out with an imaging technology such as diagnostic ultrasound, CT or MRI scans.
The outcome measures are an integral component in identifying the findings after tendon rehabilitation. The different outcome measures used in the selected research papers to evaluate results post flexor tendon repair are: Strickland original criteria, Strickland modified criteria, Total Active Motion (TAM) and Buck Gramcko criteria (for fingers and thumb).

It is important to know how and to what extent the tendon is moving inside the finger whilst mobilizing. The amount of tendon excursion during the finger/wrist mobilization is crucial to know for the therapist in order to carry out an effective rehabilitation program. If the amount of excursion is known before the start of the rehabilitation, it can then be compared during/after the completion of the therapy program. The outcome measures used tell us very little about the impairment in vivo. As a result there is a need for some new methods of research. Thus knowing the baseline and end of therapy measurement, will help to compare the tendon excursion before and after the rehabilitation program.

An imaging technology is required to see and understand the movements of the anatomical structures inside the wrist and hand. Magnetic resonance imaging (MRI), computed tomography (CT) and ultrasound (US) are few known imaging technologies. Both CT and MRI are expensive imaging procedures (Deng et al, 2009). CT scan exposes to radiation whereas MRI uses magnetic fields and radio waves to create images of our inner body. On the other hand, ultrasound is an non invasive, low cost and easily available imaging technology with no ionizing radiation (Bianchi et al, 1999; Wong et al, 2009; Ravnic et al, 2011; Puippe et al, 2011).

Therefore in the next chapter, 2D diagnostic ultrasound is used to understand, view images of the flexor tendons and its excursions in healthy human volunteers. In addition to understanding and viewing images of anatomical structures, it is also important for the therapists to know how much load is needed in the tendon to carry out an effective splinting or mobilization regime. This can be understood only with an imaging technology on how the tendon moves and what happens to the unloaded/loaded tendon.

CHAPTER 5

5 Methodology

5.1 Introduction

Any injury or cut to the flexor tendons can leave a devastating impact if not treated well and can therefore compromise our daily physical activities. The only option available for a severely damaged tendon is surgical repair followed by intensive physiotherapy management (Tang et al, 2012). Research suggests that the goal of rehabilitation of the repaired tendons is beneficial for the recovery process as it helps in healing and strengthening of the sutured tendons and thus perform activities of daily living (Farzad et al, 2014).

During a tendon repair process the surgeons are able to identify the ideal amount of load the sutured tendon can take. This information helps the therapists to plan an appropriate rehabilitation program. The therapists are unable to see what is going on around the surgical site and the amount of tendon excursion during the wrist and finger mobilization. A clear understanding on the anatomy and movement of the flexor tendons and the surrounding structures is crucial for the therapists. In this chapter an attempt has been made to develop a method to track the movement of tendons in non-impaired people with an aim to eventually use this to inform the therapy planning in surgical patients.

The diagnostic 2D ultrasound can be used to measure muscle length, thickness, tendon length and excursion. Much of the development of the methods of ultrasound measurement of muscle structure has been carried out in the lower limb where researchers are able to measure the morphology of the superficial muscles of the tricep surae muscle group in a variety of states (i.e. passive and active) (Fukunaga et al, 1997; Klimstra et al, 2007). The works in the measurement of the forearm tendons are limited.

Korstanje et al, 2012 demonstrated that it was possible to measure the tendon displacement automatically using a speckle tracking algorithm with the forearm in the brace. The brace was fixed to the midpoint of the forearm, just proximal to the wrist, and the metacarpophalangeal joints. The wrist was positioned in 30 degree of flexion, with the metacarpophalangeal joints in 60 degree of flexion and the interphalangeal joints fully extended.

Puippe et al, 2011 tracked the tendon displacement with hand placed in customized dorsal wrist splint. The dynamic imaging of the tendon movement was performed during 45 degree of passive DIP flexion with the ultrasound probe fixed in longitudinal plane at the level of the suture. The tendon excursion was analyzed by thread-and-scar tracking of the hyperechogenic signal of the fibre wire core suture and later on of the scar. The study has not clearly mentioned on how they controlled the tendon excursion.

The clinical applicability of both these methods is limited as not all patients can be put in the same wrist and finger joint position as above. Furthermore it is not possible to measure how much tendon displacement takes place before the surgery site is loaded. Therefore more work needs to be done in this area.

Previous literatures covered more on the biology of tendon injury, healing and collagen structure of the tendon and mobilization post flexion tendon repairs (Franchimet al, 2007; Sharma and Maffulli, 2006). Studies on ultrasound focused on diagnosing hand and wrist diseases, finger tendon ruptures, post flexion tendon repair functional changes (Bianchi et al, 1999; Zhang et al, 2012; Wong et al, 2009; Puippe et al, 2011).

In our daily functional activities with wrist, fingers and thumb, the normal position of the fingers/thumb can either be semi flexed (eg: while picking up objects from floor like stamps/books) or completely flexed (eg: holding a rope). Thus, these basic positions can be considered as common hand positions during flexor tendon injuries. The site of injury can either be in the fingers/thumb/palm/wrist or a combination of all. It is important to understand the flexor tendon anatomy, surrounding structures and observe the flexor tendon excursions in these hand positions. During the rehabilitation post tendon repair, focus is made to use hand effectively for daily functional activities.

Therefore, in this study, the tendon excursions were observed in two hand positions- fingers flexed to 90 degree and whilst making a fist. This was followed by another tendon excursion measurement in which JAMAR dynamometer was gripped at 5 kilogram. These two sets of tendon excursion measurements will show how a tendon responds with and without load.

The commonly injured flexor tendons are- flexor digitorum superficialis, flexor digitorum profundus, flexor pollicis longus, flexor carpi ulnaris and flexor carpi radialis. The flexor digitorum superficialis(FDS), flexor pollicis longus (FPL), flexor carpi ulnaris (FCU) and flexor carpi radialis (FCR) were chosen for this study. Flexor digitorum profundus, is a deep muscle and an important tendon which is affected mostly during zone 1 and 2 injury. It is one of the deep flexors of the forearm, and runs under the flexor digitorum superficialis very closely to the flexor carpi radialis and ulna. Therefore it was difficult to track this tendon at the wrist level. The movement of the tendon can be observed from either origin, insertion or the body of the tendon. However for measurement purpose a landmark is essential, therefore muscle tendon junction was opted to measure the tendon excursion.

5.2 Objective of this study

The primary objective of this study is to develop a method to measure flexor tendon excursion by:

a) Identifying the four flexor muscles, their tendons and the respective muscle tendon junctions (flexor pollicis longus, flexor digitorum superficialis, flexor carpi ulnaris and flexor carpi radialis).

b) Measurement of the tendon excursions using muscle tendon junction as the landmark.

c) The same measurements will be carried out two times on the same subjects on two different days.

5.3 Ethics

Ethical approval was obtained from the University Ethical Review Panel (ERP), Keele University on 22/05/2014. A minor modification was done and approved on 23/06/2014.

5.4 Sampling frame

A convenience sample of twenty healthy volunteers of age 18 to 80 years from the population of Keele University staff, students, communities living surrounding Keele village and Stoke-On-Trent were targeted for this study.

5.5 Inclusion and exclusion criteria

a) Inclusion criteria:

- Healthy volunteers without any previous history of hand injury and above 18 years of age were included in the study.
- Volunteers who can provide valid informed consent.

b) Exclusion Criteria:

- Volunteers with any musculoskeletal problems in hand: This can include generalized pain, fatigue or any other musculoskeletal problems affecting ligaments, tendons and bones. As there was no access to clinical patients therefore this research was carried out on healthy volunteers.

- Volunteers who have past history of surgeries to hand/tendon: After any hand surgery complications as inflammation, swelling and immobility can arise. At times, this can lead to hand stiffness thus affecting the normal muscle and tendon movement.

- Volunteers with any previous hand/finger/forearm fractures: The normal musculature of the hand can be disturbed after any fracture.

- Volunteers allergic to ultrasound water-based gel: The substances present in ultrasound gel can sometimes cause allergic reaction to the skin.

- Volunteers diagnosed with open wounds/skin condition (in the forearm): Skin conditions and open wound might result in wound contamination with ultrasound gel.

5.6 Experimental Protocol

The volunteers were approached and invited through known social contact, e-mails and recruitment posters (appendix-7) to participate in this study. Information sheet (appendix-8) containing all details of research and test procedures and the consent form (appendix-9) were provided to the respondents. The interested volunteers were given an hour appointment on mutual convenient time at Keele University, school of health and rehabilitation practical room. After obtaining the written valid consent from the respondents, the volunteers were briefed on the experiment process.

The volunteers were requested to wear short sleeve shirts/tops so that they could expose the forearm. Demographic data - age and gender were recorded along with the anthropometric measurements - standing height, weight and forearm length were measured. Standing height was measured with a stadiometer in centimetres. Volunteer’s mass was measured with the weighing scale in kilogram. Edinburgh handedness inventory scale was used to identify the dominant hand (appendix-10) (Schachter and Ransil, 1994). Following this, the forearm lengths were then measured on the dominant hand with a measuring tape (by palpating the anatomical landmarks from olecranon process of the elbow to the tip of the middle finger).

The volunteers were asked to lie down on a plinth with a pillow under the arm to relax and keep the hand in neutral position. The identified dominant hand was exposed and the researcher after adjusting the height of the plinth sat on the dominant side of the volunteer facing the US screen. There was no foot switch in the US machine hence, help was needed from an assistant with regards to saving images. The assistant also helped to mark the tendon junction in the skin and take the measurements according to the researcher's direction.

5.6.1 Identifying the muscle tendon junction at rest

The volunteer was asked to lie down, and ultrasound gel was applied on the hand. The ultrasound transducer was placed longitudinally over the wrist region and moved over the area. Following this, the volunteers were asked to move the thumb in opposition movement to track the flexor pollicis longus muscle first and then its distal muscle tendon junction. The volunteer was then asked to relax the thumb, the muscle tendon junction was tracked and the image was saved. This gives the position of the muscle tendon junction of flexor pollicis longus in resting state. Without moving the ultrasound probe, the point of muscle tendon junction was marked by the assistant on the skin with reference to the marker on the probe and its shadow over the muscle tendon junction image on ultrasound screen.

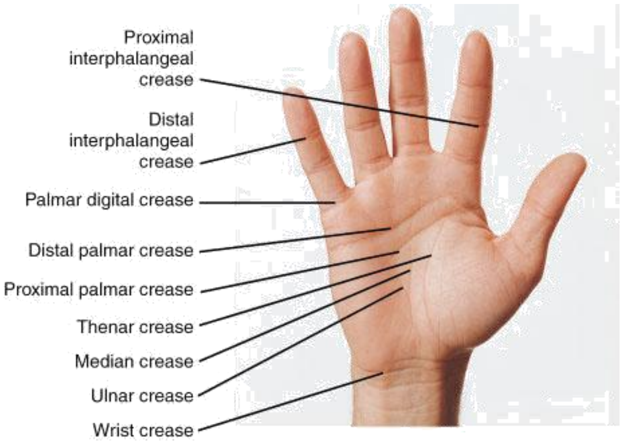


Figure 28: This image illustrates the different creases of hand. The measurement was taken from the wrist crease to the muscle tendon junction at rest.

Adapted from:
http://medicine.academic.ru/114290/flexion_crease

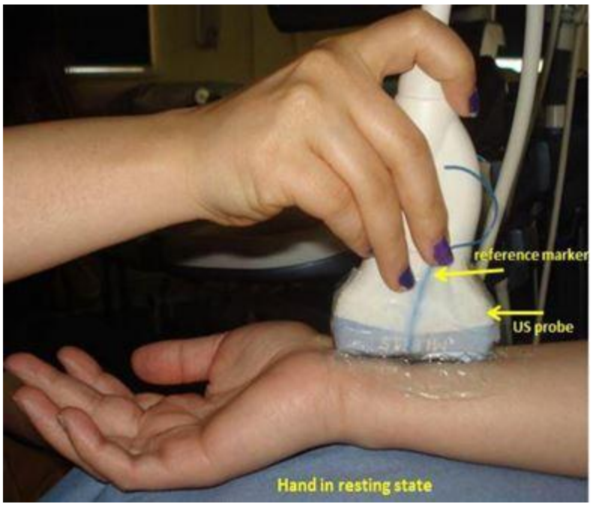


Figure 29: This image illustrates the ultrasound image showing the measurement markings whilst hand at rest

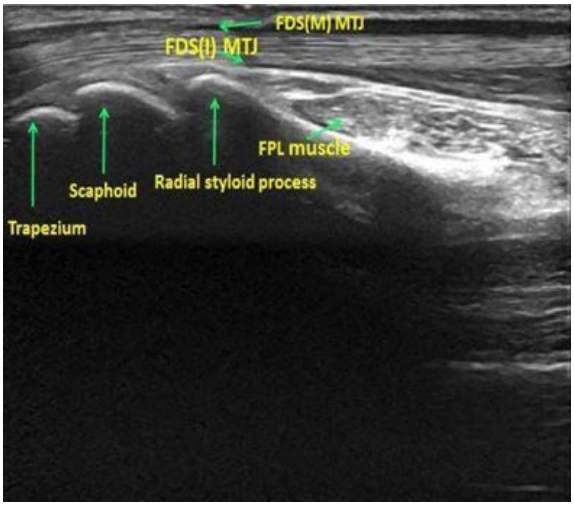


Figure 30: This image illustrates the ultrasound image showing the measurement markings whilst hand at rest- (i) flexor digitorum superficialis (index finger) muscle tendon junction, (ii) flexor digitorum superficialis (middle finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid, (v) trapezium and (vi) flexor pollicis longus muscle.

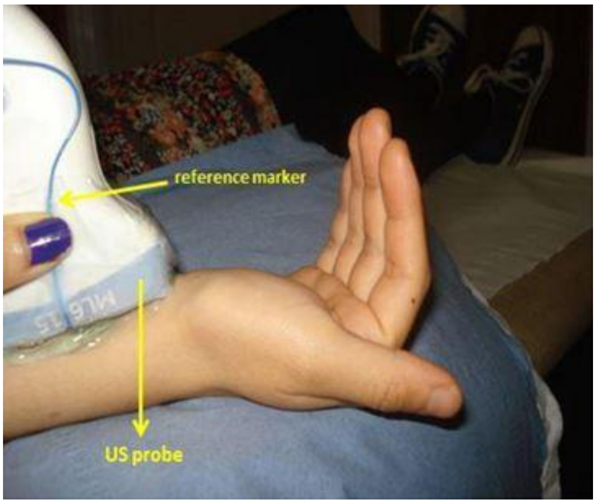


Figure 31: This image illustrates the position of ultrasound probe and the reference marker when fingers flexed to 90 degree.

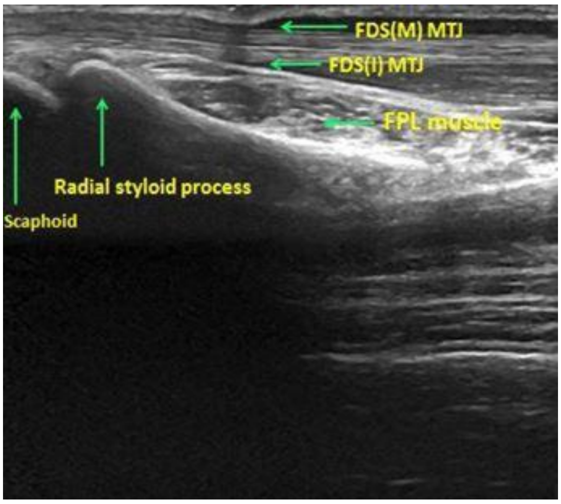


Figure 32: This image illustrates the ultrasound image showing the measurement markings when the fingers are at 90 degree flexion- (i) flexor digitorum superficialis (index finger) muscle tendon junction, (ii) flexor digitorum superficialis (middle finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid and (v) flexor pollicis longus muscle.

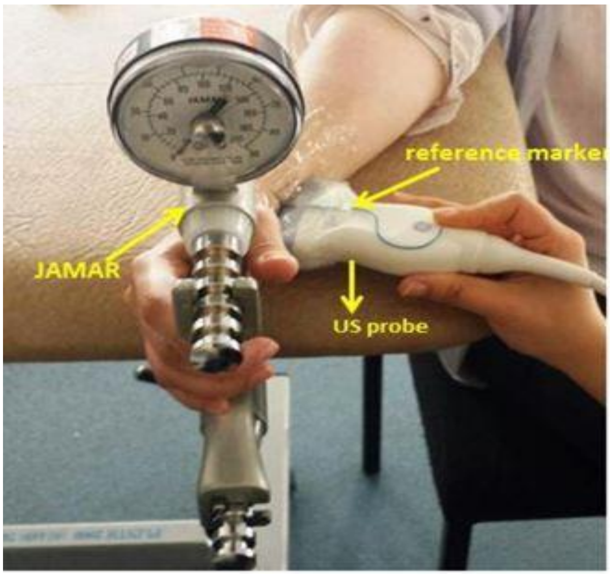


Figure 33: This image illustrates the position of hand, ultrasound probe and reference marker while gripping JAMAR at 5kgf.

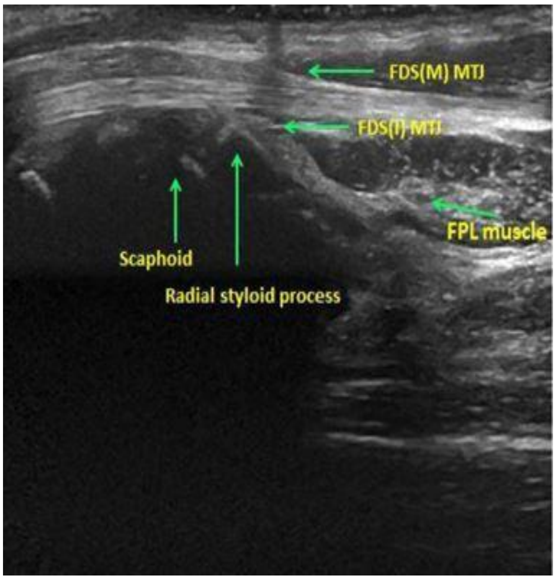


Figure 34: This image illustrates the ultrasound image showing the measurement markings while gripping JAMAR at 5kgf- (i) flexor digitorum superficialis (index finger) muscle tendon junction, (ii) flexor digitorum superficialis(middle finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid and (v) flexor pollicis longus muscle.

The next tendon to be measured was flexor digitorum superficialis (index finger). As the flexor digitorum superficials muscle splits and forms four tendons which run through index, middle, ring and little finger. The volunteers were asked to move the proximal interphalangeal joint (PIP) of the index finger first while the rest of the fingers were stabilized by the researcher. The flexor digitorum superficialis tendons of the four fingers are very close to each other, therefore stabilizing helps in isolating the index finger tendon from the rest. After identifying the tendon and muscle tendon junction, rest of the fingers were released and the volunteer was asked to bring the fingers to normal resting state. Following this, the image was saved and a landmark was made on the volunteer's skin. Same procedure was opted for flexor digitorum superficialis middle, ring and little finger tendons.

The next tendon to be identified was flexor carpi ulnaris and was done by asking the volunteers to perform flexion and ulnar deviation of the wrist. Identification of this tendon was difficult as the flexor digitorum superficialis tendon for the little finger and flexor carpi ulnaris tendon are close to each other. In order to isolate these individual structures, the researcher passively mobilised the wrist into ulnar deviation and wrist flexion. Once the tendon is tracked, the hand is brought back to normal resting state and the image is saved.

Finally, the last tendon flexor carpi radialis was identified by asking the volunteers to do flexion and radial deviation of the wrist. The researcher also did the movement to appropriately track the tendon. This technique was used when fingers were flexed to 90 degrees and while making a fist.

5.6.2 Identifying the muscle tendon junction using JAMAR

The volunteers were given a five minutes break before the start of the second part of the experiment. The break was given as the volunteers expressed some fatigue and boredom due to lying in one position for a long time and frequent finger movements to track the tendons. The volunteers sat on a chair next to the plinth with their dominant hand rested on the plinth and the fingers and wrist exposed outside the plinth. This helps to give a proper grip on the JAMAR without any restrictions. The palm facing the side and the tendons are tracked in a similar way when the volunteer is lying in the plinth. Once the tendon is tracked the JAMAR is placed on the hand by the assistant, while the researcher maintains the contact of ultrasound probe to the skin in order to track the tendon. Once, the tendon junction is noticeable on screen, the assistant marks on the volunteer's hand based on the landmark. Following this, the researcher gives a command 'start', and the volunteer slowly starts gripping the JAMAR. Once the pin touches 5 kgf, the assistant gives a command 'hold' and the volunteer has to maintain the position till the muscle tendon junction is tracked. Occasionally, the muscle tendon junctions could not be tracked on the first attempt therefore the method was repeated. When tracked, another landmark is made by the marker and the distance is measured with a measuring tape by the assistant. The assistant then reads out the numbers and the researcher notes it in the data documentation sheet.

5.6.3 Measuring the tendon excursion during movement

The reference point was marked on the skin with reference to the marker on the probe. Following this, the volunteer was asked to move all the four fingers to 90 degrees. The muscle tendon junction displacement was chased on the screen, once spotted, marking was done on the volunteer's skin. Now, the distance between the markings of relaxed muscle tendon junction and displacement on 90 degree finger flexion is measured with a measuring tape by the assistant. Once measured, the assistant reads out the numbers and the researcher noted it down on a data documentation sheet (appendix-11). The same process was followed while making a fist and gripping JAMAR at 5 kgf.

5.7 Data analysis

After finishing data collection, analysis of the data was done at School of Health and Rehabilitation, Keele University by the researcher. The data was analysed using Bland and Altman plot and by presenting its correlation. The developed methods to measure the tendon excursion were compared with the textbooks and previously published literatures.

CHAPTER 6

6 Results

Initially, a sample of ten each of male and female was target for the study. However, only 12 (six males, six females) volunteered to participate in the study and all 12 were eligible for study participation. The mean and standard deviation of the demographic data are- age (mean=35.5 years; SD=11.6 years), height (mean=169.7 cms; SD=12.18 cms), weight (mean=70 kgf; SD=15.19 kgf), length of forearm (mean=44.26 cm; SD=3.73 cms).

Prior to summarising the results, the section below, will illustrate the images that underpinned the extraction of data and description of both morphological and anatomical variations. The section below shows one each US image of all the 4 tendons at rest, 90 degree finger flexion and on gripping JAMAR at 5kgf.

The muscle tendon junction was easy to track once the tendon was isolated from the rest of the structures as shown below. In order to isolate the tendon, the volunteers were asked to do specific finger movements which will be explained below.

The displacement was based on the movement of the muscle tendon junction from the resting state to, (a) 90 degree of finger flexion, (b) whilst making a fist and (c) on gripping the JAMAR at 5kgf. These three were the fixed positions used for all the volunteers' to track the tendon excursion.

The following are some examples of ultrasound images taken from the data collection.

Flexor pollicis longus

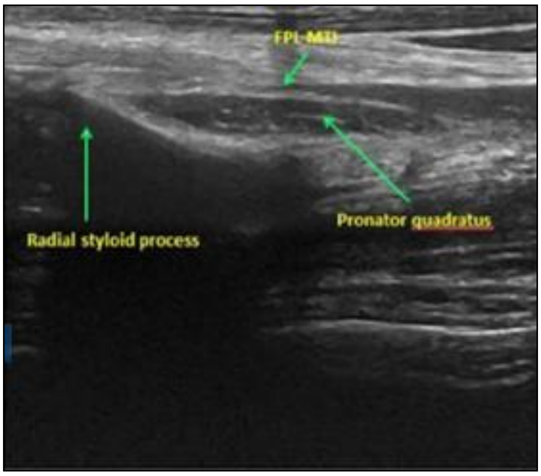


Figure 35: This image illustrates the ultrasound image showing the measurement markings when hand is at rest-(i) flexor pollicis longus muscle tendon junction, (ii) pronator quadratus muscle and (iii) radial styloid process.

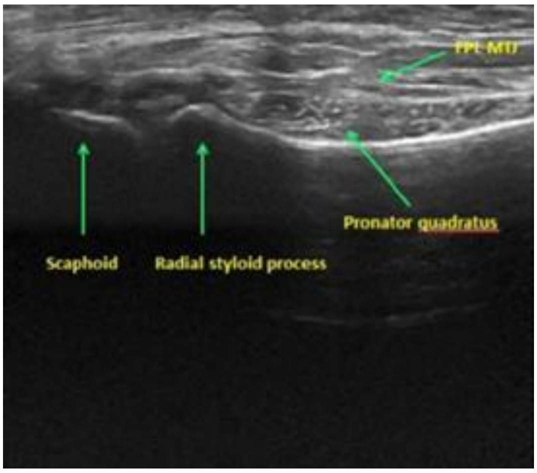


Figure 36: This image illustrates the ultrasound image showing the measurement markings when fingers are flexed to 90 degrees- (i) flexor pollicis longus muscle tendon junction, (ii) pronator quadratusmuscle, (iii) radial styloid process and (iv) scaphoid.

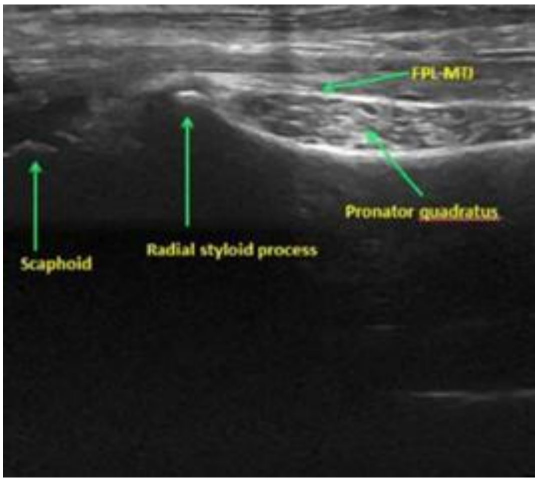


Figure 37: This image illustrates the ultrasound image showing the measurement markings whilst making a fist-(i) flexor pollicislongus muscle tendon junction, (ii) pronator quadratusmuscle, (iii) radial styloid process and (iv) scaphoid.

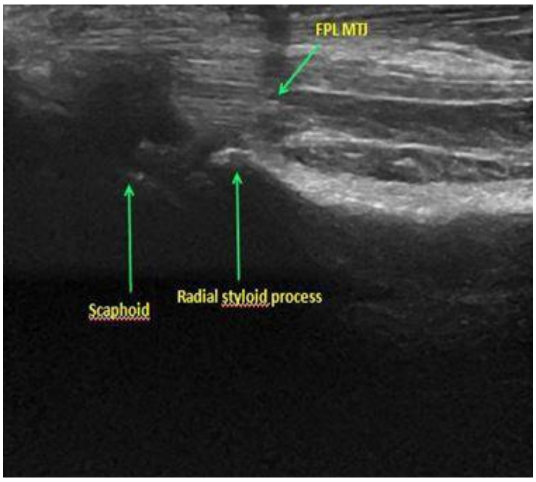


Figure 38: This image illustrates the ultrasound image showing the measurement markings whilst gripping JAMAR at 5 kgf- (i) flexor pollicislongus muscle tendon junction, (ii) radial styloid process and (iii) scaphoid.

Flexor digitorum superficialis (index finger)

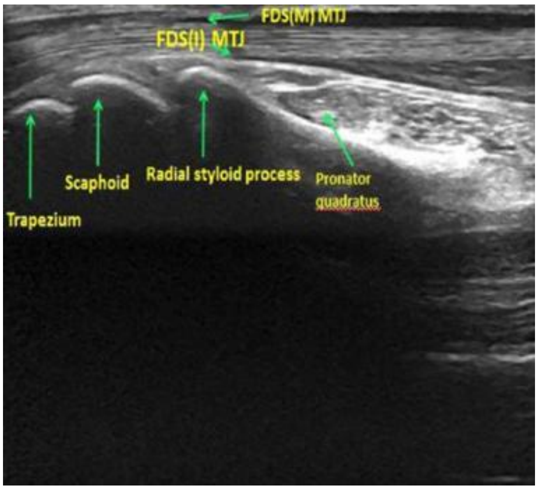


Figure 39: This image illustrates the ultrasound image showing the measurement markings whilst hand at rest- (i) flexor digitorumsuperficialis (index finger) muscle tendon junction, (ii) flexor digitorumsuperficialis (middle finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid, (v) trapezium and (vi) pronator quadratus muscle.

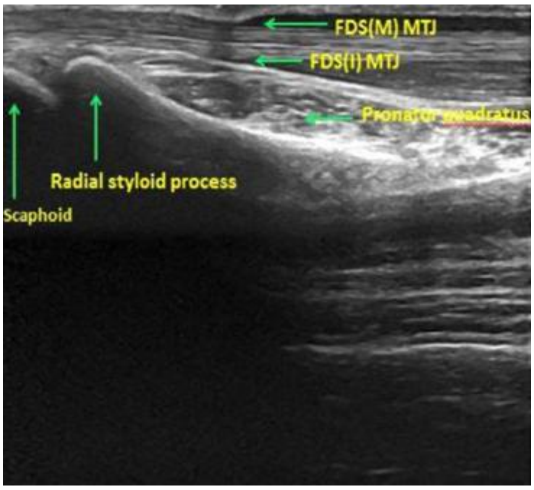


Figure 40: This image illustrates the ultrasound image showing the measurement markings when the fingers are at 90 degree flexion- (i) flexor digitorumsuperficialis (index finger) muscle tendon junction, (ii) flexor digitorumsuperficialis (middle finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid and (v) pronator quadratus muscle.

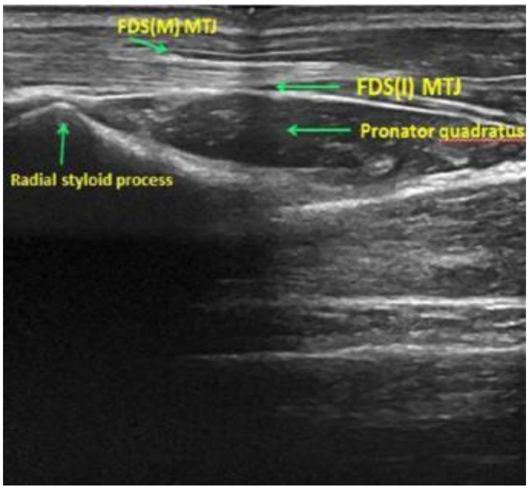


Figure 41: This image illustrates the ultrasound image showing the measurement markings while making a fist - (i) flexor digitorum superficialis (index finger) muscle tendon junction, (ii) flexor digitorum superficialis (middle finger) muscle tendon junction, (iii) radial styloid process and (iv) pronator quadratus muscle.

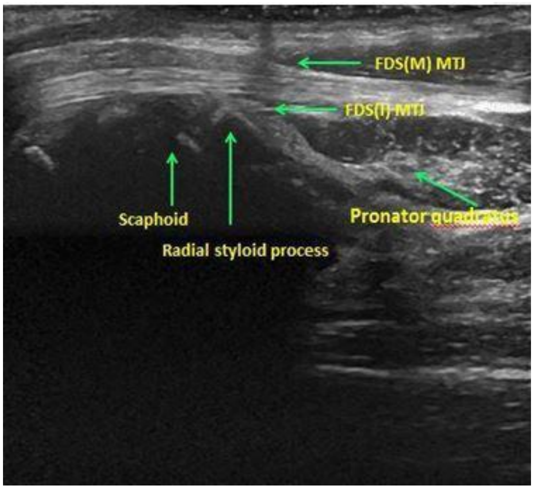


Figure 42: This image illustrates the ultrasound image showing the measurement markings while gripping JAMAR at 5kgf- (i) flexor digitorum superficialis (index finger) muscle tendon junction, (ii) flexor digitorum superficialis (middle finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid and (v) pronator quadratus muscle.

Flexor digitorum superficialis (middle finger)

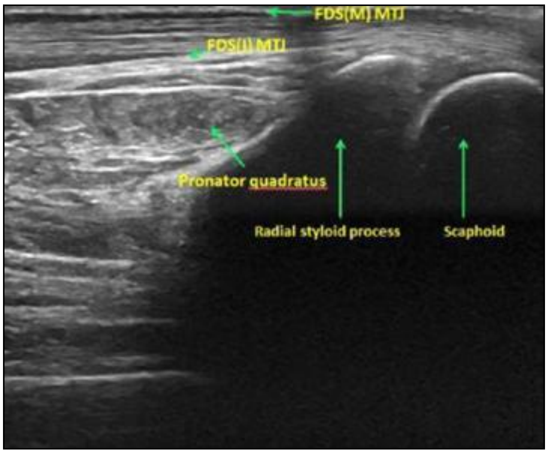


Figure 43: This image illustrates the ultrasound image showing the measurement markings whilst hand is at rest- (i) flexor digitorum superficialis (index finger) muscle tendon junction, (ii) flexor digitorum superficialis (middle finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid and (v) pronator quadratusmuscle.

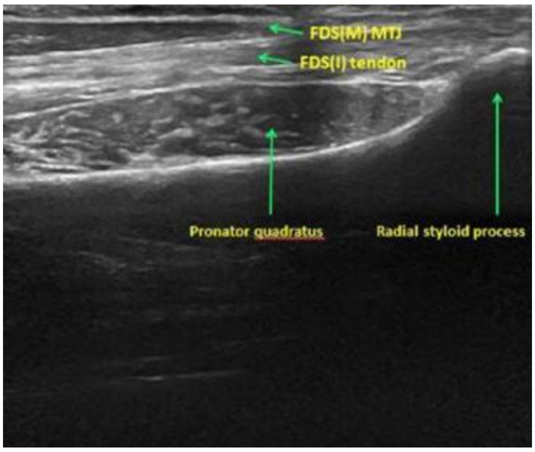


Figure 44: This image illustrates the ultrasound image showing the measurement markings when fingers are flexed to 90 degrees- (i) flexor digitorum superficialis (index finger) tendon, (ii) flexor digitorum superficialis (middle finger) muscle tendon junction, (iii) radial styloid process and (iv) pronator quadratus muscle.

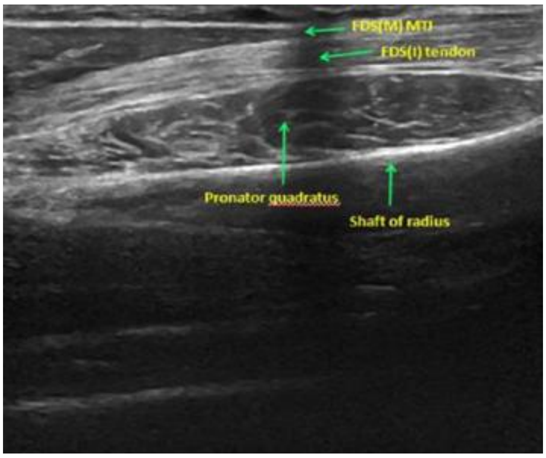


Figure 45: This image illustrates the ultrasound image showing the measurement markings whilst making a fist- (i) flexor digitorumsuperficialis (index finger) tendon, (ii) flexor digitorumsuperficialis (middle finger) muscle tendon junction, (iii) radial bone and (iv)pronator quadratus muscle.

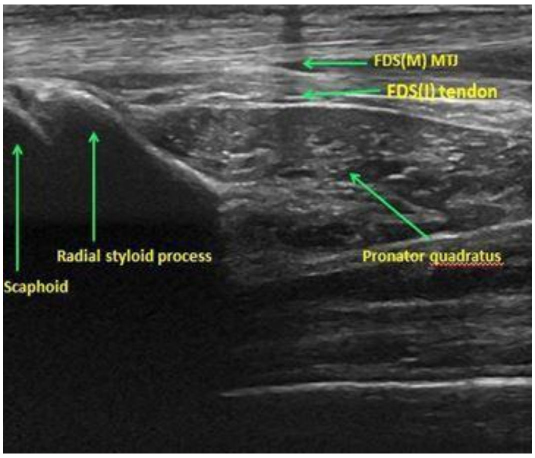


Figure 46: This image illustrates the ultrasound image showing the measurement markings when gripping a JAMAR at 5kgf- (i) flexor digitorum superficialis (index finger) tendon, (ii) flexor digitorum superficialis (middle finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid and (v) pronator quadratus muscle.

Flexor digitorum superficialis (ring finger)

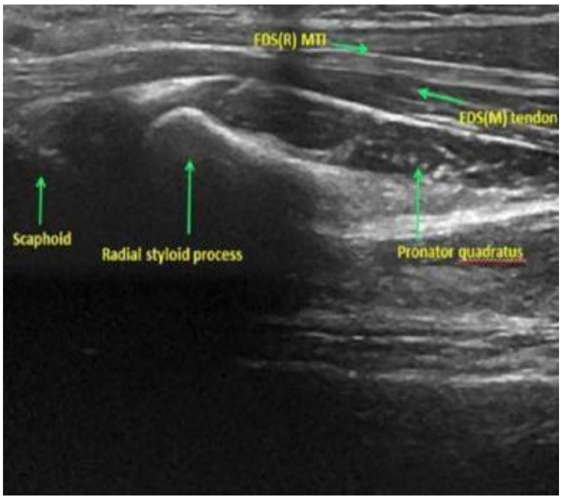


Figure 47: This image illustrates the ultrasound image showing the measurement markings when hand is at rest- (i) flexor digitorumsuperficialis (middle finger) tendon, (ii) flexor digitorum superficialis (ring finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid and (v) pronator quadratusmuscle.

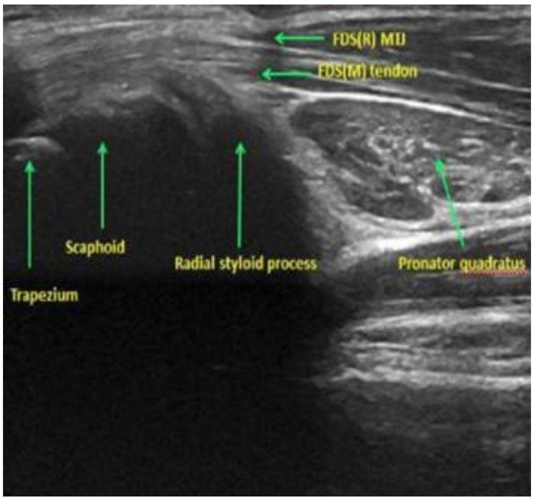


Figure 48: This image illustrates the ultrasound image showing the measurement markings when fingers are flexed to 90 degrees- (i) flexor digitorumsuperficialis (middle finger) tendon, (ii) flexor digitorum superficialis (ring finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid, (v) trapezium and (vi) pronator quadratus muscle.

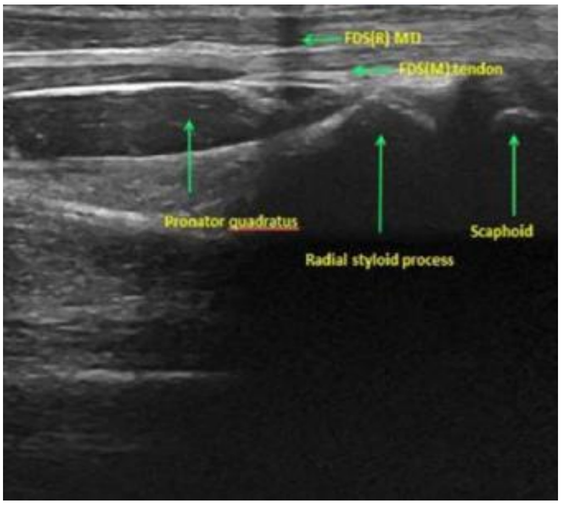


Figure 49: This image illustrates the ultrasound image showing the measurement markings whilst making a fist- (i) flexor digitorum superficialis (middle finger) tendon, (ii) flexor digitorumsuperficialis (ring finger) muscle tendon junction, (iii) radial styloid process, (iv) scaphoid and (v) pronator quadratus muscle.

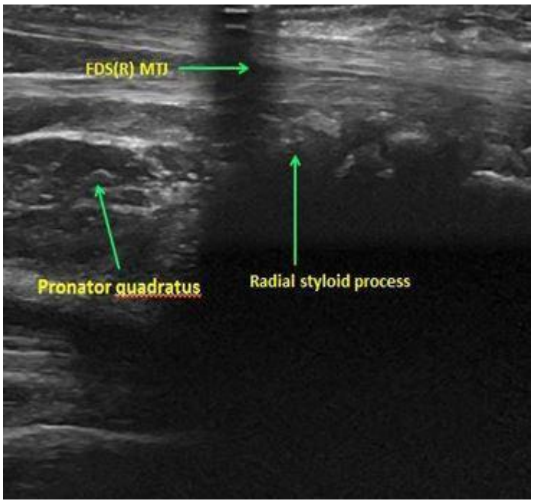


Figure 50: This image illustrates the ultrasound image showing the measurement markings when gripping JAMAR at 5kgf- (i) flexor digitorum superficialis (ring finger) muscle tendon junction, (ii) radial styloid process and (iii) pronator quadratus muscle.

Flexor digitorum superficialis (little finger)

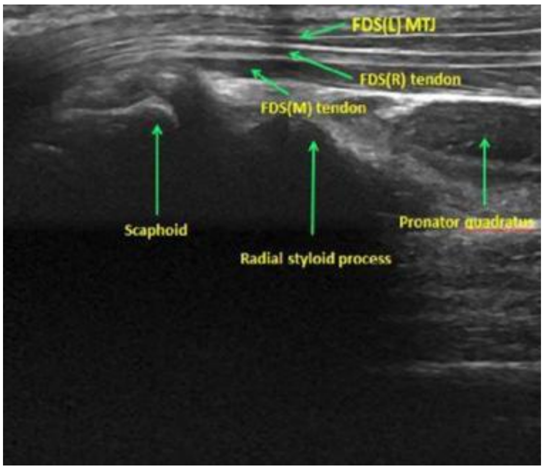


Figure 51: This image illustrates the ultrasound image showing the measurement markings when hand is at rest- (i) flexor digitorum superficialis (middle finger) tendon, (ii) flexor digitorum superficialis (ring finger) tendon, (iii) flexor digitorum superficialis (little finger) muscle tendon junction, (iv) radial styloid process, (v) scaphoid and (vi) pronator quadratus muscle.

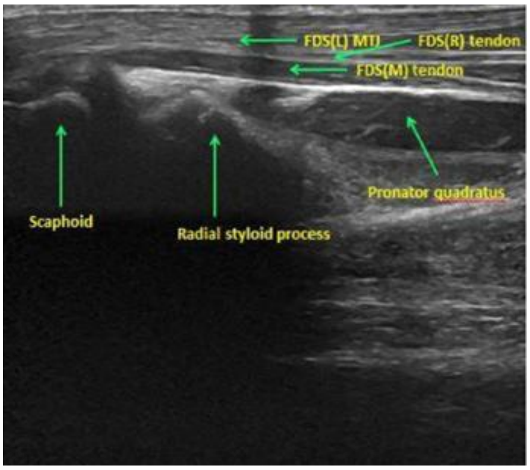


Figure 52: This image illustrates the ultrasound image showing the measurement markings when fingers are flexed to 90 degrees- (i) flexor digitorum superficialis (middle finger) tendon, (ii) flexor digitorum superficialis (ring finger) tendon, (iii) flexor digitorum superficialis (little finger) muscle tendon junction, (iv) radial styloid process, (v) scaphoid and (vi) pronator quadratus muscle.

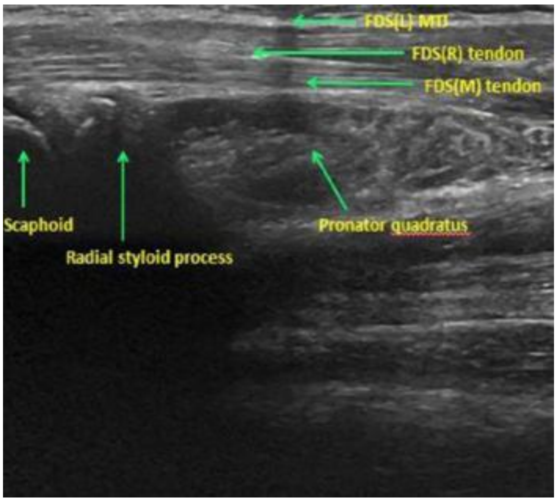


Figure 53: This image illustrates the ultrasound image showing the measurement markings whilst making a fist- (i) flexor digitorum superficialis (middle finger) tendon, (ii) flexor digitorum superficialis (ring finger) tendon, (iii) flexor digitorum superficialis (little finger) muscle tendon junction, (iv) radial styloid process, (v) scaphoid and (vi) pronator quadratus muscle.

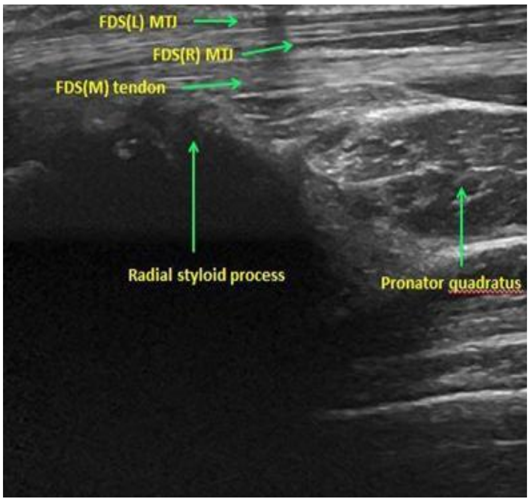


Figure 54: This image illustrates the ultrasound image showing the measurement markings when gripping a JAMAR at 5 kgf- (i) flexor digitorum superficialis (middle finger) tendon, (ii) flexor digitorum superficialis (ring finger) muscle tendon junction, (iii) flexor digitorum superficialis (little finger) muscle tendon junction, (iv) radial styloid process and (v) pronator quadratus muscle.

Flexor carpi ulnaris

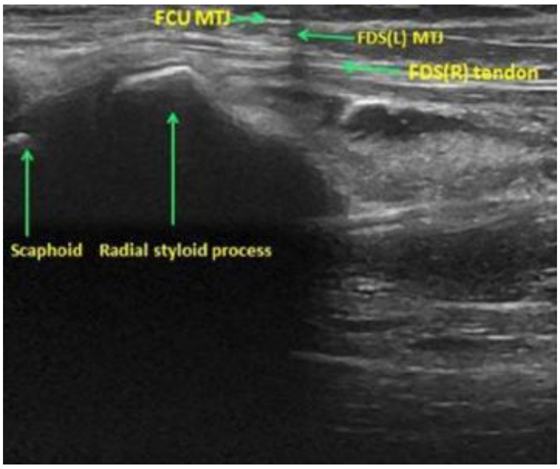


Figure 55: This image illustrates the ultrasound image showing the measurement markings when hand is at rest- (i) flexor carpi ulnaris muscle tendon junction, (ii) flexor digitorum superficialis (little finger) muscle tendon junction, (iii) flexor digitorum superficialis (ring finger) tendon, (iv) radial styloid process and (v) scaphoid.

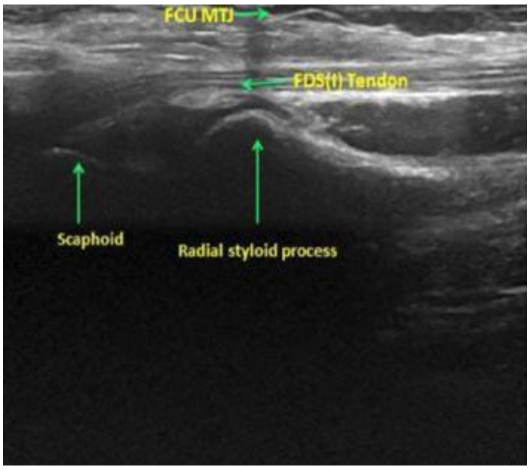


Figure 56: This image illustrates the ultrasound image showing the measurement markings when fingers are flexed at 90 degrees- (i) flexor digitorum superficialis (index finger) tendon, (ii) flexor carpi ulnaris muscle tendon junction, (iii) radial styloid process and (iv) scaphoid.

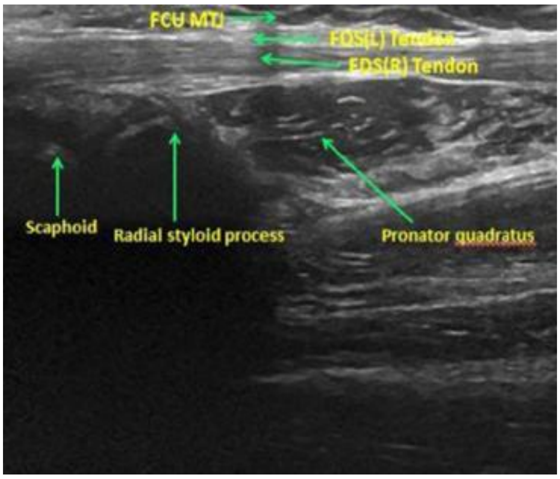


Figure 57: This image illustrates the ultrasound image showing the measurement markings whilst making a fist- (i) flexor carpi ulnaris muscle tendon junction, (ii) pronator quadratus muscle, (iii) flexor digitorum superficialis (little finger) tendon, (iv) flexor digitorum superficialis (ring finger) tendon, (v) radial styloid process and (vi) scaphoid.

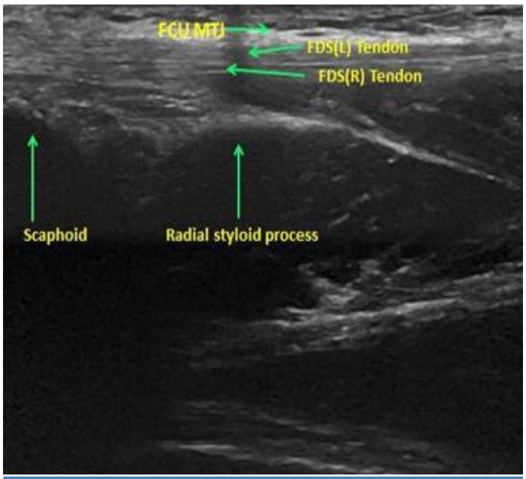


Figure 58: This image illustrates the ultrasound image showing the measurement markings while gripping JAMAR at 5kgf - (i) flexor carpi ulnaris muscle tendon junction, (ii) flexor digitorum superficialis (little finger) tendon, (iii) flexor digitorum superficialis (ring finger) tendon, (iv) radial styloid process and (v) scaphoid.

Flexor carpi radialis

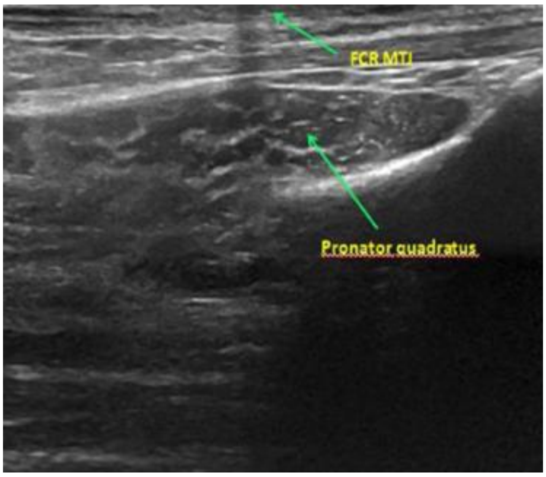


Figure 59: This image illustrates the ultrasound image showing the measurement markings at rest- (i) flexor carpi radialis muscle tendon junction, (ii) pronator quadratus.

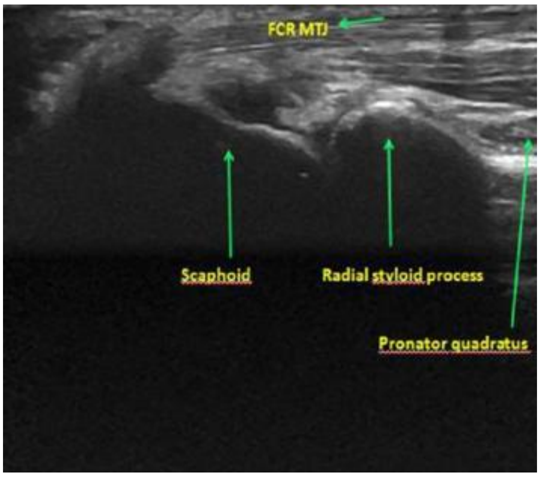


Figure 60: This image illustrates the ultrasound image showing the measurement markings at 90 degree finger flexion- (i) flexor carpi radialis muscle tendon junction, (ii) pronator quadratus, (iii) scaphoid, (iv) radial styloid process.

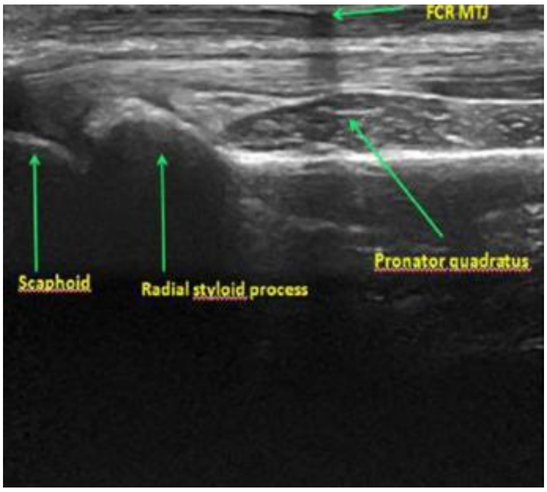


Figure 61: This image illustrates the ultrasound image showing the measurement markings while making a fist- (i) flexor carpi radialis muscle tendon junction, (ii) pronator quadratus, (iii) scaphoid, (iv) radial styloid process.

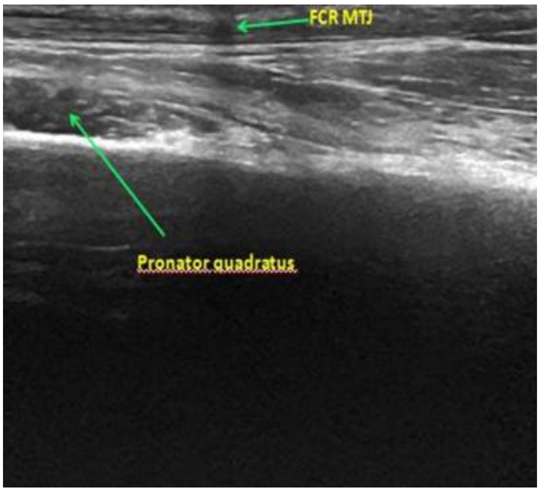
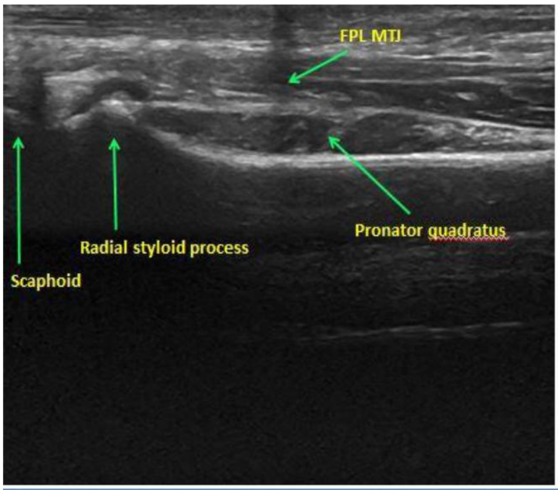


Figure 62: This image illustrates the ultrasound image showing the measurement markings while gripping JAMAR at 5 kgf - (i) flexor carpi radialis muscle tendon junction, (ii) pronator quadratus.

The FPL and FDS (index) tendons were mimicking the FCR tendon at times. Therefore majority of time was spent in identifying the FCR tendon. After repeated attempts, the tendon was visible only in two volunteers.

a) Differences in the muscle tendon junction of FPL (rest) in two different volunteers:



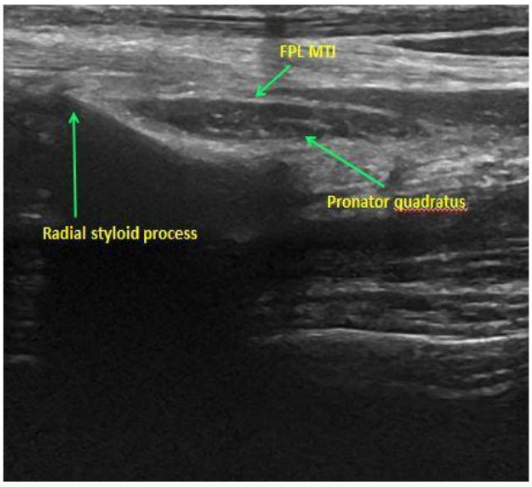


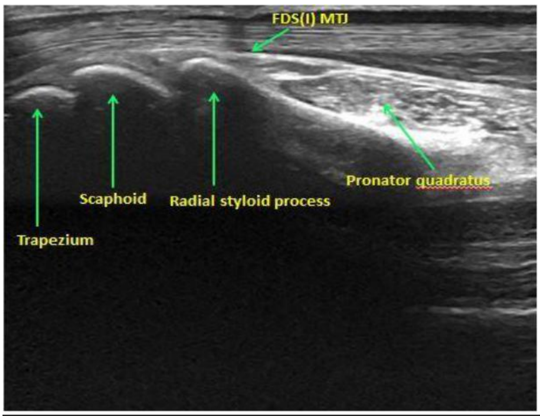
Figure 63: This image shows FPL (rest) muscle tendon tendon junction for volunteer 1

Figure 64:This image shows FPL (rest) muscle junction for volunteer 2

The position of muscle tendon junction in both the images are not exactly in same place. The tendon junction at figure 64 is more close to pronator quadratus muscle than in figure 63. The key point shown here is an illustration of anatomical variability.

The US image above is of two different volunteers showing the FPL muscle tendon junction. The tendon junction is not exactly in the same place for both the volunteers. The tendon junction at fig 64 is more close to the pronator quadratus muscle than in fig 63.

b) Differences in muscle tendon junction of FDS(I)at rest in the same volunteer (day 1 and day 2):



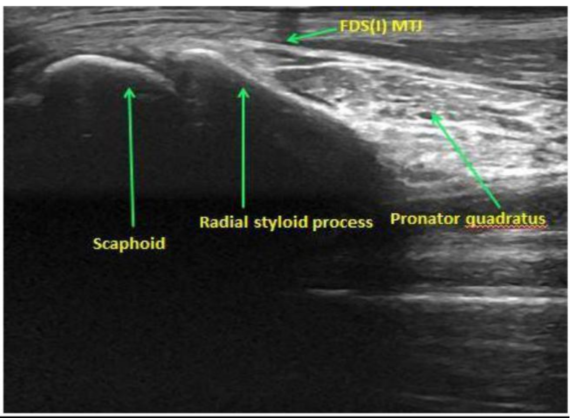


Figure 65: The image shows Day 1, FDS(I) at rest

Figure 66: The image shows Day 2, FDS(I)

* The above images are of the same volunteers in day 1 and day 2. The images both the days varied in terms of the location of the muscle tendon junction. The tendon junction in day 1 image is slightly higher than day 2 image. The tendon junction in the day 1 image is slightly closer to the radial styloid process than the day 2 image.*

The day 1 and day 2 images for the same volunteer varied in terms of the location of the muscle tendon junction. The tendon junction in day 1 image is slightly higher than day 2 image. The tendon junction in the day 1 image is slightly closer to the radial styloid process than the day 2 image.

The landmarks of the anatomical structures were identified in the ultrasound images using 'Gray's anatomy' and 'examination of the hand and wrist' text book (Gray 2010; Tubiana et al, 1998). Following this, the muscles, bones, tendons and surrounding structures were compared with these textbooks. On comparison, the muscle tendon junction at the resting state appeared to be different for all the volunteers. Similarly, variance was noted in 90 degree finger flexion, fist and on gripping JAMAR at 5kgf.

From the above images it can be inferred that position of the muscle tendon junction varied in the volunteers. In addition, the position of anatomical structures like bones and muscles were not similar in the ultrasound scans. There was variation in the values of day one and day two for the same volunteers. The distance from the crease to the muscle tendon junction was also different for all the volunteers. This vividly showed that there is variability in the anatomical structure of different individuals.

c) <u>Distance from crease to the tendon junction a rest:</u>

The forearm lengths of all the 12 volunteers were documented followed by the length from the crease to the muscle tendon junction at rest. Following this, the normalized length in percentage was also calculated. The distal wrist crease was used as a landmark to measure the distance from the crease to the muscle tendon junction at rest.

The distance from the wrist crease to the FPL muscle tendon junction varied from 2.5cm - 5.5cm in all the 12 participants. Similarly, the distance in FDS (I) was 2cm - 4.1cm, FDS(M) was 1.7cm - 4.7cm, FDS(R) was 1.8cm - 4.3cm, FDS(L) was 1.8cm - 4.6cm, FCU was 2cm - 5cm, FCR was 3.5cm and 3.9cm (identified only in 2 participants).

The volunteers were first asked to move the FPL tendon by attempting to touch the base of the little finger with the tip of the thumb. Once the FPL tendon was identified, its muscle tendon junction was tracked and patient was then asked to bring back the fingers in the resting state. The tendon junction was followed till the resting state and based on the shadow of the reference marker on the screen, the skin was marked. The distance from the wrist crease (Fig: 28) to the skin mark of the resting tendon junction was measured in centimetres with a measuring tape. The researcher documented the number in a data documentation sheet. This procedure was followed for all the tendons. The results of the individual participants and length of the forearm are documented in table 11. The distance from crease and the normalized lengths are documented in table 12.

Participants (Serial No.)	**Length of the forearm**
1	46.0
2	48.0
3	48.5
4	42.2
5	48.0
6	46.5
7	47.0
8	45.5
9	42.0
10	39.0
11	38.0
12	40.5

Table 11: This table lists the participants and their length of forearm

The length of the forearm for all the 12 participants also varied from 38 - 48.5 cm. There was no relationship between the length of the forearm and the distance from the wrist crease to the muscle tendon junction. For example, 48.5 cm long forearm had only 2.8 cm distance from the wrist crease to the muscle tendon junction, whereas in 38 cm long forearm had 3 cm (both for FDS, little finger).

Serial No.	FPL Length from the crease to MTJ (cms) (At rest)	FPL NormAlised Length In PerceNtage	FDS(I) Length from the crease to MTJ (At rest)	FDS(I) NormAlised Length In PerceNtage	FDS(M) Length from the crease to MTJ (At rest)	FDS(M) Normalised length in percentage	FDS(R) Length from the crease to MTJ (At rest)	FDS(R) Normalised length in percentage	FDS(L) Length from the crease to MTJ (cms) (At rest)	FDS (L) Normalised length in percentage	FCU Length from the crease to MTJ (At rest)	FCU Normalised length in percentage	FCR Length from the crease to MTJ (At rest)	FCR Normalised length in percentage
1	2.9	6.3	2	4.3	2.5	5.4	3.2	7	1.8	3.9	2.3	5		
2	3.2	6.7	3.4	7.1	3.7	7.7	3.8	7.9	3.4	7.1	3.2	6.7	3.5	7.3
3	2.7	5.6	3.4	7	2.4	4.9	4.2	8.7	2.8	5.8	2.9	6		
4	2.5	5.9	2.3	5.5	3.3	7.8	1.9	4.5	1.8	4.3	3	7.1		
5	4.6	9.6	3.9	8.1	3.8	7.9	3.5	7.3	3.2	6.7	4	8.3	3.9	8.1
6	5.5	11.8	2.6	5.6	4.7	10.1	3.7	8	4.6	9.9	4	8.6		
7	3.6	7.7	4.1	8.7	3.4	7.2	3.3	7	2.5	2.5	5.3	5		
8	3.7	8.1	2.6	5.7	2.7	5.9	3.6	7.9	3.2	3.2	7	2.8		
9	4	9.5	2.8	6.7	3.6	8.6	4.3	10.2	3.3	3.3	7.9	2		
10	2.7	6.9	2.3	5.9	3.5	9	3.2	8.2	2.5	2.5	6.4	3.2		
11	2.8	7.4	2.4	6.3	1.7	4.5	1.8	4.7	3	3	7.9	2.7		
12	2.8	6.9	2.8	6.9	2.3	5.7	2.7	6.7	3.1	3.1	7.7	3.2		

Table 12: The above table lists the normalized lengths in percentage for all the tendons

Following this, the tendon excursion on day 1 and day 2 for 90 degree finger flexion, fist and JAMAR was documented. The normalized lengths in percentage for both the days were calculated in all the 12 volunteers. Based on the normalized length (day 1 and day 2), the normalized mean and normalized difference was calculated. This process was repeated for all the four tendons at 90 degree finger flexion, making a fist and on gripping JAMAR at 5kgf (appendix 12). Following this, the mean difference, SD of difference was calculated from the normalized difference and SD of mean was calculated from the normalized mean.

A Bland-Altman plot was used to analyse the data are documented below. A tabulated form of the Bland-Altman plot is described in appendix 13. Based on the results from the plot, the clinical applicability (2 point measurement) is documented in the table 13.

a) <u>Bland-Altman Plot</u>

The Bland and Altman plot illustrated below (Figure 67- 87) shows that variability in the repeated measures taken over the study. In the 90 deg positon variability was highest for FCU tendon and lowest for FCR tendon. In the fist position variability was highest for FDS (middle finger) tendon and lowest for FCR tendon. In the 5KG loading condition variability was highest for FDS(middle finger) tendon and lowest for FCR tendon.

<u>Flexor pollicis longus:</u>

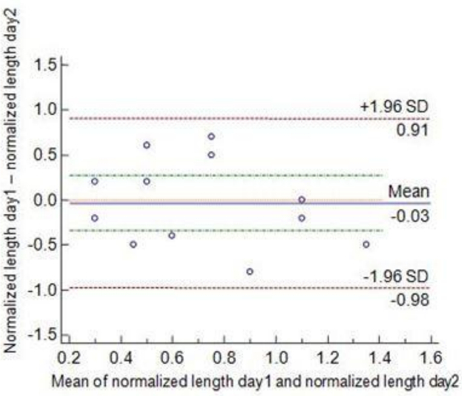


Figure 67: This figure illustrates the Bland and Altman plot of FPL at 90 degree finger flexion

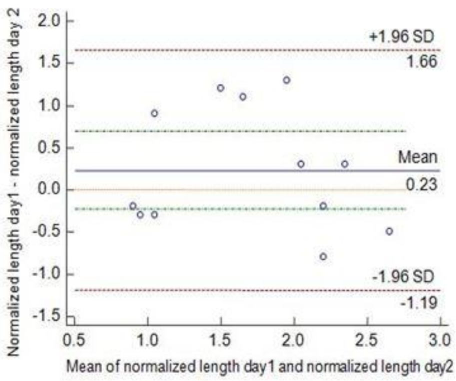


Figure 68: This figure illustrates the Bland and Altman plot of FPL whilst making fist

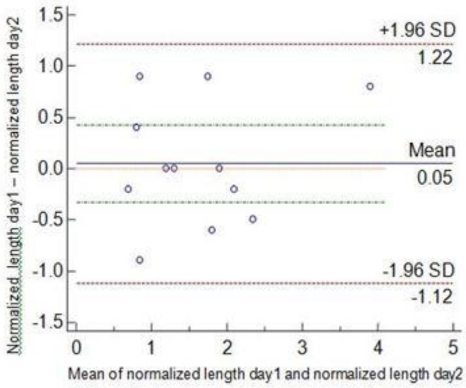


Figure 69: This figure illustrates the Bland and Altman plot of FPL whilst making fist

Flexor digitorum superficialis (index)

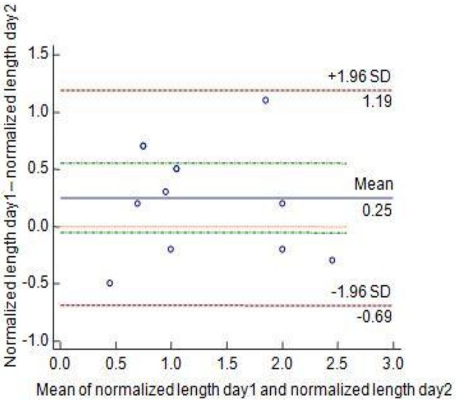


Figure 70: This figure illustrates the Bland and Altman plot of FDS(I) at 90 degree finger flexion

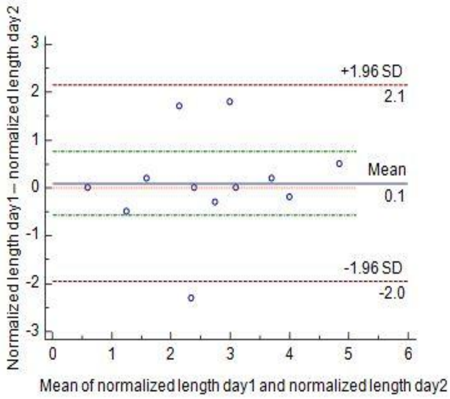


Figure 71: This figure illustrates the Bland and Altman plot of FDS(I) whilst making fist

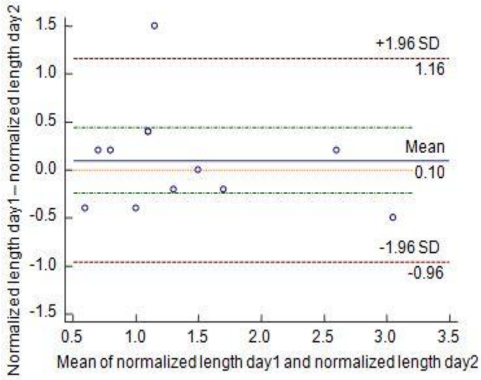


Figure 72: This figure illustrates the Bland and Altman plot of FDS(I) whilst making fist

Flexor digitorum superficialis (middle)

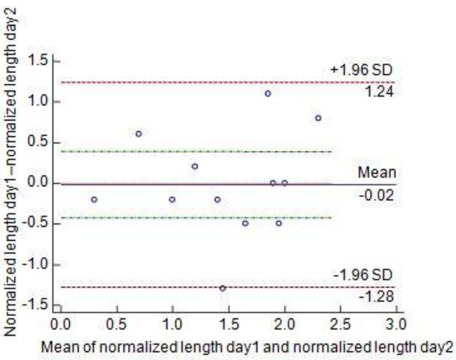


Figure 73: This figure illustrates the Bland and Altman plot of FDS(M) at 90 degree finger flexion

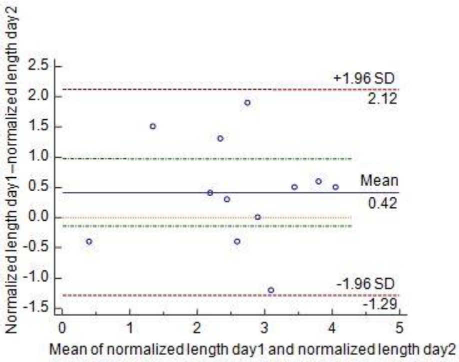


Figure 74: This figure illustrates the Bland and Altman plot of FDS(M) whilst making fist

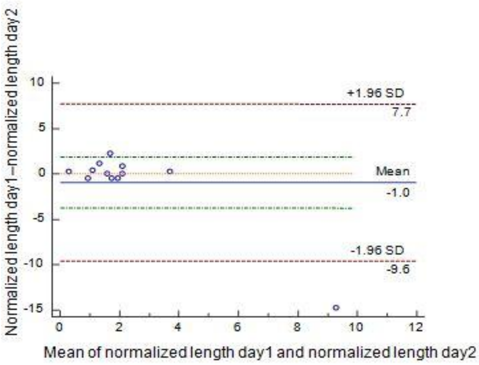


Figure 75: This figure illustrates the Bland and Altman plot of FDS(M) whilst making fist

Flexor digitorum superficialis (ring)

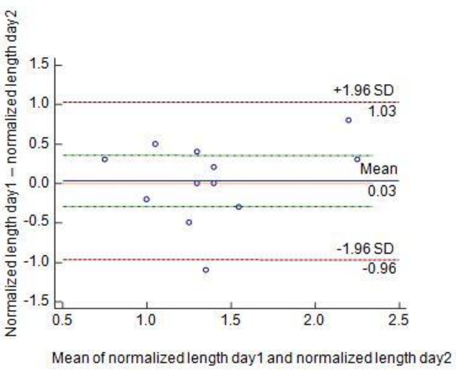


Figure 76: This figure illustrates the Bland and Altman plot of FDS(R) at 90 degree finger flexion

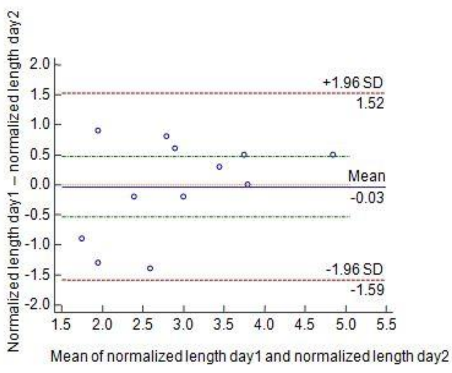


Figure 77: This figure illustrates the Bland and Altman plot of FDS(R) whilst making fist

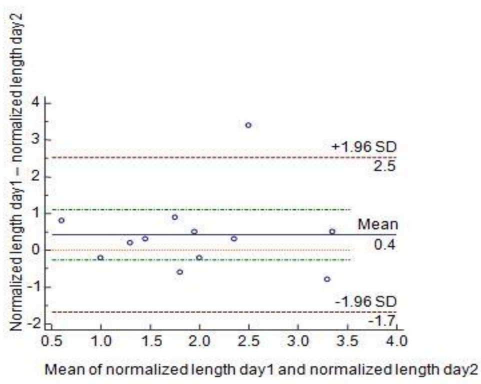


Figure 78: This figure illustrates the Bland and Altman plot of FDS(R) whilst making fist

Flexor digitorum superficialis (little)

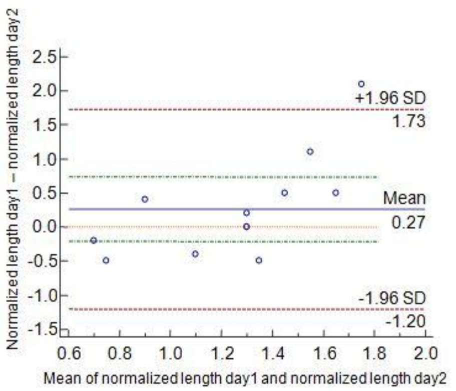


Figure 79: This figure illustrates the Bland and Altman plot of FDS(L) at 90 degree finger flexion

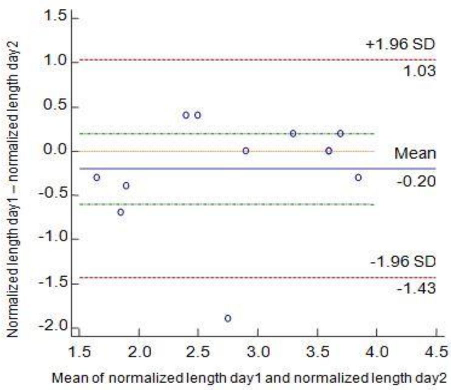


Figure 80: This figure illustrates the Bland and Altman plot of FDS(L) whilst making fist

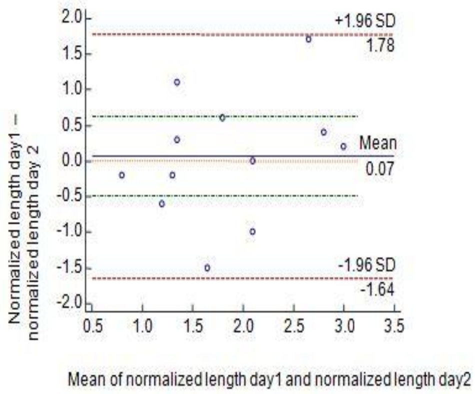


Figure 81: This figure illustrates the Bland and Altman plot of FDS(L) whilst making fist

Flexor carpi ulnaris

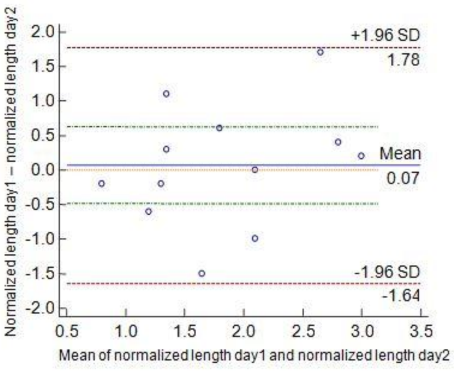


Figure 82: This figure illustrates the Bland and Altman plot of FCU at 90 degree finger flexion

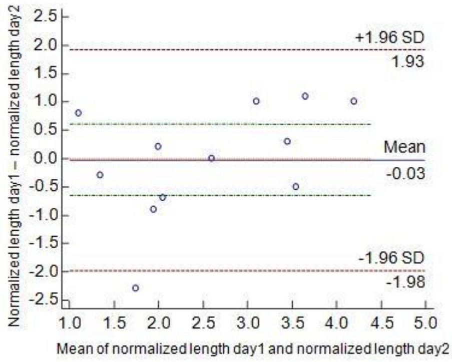


Figure 83: This figure illustrates the Bland and Altman plot of FCU whilst making fist

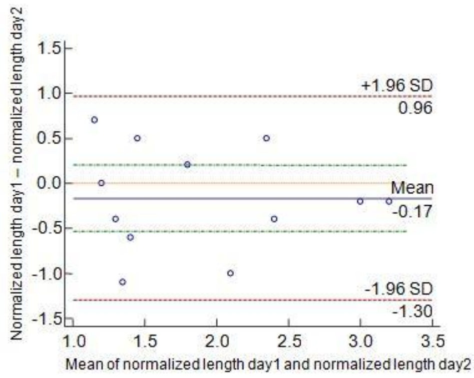


Figure 84: This figure illustrates the Bland and Altman plot of FCU whilst making fist

Flexor carpi radialis

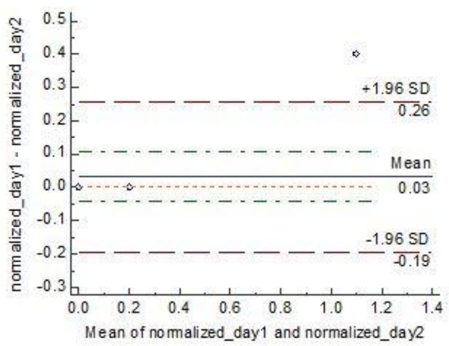


Figure 85: This figure illustrates the Bland and Altman plot of FCR at 90 degree finger flexion

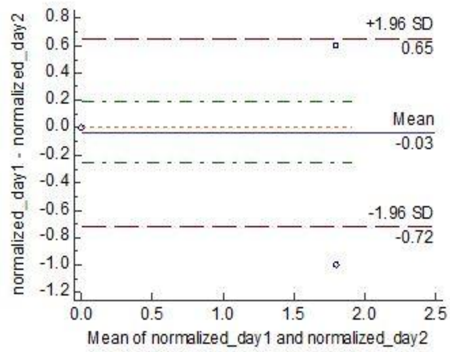


Figure 86: This figure illustrates the Bland and Altman plot of FCR whilst making fist

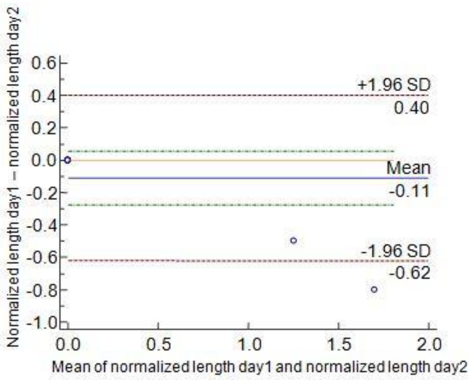


Figure 87: This figure illustrates the Bland and Altman plot of FCR whilst making fist

The Bland and Altman plot for all the tendons during three activities show high degree of variability between the numbers

b) Clinical application

The table 13 represents the slope based on displacement and force. The displacement is documented at 90 degree finger flexion (percent per degree) and the force by gripping JAMAR (per Newton load). The 5 kgf is converted to newton (49.03 N). The values are measured in normalized length in percentage.

Serial No.		FPL	FDS (I)	FDS (M)	FDS (R)	FDS (L)	FCU	FCR
1		0.0122	0.0206	0.0217	0.0144	0.0194	0.0194	
		0.0795	0.0224	0.0398	0.0398	0.0245	0.0286	N/A
2		0.0056	0.0156	0.0078	0.0117	0.0144	0.01	0.0122
		0.0265	0.0143	0.0061	0.0122	0.0275	0.0235	0.0255
3		0.0056	0.0078	0.0161	0.0156	0.0183	0.0311	N/A
		0.0143	0.0204	0.0275	0.0673	0.0612	0.0612	
4		0.005	0.0222	0.0183	0.025	0.0161	0.0156	N/A
		0.0245	0.0163	0.0194	0.0265	0.0163	0.0306	
5		0.0067	0.0117	0.0256	0.015	0.0078	0.0139	0.0022
		0.0163	0.0122	0.1897	0.051	0.0367	0.0275	0.0347
6		0.0033	0.0083	0.0133	0.0083	0.0144	0.01	N/A
		0.0173	0.0235	0.0347	0.0204	0.0337	0.0489	
7	**0-90 degree:** [1]	0.0033	0.0083	0.0033	0.0156	0.0122	0.0072	N/A
	0-49.03 Newton: [2]	0.0173	0.0224	0.0224	0.0367	0.0571	0.0367	
8		0.0083	0.0111	0.0011	0.0111	0.01	0.0083	N/A
		0.0357	0.0306	0.0357	0.0357	0.054	0.0265	
9		0.0122	0.0222	0.0211	0.0172	0.0144	0.0133	N/A
		0.0387	0.0265	0.0755	0.0408	0.0265	0.0479	
10		0.01	0.0272	0.0156	0.0244	0.0172	0.0172	N/A
		0.0367	0.0622	0.0591	0.0683	0.0428	0.0479	
11		0.015	0.0106	0.0206	0.0144	0.015	0.0117	N/A
		0.0479	0.0347	0.0326	0.0296	0.0428	0.0428	
12		0.0083	0.005	0.0222	0.0139	0.0083	0.0067	
		0.0428	0.053	0.0428	0.0479	0.0275	0.0296	N/A

Table 13: This table lists the displacement and force of all the tendons

[1] First Row [2] Second Row

The above table suggests that the maximal tendon excursion for 1 degree of movement (while performing MCP joint flexion) was noticed in FDS(I) followed by FCU, FDS(M) tendons. With the use of JAMAR, it showed a maximal tendon excursion at 1N load in FPL followed by FDS(M) and FDS(R) tendons.

7 Discussion

This is a description of a method to study in vivo variations in flexor tendon movement non-invasively. In this study the tendon excursion of the four major flexor tendons of hand- flexor pollicis longus, flexor digitorum superficialis, flexor carpi ulnaris and flexor carpi radialis were measured. The protocol helped to identify the four individual muscles, its tendons and the muscle tendon junctions. The muscle tendon junction was used as a landmark to track the tendon excursion.

The tendon displacement could be measured under the three experimental conditions 90 degree finger flexion, making a fist, and griping JAMAR at 5kgf. Many volunteers could not hold the JAMAR at 10, 15 and 20 kgf, therefore these measurements were not taken.

The flexor carpi radialis tendon was only measureable in two participants. The main challenges in tracking this tendon was due to movement of the surrounding structures such as tendon of flexor digitorum superficialis (index finger) and flexor policis longus. The flexor pollicis longus crosses the flexor carpi radialis tendon at the level of carpometacarpal joint by running superficially to it. On the ulnar side of the flexor carpi radialis tendon lies the median nerve and flexor pollicis longus and on the radial side lies the radial artery (Luong et al, 2014). During the experimental protocol, radial deviation and wrist flexion was performed to isolate flexor carpi radialis tendon. The movement of the aforementioned structures surrounding the tendon made the process of tendon isolation difficult. The time allotted for the experiment was exceeding on trying to locate the tendon. Therefore the researcher skipped this tendon and continued with the remaining experiment.

The anatomical structures surrounding the tendons were identified and annotated in the results section. These images could only be studied at the wrist level. Similar method can be used to study the variations at the palmar and tendon insertion level. The different variations observed are described below:

The anatomical structures surrounding the tendons were identified and annotated in the results section. These images could only be studied at the wrist level. Similar method can be used to study the variations at the palmar and tendon insertion level. The variations are described below:

The anatomical variation noted was the difference in the size of the pronator quadratus muscle. The images were compared with papers on ultrasound imaging. The pronator quadratus is a quadrilateral muscle around the wrist region and has two heads- superficial head is for pronation and the deep head acts as a stabilizer of the distal radio-ulnar joint (Tufts et al, 2015; Yi Lo and Cheng, 2014; Creteur et al, 2012). It is in close proximity to the flexor pollicis longus muscle and median nerve laterally and the ulnar nerve and flexor carpi ulnaris medially. The identification of anatomical variability is important to report clinical diagnosis such as trauma to the muscle due to fracture of the distal end of the radius or injury to the wrist area and a compartment syndrome which can be identified as thickened pronator quadratus muscle, loss of fibrillar structure under the ultrasound imaging.

Anatomical variations such as difference in the size of the flexor digitorum profundus, flexor digitorum superficialis and flexor pollcis longus tendons were noted under ultrasound imaging. As these tendons enters the carpal tunnel, therefore anomalies in these tendons can affect the normal anatomy of the carpal tunnel. This can sometimes lead to median nerve compression thus resulting in carpal tunnel syndrome (Ray et al, 2015). Also, due to the bigger size and close proximity of the flexor digitorum superficialis muscle to the radial artery can sometimes result in pain due to the pressure symptoms. These anatomical variations suggests that the structures affected by injury can vary and therefore the resulting impact on activity and participation can also vary. Understanding these variations with the help of ultrasound imaging is important before any clinical diagnosis or conducting surgery in the tendon.

Due to the anatomical variability, the nerves/arteries can sometimes be very close to the tendon area where the repair is required. If the repair is not done well, the nerves and arteries can also be damaged resulting in poor sensory function (Hassan and Noaman, 2007). The anatomical variability can differ in patients therefore a thorough understanding of the structures under ultrasound imaging is crucial to plan an effective surgery without disrupting the sensory function. The surgery and rehabilitation after tendon repair are interlinked therefore the understanding of the anatomical structures will help in planning an effective rehabilitation protocol to predict the outcome post flexor tendon repair (Chesney et al, 2011).

There is variability in the positions and proximity of the muscle tendon junction. It is important to understand the proximity of the tendons before planning a surgery. During tendon mobilization, if the adjacent fingers are not stabilized well, multiple tendons will move thus the focus will be less on the repaired tendon. With the help of the ultrasound images the close proximity of the tendons can be viewed and thus help in planning an effective mobilization for the repaired flexor tendons.

From tendon excursion point of view, it is understood that not all fingers have the same amount of tendon excursion. An understanding on the amount of tendon excursion is necessary for both the surgeons and the therapists to plan an effective surgery and rehabilitation protocol. Using this study method, the patients who are unable to move their fingers can be passively moved and viewed under the diagnostic ultrasound.

As described in literatures, splinting plays an important role in rehabilitation and is highly recommended in patients post tendon repair. It is still not clear about the optimum wrist and MCP joint angle required for splinting (Recaj et al, 2014). The results from this study have shown the amount of tendon excursion per degree of finger flexion and per newton load in healthy human volunteer (at MCP joint). These results can help to plan an effective splinting angle of the MCP joint. Although in this study only MCP joint angle is addressed, a similar technique can be used to find out the tendon excursion at PIP and DIP joints. Similarly, tendon excursion at the carpometacarpal joint of the thumb and the wrist can be measured. This will eventually help to plan an effective splinting regime for both thumb and the wrist.

During the mobilization process keeping a track on the amount of tendon excursion will help to understand if mobilization is actually contributing towards increased tendon excursion. As discussed, using this method of measurement, the tendon excursions can be monitored at various levels such as-DIP, PIP, MCP and wrist joint levels. Stabilizing the PIP/DIP joints the fingers can be moved inorder to isolate the tendon. A goniometer can also be placed at the PIP/DIP joint to see the degree of movement.

On monitoring, increased tendon excursion suggests that the mobilization protocol used is an effective one. However if the results does not show any/much change in the amount of tendon excursion during and after the mobilization, this suggests that the protocol is not effective enough to produce positive results. There are different types of exercises used to mobilize the repaired tendon (as discussed in the literature review). Most of the mobilization protocols include active/passive, flexion and extension exercises. This ultrasound method of measuring tendon excursion can be incorporated in patients with tendon repair whilst performing active and passive finger mobilization. The amount of tendon excursion resulted from performing active finger flexion can be compared with the passive finger flexion and the values can therefore help in planning an effective mobilization protocol for the repaired tendon.

In addition to active/passive flexion and extension exercises, resistance exercises were also incorporated in the studies to increase the strength of the repaired tendon. Increased load on the repaired tendon during the rehabilitation process can sometimes result in ruptures. It is always recommended to start with less load on the tendon while doing the strengthening exercises. The surgeons conducting the operation will be able to tell how much load the tendon can take based on the surgical material and technique used. Therefore knowing the exact amount of load the repaired tendon can take, an appropriate strengthening program can be planned without risking the tendon rupture. Load can be one factor contributing to the tendon rupture, other contributing factors based on the literatures are repair technique, suture material and thickness of the material.

As from the table 13, it is evident that the amount of excursion is more under the load. However as the participants were not able to manage multiple loads (10, 15, 20 kgf) therefore we could not check if the displacement was non-linear.

The loaded tendon did more work than the unloaded tendon. This could indicate that under the unloaded condition in the flexor tendons, the human system is in a position to draw on a variety of muscle for a simple movement. It therefore explains the variability in the magnitude of displacement of the flexor tendons. This study has not looked across the movement in the muscles, however a future experiment can be conducted where the displacements can be monitored simultaneously. In this study the displacement was observed one tendon at a time. A future study can be conducted to see the displacement in all the tendons during a particular movement.

Appropriate tendon loading in vivo helps towards healing, reducing adhesions and strengthening of the repaired tendon. However excessive loading can also result in ruptures. Active mobilization helps in tendon motion through muscular contraction whereas passive mobilization involves movement without the application of musculotendinous forces. Literature suggests that exercises after a tendon repair is beneficial. The effect of short term exercises (eg: 3 months) have less effect on tendon properties, however long term exercises (eg: 12 months) have shown increased effects (Lin et al, 2004). Mobilization helps in increasing the tendon excursion and gliding function thereby minimizing the adhesions. A fine balance between progression of tendon healing and prescribing safe exercises exists, therefore before prescribing any exercises it is very important to know how a tendon works under load and this can be understood under diagnostic ultrasound. Thus following this ultrasound method one can monitor the tendon excursion throughout the rehabilitation phase and can help in improving the clinical outcomes post flexor tendon repair.

Most of the literatures have studied flexor digitorum profundus tendon excursion under diagnostic ultrasound either in patients or healthy volunteers (Soeters et al, 2004; Korstanje et al, 2010; Puippe et al, 2011; Korstanje et al, 2012). Some of these studies placed wrist in 0/30 degree flexion and MCP joints in 60/70 degree flexion (Soeters et al, 2004; Korstanje et al, 2012). The tendon excursion values for flexor digitorum profundus were variable in these studies. Inadequate in vivo studies on flexor carpi radialis, flexor capi ulnais, flexor digitorum superficialis and flexor pollicis longus tendon excursion makes the comparison of the present findings difficult.

Based on the results, it is seen that the maximal tendon excursion for 1 degree of movement (MCP joint flexion) was noticed in FDS(I) followed by FCU, FDS(M) tendons. With the use of JAMAR, it showed a maximal tendon excursion at 1N load in FPL followed by FDS(M) and FDS(R) tendons. Although, there is variance in the numbers, it is evident that, this study has developed a method of measurement which suggests that it is able to measure the tendon excursion and also can predict the amount of movement.

8 Limitations

The values of tendon excursion from rest to- 90 degree finger flexion, fist and whilst gripping JAMAR at 5 kgf varied in all the volunteers on day 1 and day 2 of the same volunteer. This could be due to various factors like, the perception of 90 degree finger flexion which was different for the volunteers. Similarly, some volunteers made a tight fist whereas it was loose for others. Prior to the experiment a demonstration was given to the volunteers showing 90 degree finger flexion, fist and gripping JAMAR at 5kgf.

Figure 88: This figure illustrates Day 1 image at 90 degree finger flexion

Figure 89: This figure illustrates Day 2 image at 90 degree finger flexion

*The index finger in day 1 image is more flexed than the day 2 image of the same volunteer. The above images suggests limitations of this study *

Figure 90: This figure illustrates Day 1 image whilst making fist

Figure 91: This figure illustrates Day 2 image whilst making fist

The thumb in day 1 image is close to the index finger than the day 2 image of the same volunteer. The above images suggests limitations of this study

Figure 92: The above image shows that the Day 2 position of the fist changed in the middle of the experiement.

This points out the limitation of this study

Figure 93:The above image shows the Day 1 starting position of JAMAR

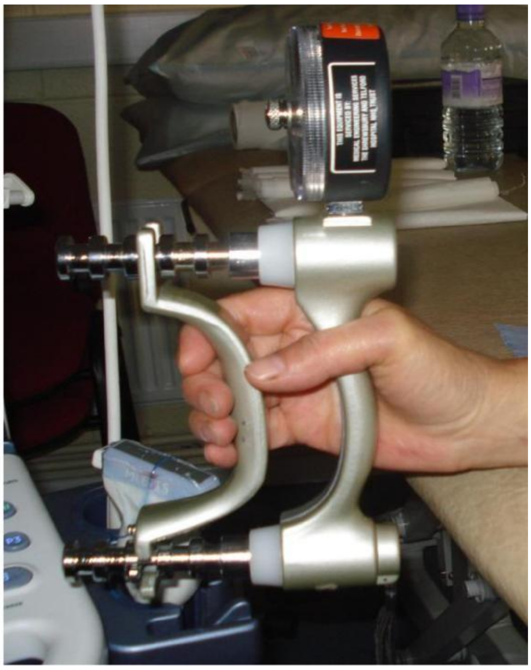


Figure 94: The above image shows the Day 2 starting position of JAMAR

The starting position varies in both days which points out the limitation of this study. The index finger in figure 93 is close to the thumb whereas it is away in figure 94

On gripping the JAMAR it was noticed that some volunteers exerted more force from the index and middle finger whereas for the rest the ring and little finger were more active. It was noted in some volunteers that the hand positions changed in the middle of the experiment. Also, the normal relaxed wrist and fingers position appeared to be dissimilar in all the volunteers. This could also be due to the pillow positioning under the arm, boredom, fatigue after constantly moving the fingers to track the muscle tendon junction. All these could be the common factors contributing towards unstable tendon excursion values.

In some volunteers, the fingers were not completely flexed to 90 degrees whereas others flexed more than 90 degrees. These variations in finger positions resulted in the fluctuation of tendon excursion values. On giving the command 'start' by the researcher, volunteers started gripping the JAMAR slowly and when the assistant said 'hold', they were supposed to hold the pin on 5kgf force.

However this seemed to be difficult in some volunteers. The pin was not stable and kept moving either slightly higher or lower than 5 kgf. Thus, the researcher had to rerun the procedure. A definite element of boredom and fatigue was expressed by some volunteers. Lack of interest can also interrupt the experiment process.

Apart from the hand positions, there are certain other factors which could contribute towards the unstable values of tendon excursion. Material errors such as measuring tape and thickness of the marker could have created some errors. Firstly, Vernier Caliper was considered to measure the flexor tendon excursion however, due to unavailability of the equipment measuring tape was used as an alternative. Precautions were taken while taking measurements with the tape like not to overstretch the tape. Secondly, the thickness of the marker on the volunteer's skin created some errors during measurement. To avoid the errors, midpoint of the marker on the skin was considered and thus used for all the measurements. The control on measuring tape, marking on skin, handling JAMAR and reading out the values were the duties of the assistant. The role of the assistant was very important in this project as it involved tasks like freezing image, taking measurements and handling JAMAR. The researcher carefully briefed the assistant prior to the experiment to avoid any potential errors.

The data from this research will eventually help in the rehabilitation process after a tendon repair. This research shows that it is possible to measure the tendon excursions at 90 degree finger flexion, on making a fist and gripping JAMAR. The results from this study will give an idea on the range of tendon excursions in healthy subjects at different finger and wrist positions.

In this research, using JAMAR helped to see the whether the tendon can take enough load. After a tendon repair the consulting surgeon will be able to tell how much load the repaired tendon can take and accordingly a mobilization regime can be planned for the respective patient. As the results from this study showed variations in the tendon excursion for all the volunteers so it is important to discuss with the respective surgeon on the possible load the repaired tendon can take. A tendon rupture post repair can be due to various factors like repair technique, suture material, thickness of the material and most importantly the mobilization exercises. Thus following an appropriate rehabilitation protocol can help to minimize the tendon ruptures post repair.

9 Conclusion

This project has developed a method to study flexor tendon excursions in hand using diagnostic 2D ultrasound. The developed method and data would assist in planning an effective rehabilitation regime for the patients post flexor tendon repair. After a tendon repair, along with the tendons, the surrounding structures such as muscles and bones can also be visualized under the diagnostic US. This can eventually help to rule out if there is any trauma to the surrounding structures. This study opens doors for various potential future research.

Although the present study has addressed its limitations, however it can be used for wider clinical applications. Future research is necessary to see the clinical outcomes by implementing this experimental protocol in patients with flexor tendon repair.

A repair can be said successful when the person is able to go back to activities of daily living. Success in terms of repair is the ability to have normal range of movement and a tendon that is fully healed and load bearing. Whereas, unsuccessful repair can result in ruptures, contractures and fixed flexion deformity. It is possible that not everybody will fully recover and have full range of movement however the deficit can be measured.

The therapists follow different rehabilitation protocols post tendon repair and the current literature do not provide clear information on the most effective rehabilitation protocol.

Therefore there is a need to explore on the effects of various rehabilitation protocols so that the best treatment can be provided to the patient.

The anatomical variability of the structures can be studied in depth under ultrasound imaging in both longitudinal and cross-sectional views. *In-vivo* studies with higher sample size can be included so that more data can be extracted. A sample group who can hold JAMAR at 10 kgf, 15 kgf, 20 kgf or even higher is required to understand the tendon behaviour at increased loads. This will also help to check if muscle tendon behaviour is non-linear. This experimental protocol along with some modifications can also be used to measure the tendon excursion at the wrist, PIP and DIP joint levels. As the literature provides very less information on the optimal splinting angle of the wrist and the finger joints therefore, this type of study can eventually contribute in planning an effective splinting regime.

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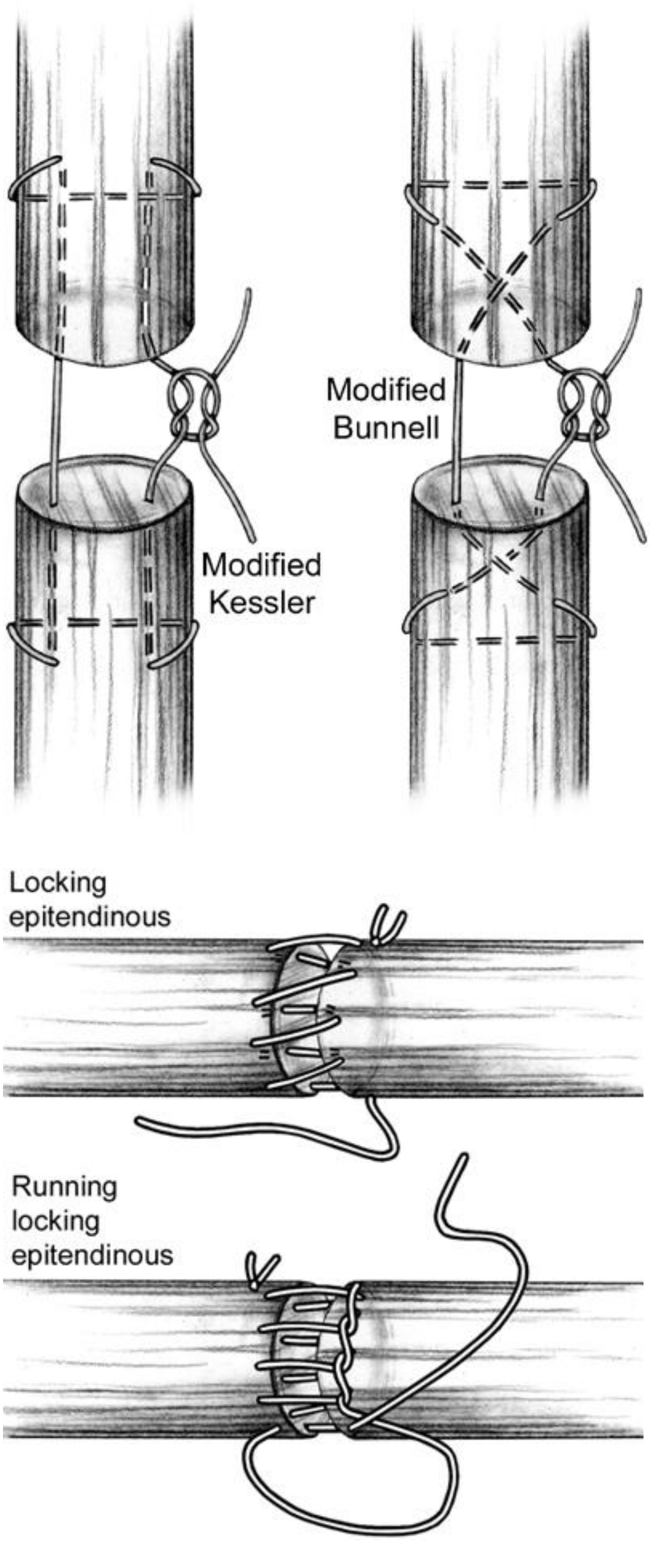
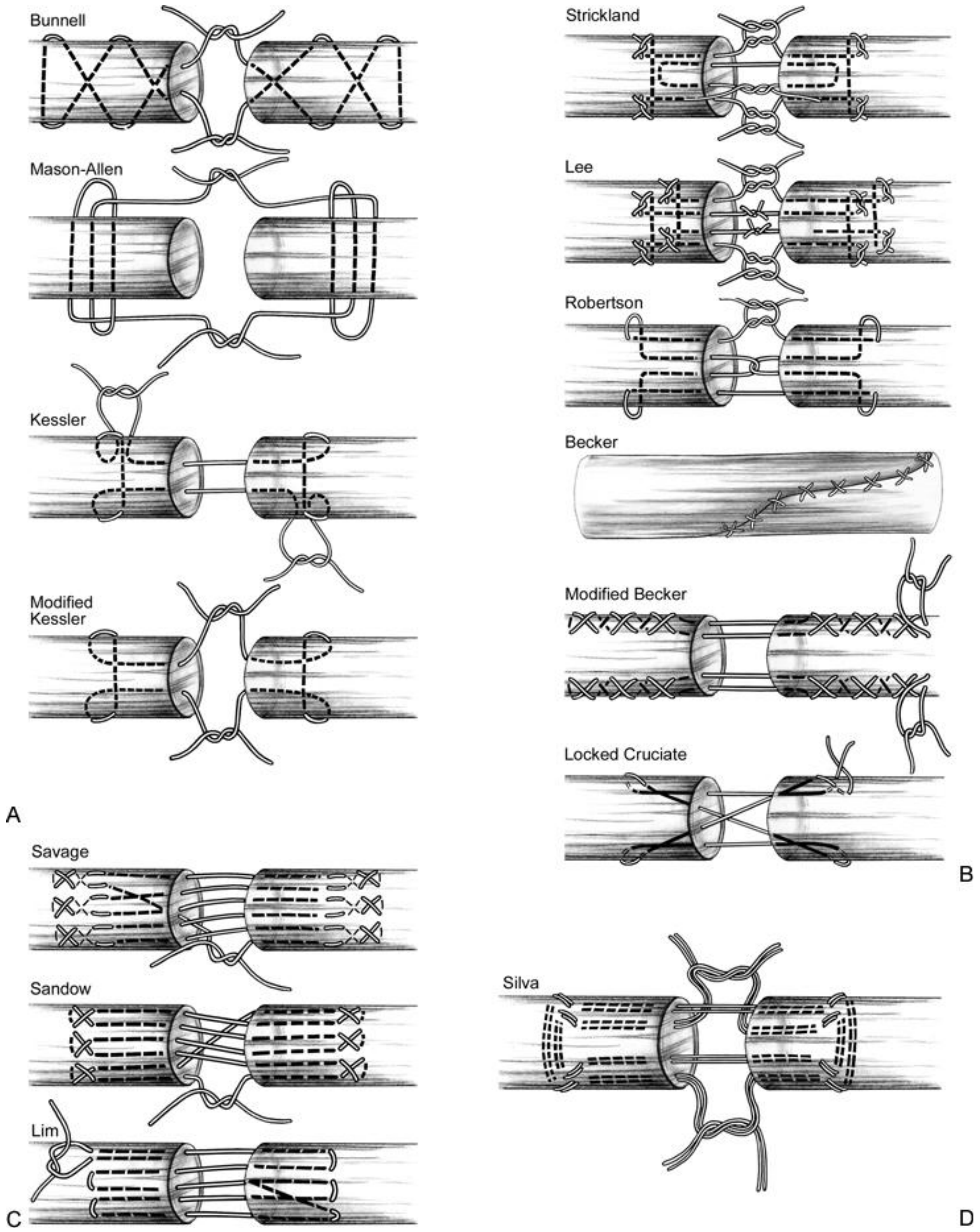
11 Appendix

Appendix 1:

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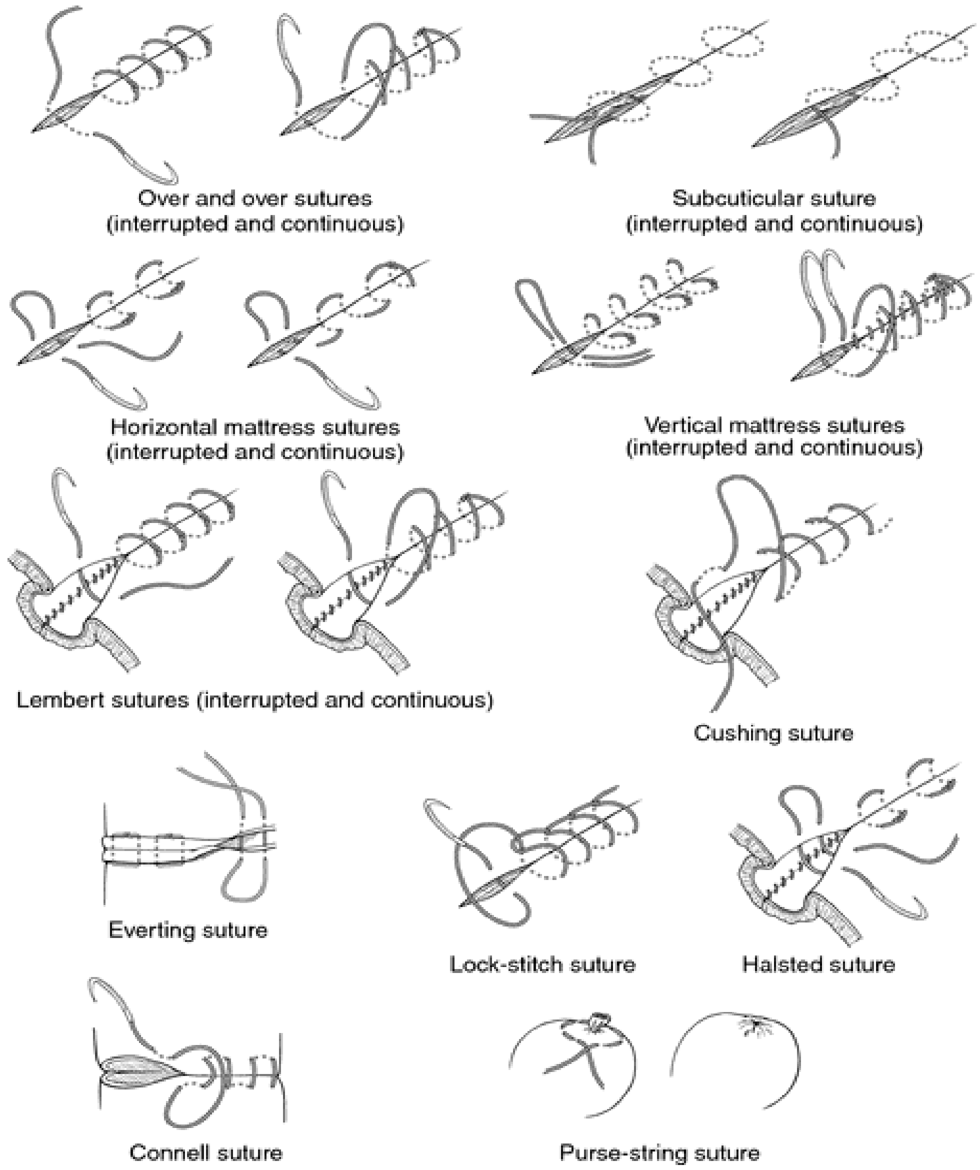


Appendix 2:

Nylon/Polyamide (Ethilon, Monosof, Nurolon, Dermalon, Bralon, Surgilon):

Monofilament (e.g., Ethilon, Monosof*)* and braided [e.g., Nurolon, Surgilon polyamide polymer suture]. Braided forms coated with silicone. Stronger than silk and elicits minimal acute inflammatory reaction. Maintains elasticity post implantation, even when moist.Inert and non-capillary.Supramid, a twisted multifilament suture, is available in large diameters only.

Polypropylene (Prolene®, Surgipro®, Surgilene): Synthetic monofilament suture consists of a stereoisomer of polypropylene. Remains biologically inert. May be used as a pullout suture (e.g., subcuticular or skin closure) since it does not adhere to tissues. Often used in vascular surgery due to being the least thrombogenic. Also good for use during hernia and tendon repair and in contaminated or infected wounds.

Stainless steel (Flexon): Comprised of monofilament or twisted multifilament ironchromium- nickel-molybdenum alloy, but also manufactured without toxic elements.

Demonstrates excellent knot holding capabilities, high tensile strength with little loss over time and biologically inert.Used in orthopedic, neurosurgical and thoracic (e.g., sternum closure) applications as well as for abdominal wall closure or in contaminated or infected wounds. Visible radiographically but may interfere with magnetic resonance imaging (MRI) and requires special cutting scissors.

Polyester fiber (Mersilene/Surgidac, Dacron, [uncoated] and Ethibond/Ticron,

Ethiflex [coated]): Multifilament braided material comes coated with polybutilate (Ethibond),

Teflon (Ethiflex), or silicone (Ticron) to reduce friction and improve pliability. Lasts indefinitely in the body. Can be used in slow healing tissues, vessel anastomosis and during placement of prosthetic materials. Avoid in infected wounds where bacteria entrapped between fibers can cause persistent incisional drainage.

Appendix 3:

Continuous suture: one in which a continuous, uninterrupted length of material is used.

Figure-of-eight suture: one in which the threads follow the contours of the figure 8.

Running suture: The benefit of this suture is the minimal epidermal puncture points allowing the suture to be left in place longer without suture-track scarring.

Adelaide repair: The aim of treatment is to restore maximum function to the injured digit.

As treatment depends on associated injuries this protocol provides guidelines for the Management of the flexor tendon only and will be considered under the following headings:

- Skin incision
- tenorrhaphy technique
- protection of tendon during tendon healing
  restoration of joint range of motion and strength
- oedema control
- scar management
- prevention of interphalangeal joint contracture

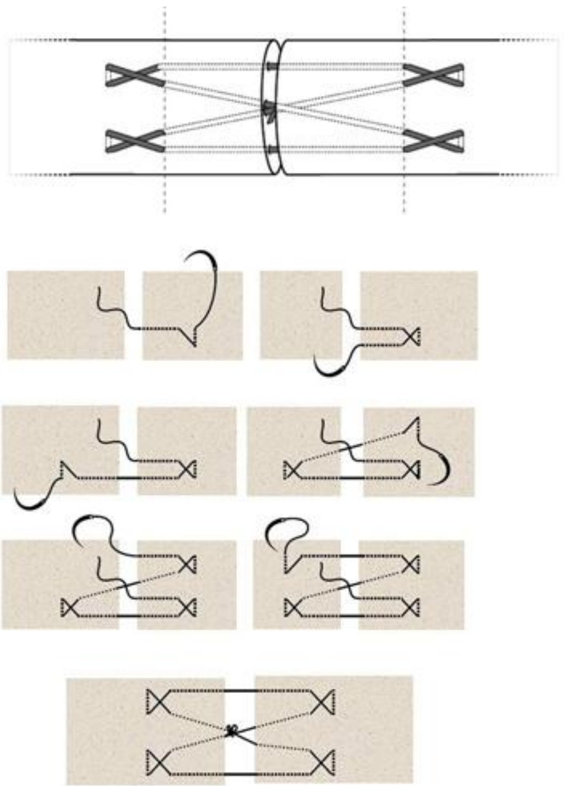
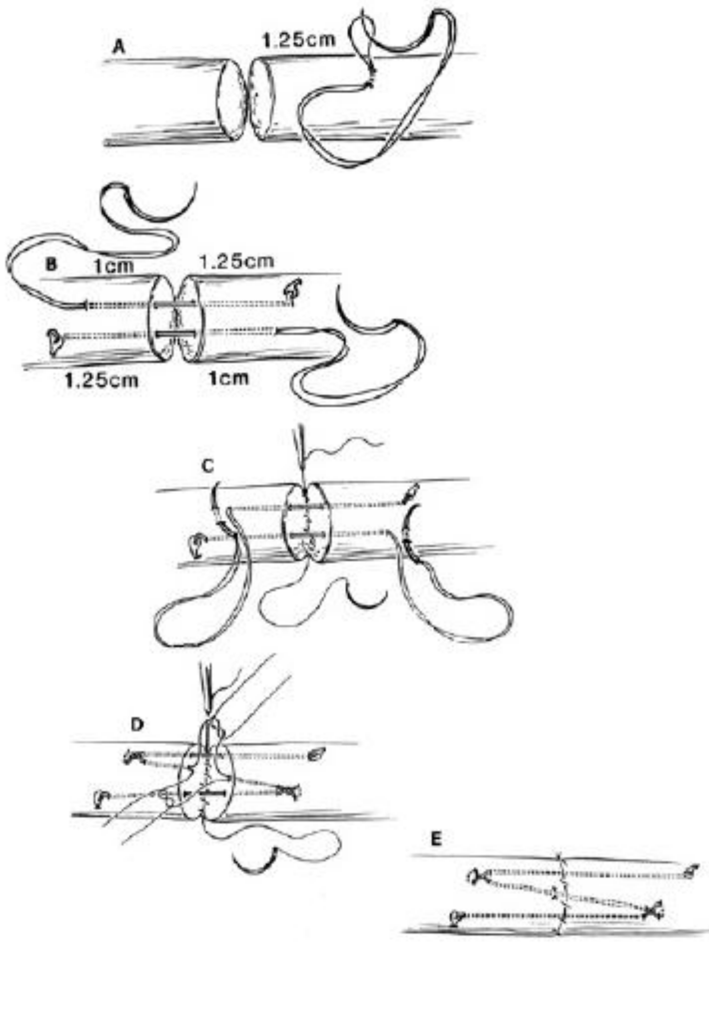


Fig: Lim and Tsai technique



Mantero technique: Mantero and colleagues have reported a modification of the Bunnell pull-out method for the repair of zone 1 flexor digitorumprofundus (FDP) lacerations that allows active postoperative mobilization and thus minimizing the risk of tendon adhesions.

Appendix 4:

Tenodesis mobilization:

This exercise can help improve the strength of your grasp in your hand. You may find it helpful to do this exercise with your lower arm supported on the arm rest of a chair or on a table.

1. Start with your arm at your side, elbow bent to 90 degrees or a right angle. Have your hand in a relaxed position with your palm facing down.
2. Gently bend your wrist up towards the ceiling while bending your fingers towards the palm of your hand to make a fist.
3. Bend your wrist down towards the floor as far as you can while you gently straighten your fingers.

Isolated tendon gliding:

Isolated FDS Exercises:

The superficialis tendons have separate muscle bellies which allow isolated PIP flexion of each digit. This is in contrast to FDP to the MF - LF which share a common muscle belly. To achieve isolated FDS activity, flex one finger at a time at the PIPJ, with the uninvolved hand keeping the other fingers in extension.

Blocking Exercises:

DIP joint flexion, with the PIP stabilised into extension, inactivates FDS and produces gliding of FDP on FDS and its surrounding tissues.

PIP joint flexion with stabilisation of the MCPJ in extension encourages gliding of FDS with respect to surrounding tissue (do not let pt. Bend the DIP as this will initiate FDP).

Patients will often present with good FDP pull-through when the finger is blocked in extension, but are poor at making a full fist. It is possible there is not enough force on the tendon adhesion when in extension. Therefore exercise with the MCP and PIP joints flexed to the point where the patient starts to lose DIP motion.

Tendon Gliding Exercises

Hook fist: Maximum glide is achieved between FDS and FDP

Fist position: FDP achieves maximum glide with respect to sheath and bone as well as a fair amount of glide over FDS.

Straight fist: Achieves maximum glide of FDS with respect to flexor sheath and bone.

Appendix 5:

Indiana/Strickland protocol:

Early active motion program (Strickland/Indiana Hand Center)

0–3 days	0–4 weeks	4 weeks	5 weeks	6 weeks	8 weeks	14 weeks
Dorsal blocking splint with wrist in 20° flexion, MCP joints in 50° flexion Tenodesis splint allowing 30° wrist extension and full wrist flexion, maintaining MCP joints in 50° flexion (a single hinge splint with a detachable extension block can also be used)	Duran passive motion performed 15 times every 2 hours Tenodesis exercises within hinged splint 15 times every 2 hours	Dorsal blocking splint removed during exercise but continued for protection Tenodesis exercises continue Instruction to avoid simultaneous wrist and finger extension	Active IP flexion with MCP extension followed by full digital extension	Blocking exercises begin if active tip to distal palmar crease is more than 3 cm Passive extension can begin at 7 weeks	Progressive resistive exercises initiated	Unrestricted use of hand

Duran Protocol:

Duran program

0–3 days	0–4.5 weeks	4.5–5.5 weeks	5.5 weeks	7.5 weeks
o Dorsal Protective splint applied with wrist in 20° flexion, MCP joints in ~50° flexion, IP joints full extension	o Hourly exercises within the splint: o 10 repetitions passive DIP extension with PIP and MCP flexion o 10 repetitions passive PIP extension with MCP and DIP joint flexion	o Splint replaced by wrist cuff with elastic flexion traction from fingernail to cuff o Continue active extension/passive flexion	o Wrist cuff discontinued o Blocking and fisting exercises initiated	o Light resistive exercises with putty o Splinting to correct any joint or extrinsic flexor tightness

Modified Duran Protocol:

Fig: Modified Duran

This is to apply a dorsal protective splint (40 to 50 degrees at the MP joints and from 20 degrees of extension to 20 degrees of flexion at the wrist, with the IP joints allowed to extend to neutral in the splint) but to omit the rubber band traction and strap the IP joints in extension between exercises or at night Patients perform passive individual and composite flexion and extension, active composite extension exercises (manually blocking the MP in greater flexion for more complete active IP extension), and the passive flexion and extension exercises advocated by Duran and Houser. In therapy only, the splint is removed for careful protected tenodesis exercises (passive or assisted simultaneous wrist flexion and finger extension, alternating with simultaneous wrist extension and finger flexion).

Kleinert Protocol:

Kleinert program

0–3 days	0–4 weeks	4–6 weeks	6–8 weeks
∘ Dorsal protective splint applied with wrist and MCP joints in flexion and IP joints in full extension; elastic traction from fingernail, through palmar pulley, to volar forearm ∘ Velcro strap to allow night release of elastic traction, splinting IPs in full extension	∘ Hourly active extension to limits of splint, followed by flexion with elastic traction only ∘ Wound and scar management and education	∘ Dorsal protective splint discontinued, sometimes replaced with wrist cuff and elastic traction ∘ Night protective splint to prevent flexion contracture ∘ Active wrist and gentle active fisting initiated unless signs of minimal adhesions ∘ At 6 weeks blocking exercises begin	∘ Progressive resistive exercises begin

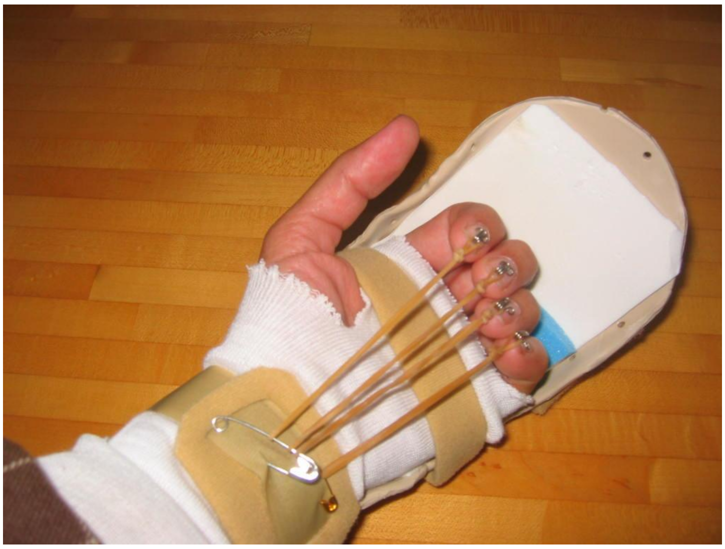


Fig: Modified Kleinert Protocol

0-4 weeks: Dorsal splint: wrist and MCPJs flexed, IPJs extended. Elastic traction from fingernail through palmer pulley to volar forearm. Velcro stap to allow night release of elastic traction, splinting IPJs in full extension. Hourly active extension, passive flexion

4-6 weeks: Splint discontinued for wrist cuff with elastic traction. Night splint to prevent flexion contracture. Active wrist and finger flexion.

6 weeks: Begin blocking exercises. Progressive resisted exercises.

Washington Regimen:

This regimen is derived from a combination of Kleinert's controlled active extension with rubberband passive flexion, Duran's controlled passive techniques, and the modification of the Kleinert orthosis that uses a palmar pulley system.

The Washington Regimen of controlled motion for flexor tendon rehabilitation is divided into three stages, each of two weeks' duration.

- The first stage consists of therapist-assisted controlled passive flexion and extension exercises active extension exercises against passive flexion provided by a dynamic splint.
- The second stage consists only of active extension exercises against the passive flexion of the dynamic splint.
- Active flexion and active extension exercises without the use of the rubber-band passive flexion constitute the third stage of the rehabilitation regimen.

Appendix 6:

Evaluation of result of flexor tendon repair using the Buck-Gramcko II criteria[5]

Buck-Gramcko II criteria*	Units	Points
Free nail palm crease distance measured from the free nail margin to the distal palmar crease	0.0–0.5 cm	6
	0.6–1.5 cm	5
	1.6–2.5 cm	4
	2.6–4.0 cm	3
	4.1–6.0 cm	2
	>6.0 cm	1
Total extension deficit (MPJ+PIP+DIP)	0°–30°	3
	31°–50°	2
	51°–70°	1
	>70°	0
Modified total active motion (MPJ+2xPIP+3xDIP)	>400°	8
	>320°	6
	>280°	4
	>240°	2
	>240°	0
Classification		
Excellent	-	16–17
Very good	-	14–15
Good	-	11–13
Fair	-	7–9
Poor	-	0–6

Table III. Evaluation of the recovery of the FPL according to the criteria of Tubiana et al[12]

	Degrees	Assessment
Flexion of IP joint	>60	F1
	>30	F2
	<30	F3
Extension deficit	<15	E1
	<30	E2
	>30	E3
Evaluation		
Excellent		F1E1
Good		F2E1
Fair		F3E1 or F2E2
Poor		F3E2 or E3

Table III. Evaluation of the recovery of the FPL according to the criteria of Tubiana et al[12]

	Degrees	Assessment
Flexion of IP joint	>60	F1
	>30	F2
	<30	F3
Extension deficit	<15	E1
	<30	E2
	>30	E3
Evaluation		
Excellent		F1E1
Good		F2E1
Fair		F3E1 or F2E2
Poor		F3E2 or E3

Table II

Strickland's evaluation systems

Score	Original Strickland %	Adjusted Strickland %
Excellent	85-100	75-100
Good	70-84	50-74
Fair	50-69	24-49
Poor	< 50	0-24

$$\text{Strickland} = \frac{(\text{active flexion PIP + DIP}) - (\text{extension deficit PIP + DIP})}{175^\circ} \times 100\%$$

Table I

TAM evaluation system of the ASSH

Score	%
Excellent	Normal
Good	> 75
Fair	50-75
Poor	< 50
Worse	< pre-operative

TAM = total active flexion – total extension deficit (MCP, PIP, DIP)
% = TAM of the injured finger / TAM of the contralateral finger.

Zone 1 **Moieman- Elliot**[102]	TAM = (DIP) Active flexion (DIP)−extension deficits (DIP) Expressed as percentage of the hypothetical normal finger for which TAM = 74			
Excellent: 85–100% or >62		*Good: 70–84% or 52–62*	*Fair: 50–69% or 37–51*	*Poor: <50% or <37*

The Louisville method	Grade1	Grade 2	Grade 3	Grade 4
Pulp to distal palmar crease	0–1 cm	1.1–1.5 cm	1.5–3 cm	3 cm+
Extension deficit	0–15	16–30	31–50	50+
Excellent: both deficits grade 1		*Good: both deficits at grade 2*	*Fair: both deficits at grade 3*	*Poor: either deficit worse than grade 3*

Baseline pinch gauge:

Key (lateral pinch)

Tip (pulp pinch)

	PATIENT START POSITION	PLACEMENT OF PINCH GAUGE	POSITION OF THERAPIST	TEST
LATERAL (KEY) PINCH (RIGHT/LEFT)	- seated or upright - test arm at side with elbow flexed 90° - palm facing inward	Pinch gauge between flexed PIP joint of index finger and thumb.	In front of patient, to the side, stabilizing pinch gauge.	Have patient squeeze, hold and release.
CHUCK PINCH (PALMER) (RIGHT/LEFT)	- seated or upright - test arm at side with elbow flexed 90° - palm facing down	Pinch gauge between thumb and the index and middle fingers.	In front of patient, to the side, stabilizing pinch gauge.	Have patient squeeze, hold and release.
PULP PINCH (TIP) (RIGHT/LEFT ON EACH FINGER)	- seated or upright - test arm at side with elbow flexed 90° - palm facing down - test finger on button	Pinch gauge between thumb and test finger (make sure other fingers do not interfere).	In front of patient, to the side, stabilizing pinch gauge.	Have patient squeeze, hold and release.

Jamar dynamometer:

Appendix 7:

INVITATION LETTER

Dear volunteers,

My name is Rani Sharma and am a MPhil research student (Physiotherapy) from School of Health and Rehabilitation at Keele University. I am looking for volunteers to help me with a study on,measurement of flexor tendon excursion during simple hand movement using 2D diagnostic ultrasound. If you are an adult and interested in this research, can you please consider volunteering for my study.

As a participant, you will be asked to come twice and volunteer approximately for **an hour and half** of your time so that the measurements of the tendon excursion can be taken with the help of diagnostic ultrasound (non-invasively) in three different positions: wrist and fingers in straight, 90 deg finger flexion and fully clenched fist.

There are minimal to no risk intended to you during this study nor is there compensation for participating. However, your contribution to the research will hopefully allow us to compare tendon excursions in various groups of people.

If you would like to participate in this research study, or have any questions please email me at r.sharma@keele.ac.uk or call me at 01782734250 (office).

Appendix 8

INFORMATION SHEET

Study title: Measurement of flexor tendon excursion during simple hand movement using 2D diagnostic ultrasound

You are being invited to consider taking part in the research study aimed at measuring the movements of your muscles and tendons (non-invasively) when you carry out simple movements in your hand. The data from this study will help us develop new methods of measurement and treatment for patients who have serious amputation or crush injuries to the hand and forearm. This project is being undertaken by Ranishree Sharma, as a researchstudentat the School of Health and Rehabilitation, Keele University as part of her MPhil study. The project will be supervised by AnandPandyan, Kim Major and Cath Bucher.

Before you decide whether or not you wish to take part, it is important for you to understand why this research is being done and what it will involve. Please take time to read this information carefully and discuss it with friends and relatives if you wish. Ask us if there is anything that is unclear or if you would like more information.

Do I have to take part?

You are free to decide whether you wish to take part or not. If you do decide to take part you will be asked to sign two consent forms, one is for you to keep and the other is for our records. Additionally, the researcher will screen your health status to ensure that any risk of harm to you, by volunteering for the study, is minimal. Furthermore, even if you do consent for the study, you are able to withdraw from this study at any time and without giving reasons.

What will happen if I take part?

You will be required to attend two sessions, lasting 1 hour at the School of Health and Rehabilitation (SHAR), Keele University. You must be willing to expose your arm (ideally dressed in a shirt with short sleeves) so that we can use an ultrasound machine to non-invasively study the movement in the muscles and tendon of the forearm.

If I take part, what do I have to do?

- If you are willing to volunteer for the study, you will be asked to sign the information sheet and consent form agreeing to participate in this research. The date and time of testing will be arranged only after you have signed the consent form. The study will take place in a laboratory within the School of Health and Rehabilitation

- On the first day of testing the researcher will record your age, gender, height, weight, and length of the upper limb (using a simple tape measure). We will ask you to fill in a questionnaire to identify your dominant hand.
- All measurements will be taken on the dominant hand and the measurements will be taken on two separate days – the measurements will last an hour. During each visit the following procedure will be followed.
  - You will be asked to lie supine (i.e. on your back) on a physiotherapy examination couch with your exposed forearm on the side and fingers straight.
  - A water soluble gel will be applied over the forearm (this is needed to get a good picture of your muscles and tendon) and the special probe will be placed over your forearm. The researcher will then move the probe over the forearm to identify the four muscle we are interested in (we can give you the technical details if you so wish during our meeting and during the procedure). When the appropriate structures are identified a marker pen will be used to place a mark on your skin.
  - This process will be repeated with (a) palm open fingers bent and (b) hand making a fist without squeezing hard. This distance between the marks will be measured with a special tape measure and this gives us a measure of the distance travelled by the muscle and tendon.
  - After a short period of rest, if you ask for this, we will repeat the measurement procedure with your fists clenched around a device that measures the strength of your grip. For this test we will only be asking you to grip at three strengths 5Kg, 10 Kg and 15 Kg. From this we can find out how much movement occurs when your muscles are producing a force.
- Once the measurements are taken the ultrasound water-based gel will be wiped from your skin and you are free to go.

What are the benefits (if any) of taking part?

There will be no personal benefits to you by volunteering your time for the study. However, your participation will help us learn more about the movements of the forearm muscles and tendons. This information is very useful for surgeons and physiotherapist treating patients with severe injuries (reattachment of hands/fingers, crush injuries, and amputations) to the forearm, wrist and fingers.

What are the risks (if any) of taking part?

There is minimal to no risk to you. The ultrasound device we use has been in use for many years is not known to cause harm at the intensities we use. Furthermore we are making sure that you have no conditions that can be exacerbated by taking part in this study. Lying in one position for a long time can be tiring and uncomfortable. However, you are permitted to ask for breaks between the periods of testing.

How will information about me be used?

The data collected and results will be analysed, and reported in a thesis, In addition, the data and results may be reported in possible scientific publications. However your personal identity will not be revealed in any research publications

Who will have access to information about me?

Only the researcher and the supervisors will have access to any personal information. All data will be kept in a secured, password protected PC and locked in a secure office, and no individual will be identifiable; except by numerical code. Any personal data will be disposed of as per the requirements of the Data Protection Act.

Who is funding the organizing the research?

There is no funding for the research and the project will be using available reAdapted froms provided by the School of Health and Rehabilitation, Keele University.

What if there is a problem?

If you have a concern about any aspect of this study, you may wish to speak to the researcher (Rani Sharma on r.sharma@keele.ac.uk or 01782734250). Alternatively, if you do not wish to contact the researcher, you may contact her supervisorAnandPandyan at a.d.pandyan@keele.ac.uk or 01782 734252. If you remain unhappy about the research and/or still wish to raise a complaint about any aspect of the way that you have been approached or treated during the course of the study please write to Nicola Leighton who is the University's contact for complaints regarding research at the following address:-

Nicola Leighton
Research Governance Officer
Research & Enterprise Services
Dorothy Hodgkin Building
Keele University
ST5 5BG
E-mail: n.leighton@uso.keele.ac.uk
Tel: 01782 733306

Contact for further information

Researcher
Rani Sharma
School of Health and Rehabilitation
McKay Building
Keele University
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Appendix 9:

Consent Form

Title of the study: Measurement of flexor tendon excursion during simple hand movement using 2D diagnostic ultrasound

<u>Investigator's name</u>: Ranishree Sharma

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To be completed by the Participant:

		Please initial below if you agree with the statement
1	I confirm that have read and understood the information sheet for the above study and have the opportunity to ask questions.	
2	I understand that my participation is voluntary and that I am free to withdraw at any time	
3	I agree to take part in the study	
4	I understand that data collected about me during this study may be published, and the results will be anonymized before it is submitted for publication	
5	I agree to be contacted about possible participation in future research projects	

………………………………………	………………………………	………………………………………
Name of the Participant	**Date**	**Signature**
……………………………………	………………………………	………………………………………
Researcher	**Date**	**Signature**

Appendix 10:

Edinburgh Handedness Inventory

Surname___________________________ Given Name_______________________________

Date of Birth_________________________ Sex_______________________________________

Please indicate your preferences in the use of hands in the following activities by *putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forces to, *<u>put ++</u>*. If any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	Left	Right
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		
i. Which foot do you prefer to kick with?		
ii. Which eye do you use when using only one?		

Appendix 11:

Data Documentation

Identification Number	
Date	
Height	
Weight	
Age	
Length of the forearm	

Day 1

Tendons	Tendon excursion with fingers at 90 degree (mm)	Tendon excursion with fist fully clenched (mm)	Tendon excursion JAMAR 5 Kgs (mm)

Flexor pollicislongus			
Flexor digitorumsuperficialis	Index: Middle: Ring: Little:	Index: Middle: Ring: Little:	Index: Middle: Ring: Little:
Flexor carpi ulnaris			
Flexor carpi radialis			

Day 2

Tendons	Tendon excursion with fingers at 90 degree (mm)	Tendon excursion with fist fully clenched (mm)	Tendon excursion JAMAR 5 Kgs (mm)
Flexor pollicislongus			
Flexor digitorumsuperficialis	Index: Middle: Ring: Little:	Index: Middle: Ring: Little:	Index: Middle: Ring: Little:
Flexor carpi ulnaris			
Flexor carpi radialis			

Appendix 12:

The tables below represents the length of the forearm (only in the first table), tendon excursion on day 1 for 90 degree finger flexion and its normalized length in percentage for all the 12 volunteers. Similarly the normalized length for day 2 was also calculated. Based on the normalized length of day 1 and day 2 the normalized mean and difference was calculated. This process was repeated for all the four tendons at 90 degree finger flexion, making a fist and on gripping JAMAR at 5kgf.

Length of forearm	90 deg flex day 1	Normalised length in percentage	90 deg flex day 2	Normalised length in percentage	normalized mean	normalized diff
46	0.5	1.1	0.5	1.1	1.1	0
48	0.3	0.6	0.2	0.4	0.5	0.2
48.5	0.4	0.8	0.1	0.2	0.5	0.6
42.2	0.1	0.2	0.3	0.7	0.45	-0.5
48	0.2	0.4	0.4	0.8	0.6	-0.4
46.5	0.2	0.4	0.1	0.2	0.3	0.2
47	0.1	0.2	0.2	0.4	0.3	-0.2
45.5	0.5	1.1	0.2	0.4	0.75	0.7
42	0.4	1	0.5	1.2	1.1	-0.2
39	0.2	0.5	0.5	1.3	0.9	-0.8
38	0.4	1.1	0.6	1.6	1.35	-0.5
40.5	0.4	1	0.2	0.5	0.75	0.5
90 degree flexion FPL						

Fist day 1	Normalised length in percentage	Fist day 2	Normalised length in percentage	normalized mean	normalized diff
1	2.2	0.5	1.1	1.65	1.1
0.7	1.5	0.3	0.6	1.05	0.9
0.4	0.8	0.5	1	0.9	-0.2
0.4	0.9	0.5	1.2	1.05	-0.3
1	2.1	1.1	2.3	2.2	-0.2
1	2.2	0.9	1.9	2.05	0.3
1	2.1	0.4	0.9	1.5	1.2
1.2	2.6	0.6	1.3	1.95	1.3
1	2.4	1.2	2.9	2.65	-0.5
0.7	1.8	1	2.6	2.2	-0.8
0.3	0.8	0.4	1.1	0.95	-0.3
1	2.5	0.9	2.2	2.35	0.3
FPL (fist)					

JAMAR day 1	Normalised length in percentage	JAMAR day 2	Normalised length in percentage	normalized mean	normalized diff
2	4.3	1.6	3.5	3.9	0.8
0.6	1.3	0.6	1.3	1.3	0
0.3	0.6	0.4	0.8	0.7	-0.2
0.5	1.2	0.5	1.2	1.2	0
0.5	1	0.3	0.6	0.8	0.4
0.6	1.3	0.2	0.4	0.85	0.9
0.2	0.4	0.6	1.3	0.85	-0.9
1	2.2	0.6	1.3	1.75	0.9
0.8	1.9	0.8	1.9	1.9	0
0.6	1.5	0.8	2.1	1.8	-0.6
0.8	2.1	1	2.6	2.35	-0.5
0.8	2	0.9	2.2	2.1	-0.2
FPL JAMAR at 5Kgf					

90 degree flexion day 1	Normalised length in percentage	90 degree flexion day 1	Normalised length in percentage	normalized mean	normalized diff
1.1	2.4	0.6	1.3	1.85	1.1
0.6	1.3	0.4	0.8	1.05	0.5
0.4	0.8	0.3	0.6	0.7	0.2
0.9	2.1	0.8	1.9	2	0.2
0.6	1.3	0.4	0.8	1.05	0.5
0.5	1.1	0.2	0.4	0.75	0.7
0.5	1.1	0.2	0.4	0.75	0.7
0.4	0.9	0.5	1.1	1	-0.2
0.8	1.9	0.9	2.1	2	-0.2
0.9	2.3	1	2.6	2.45	-0.3
0.4	1.1	0.3	0.8	0.95	0.3
0.1	0.2	0.3	0.7	0.45	-0.5
90 degree flexion FDS(I)					

fist day 1	Normalised length in percentage	fist day 1	Normalised length in percentage	normalized mean	normalized diff
1.8	3.9	1.9	4.1	4	-0.2
0.5	1	0.7	1.5	1.25	-0.5
0.6	1.2	1.7	3.5	2.35	-2.3
1.6	3.8	1.5	3.6	3.7	0.2
1.5	3.1	1.5	3.1	3.1	0
1.4	3	0.6	1.3	2.15	1.7
0.3	0.6	0.3	0.6	0.6	0
1.2	2.6	1.3	2.9	2.75	-0.3
1	2.4	1	2.4	2.4	0
2	5.1	1.8	4.6	4.85	0.5
1.5	3.9	0.8	2.1	3	1.8
0.7	1.7	0.6	1.5	1.6	0.2
Fist FDS (I)					

JAMAR day 1	Normalised length in percentage	JAMAR day 2	Normalised length in percentage	normalized mean	normalized diff
0.6	1.3	0.4	0.9	1.1	0.4
0.4	0.8	0.3	0.6	0.7	0.2
0.4	0.8	0.6	1.2	1	-0.4
0.4	0.9	0.3	0.7	0.8	0.2
0.2	0.4	0.4	0.8	0.6	-0.4
0.9	1.9	0.2	0.4	1.15	1.5
0.6	1.3	0.4	0.9	1.1	0.4
0.7	1.5	0.7	1.5	1.5	0
0.5	1.2	0.6	1.4	1.3	-0.2
1.1	2.8	1.3	3.3	3.05	-0.5
0.6	1.6	0.7	1.8	1.7	-0.2
1.1	2.7	1	2.5	2.6	0.2
FDS (I) JAMAR at 5Kgf					

90 deg flexion day 1	Normalised length in percentage	90 deg flexion day 1	Normalised length in percentage	normalized mean	normalized diff
0.8	1.7	1	2.2	1.95	-0.5
0.5	1	0.2	0.4	0.7	0.6
0.4	0.8	1	2.1	1.45	-1.3
0.6	1.4	0.8	1.9	1.65	-0.5
1.3	2.7	0.9	1.9	2.3	0.8
0.6	1.3	0.5	1.1	1.2	0.2
0.1	0.2	0.2	0.4	0.3	-0.2
0.4	0.9	0.5	1.1	1	-0.2
0.8	1.9	0.8	1.9	1.9	0
0.5	1.3	0.6	1.5	1.4	-0.2
0.9	2.4	0.5	1.3	1.85	1.1
0.8	2	0.8	2	2	0
90 deg flexion FDS(M)					

fist day 1	Normalised length in percentage	fist day 2	Normalised length in percentage	normalized mean	normalized diff
1.9	4.1	1.6	3.5	3.8	-2.8
1	2.1	0.3	0.6	1.35	1.3
1.2	2.5	1.8	3.7	3.1	-0.9
1	2.4	1.2	2.8	2.6	-1.5
1.4	2.9	1.4	2.9	2.9	-1.4
1.4	3	0.8	1.7	2.35	2.1
0.1	0.2	0.3	0.6	0.4	1.5
1.1	2.4	0.9	2	2.2	-0.4
1.8	4.3	1.6	3.8	4.05	-1.3
1	2.6	0.9	2.3	2.45	-2.3
1.4	3.7	0.7	1.8	2.75	-1.8
1.5	3.7	1.3	3.2	3.45	0.5
Fist FDS (M)					

JAMAR day 1	Normalised length in percentage	JAMAR day 1	Normalised length in percentage	normalized mean	normalized diff
0.8	1.7	1	2.2	1.95	-0.5
0.2	0.4	0.1	0.2	0.3	0.2
0.9	1.9	0.4	0.8	1.35	1.1
0.3	0.7	0.5	1.2	0.95	-0.5
0.9	1.9	8	16.7	9.3	-14.8
1.3	2.8	0.3	0.6	1.7	2.2
0.6	1.3	0.4	0.9	1.1	0.4
0.7	1.5	0.9	2	1.75	-0.5
1.6	3.8	1.5	3.6	3.7	0.2
0.8	2.1	0.8	2.1	2.1	0
0.6	1.6	0.6	1.6	1.6	0
1	2.5	0.7	1.7	2.1	0.8

JAMAR 5kgf FDS(M)

90 deg flex day 1	Normalised length in percentage	90 deg flex day 1	Normalised length in percentage	normalized mean	normalized diff
0.7	1.5	0.5	1.1	1.3	0.4
0.6	1.3	0.4	0.8	1.05	0.5
0.7	1.4	0.7	1.4	1.4	0
1	2.4	0.9	2.1	2.25	0.3
0.4	0.8	0.9	1.9	1.35	-1.1
0.4	0.9	0.3	0.6	0.75	0.3
0.7	1.5	0.6	1.3	1.4	0.2
0.4	0.9	0.5	1.1	1	-0.2
0.6	1.4	0.7	1.7	1.55	-0.3
1	2.6	0.7	1.8	2.2	0.8
0.5	1.3	0.5	1.3	1.3	0
0.4	1	0.6	1.5	1.25	-0.5

90 deg flexion FDS(R)

Fist day 1	Normalised length in percentage	Fist day 1	Normalised length in percentage	normalized mean	normalized diff
0.6	1.3	1	2.2	1.75	-0.9
1.1	2.3	1.2	2.5	2.4	-0.2
1.4	2.9	1.5	3.1	3	-0.2
1.6	3.8	1.6	3.8	3.8	0
0.9	1.9	1.6	3.3	2.6	-1.4
1.5	3.2	1.1	2.4	2.8	0.8
1.5	3.2	1.2	2.6	2.9	0.6
1.1	2.4	0.7	1.5	1.95	0.9
1.5	3.6	1.4	3.3	3.45	0.3
2	5.1	1.8	4.6	4.85	0.5
0.5	1.3	1	2.6	1.95	-1.3
1.6	4	1.4	3.5	3.75	0.5
Fist FDS(R)					

JAMAR day 1	Normalised length in percentage	JAMAR day 1	Normalised length in percentage	normalized mean	normalized diff
1	2.2	0.8	1.7	1.95	0.5
0.5	1	0.1	0.2	0.6	0.8
1.4	2.9	1.8	3.7	3.3	-0.8
0.6	1.4	0.5	1.2	1.3	0.2
2	4.2	0.4	0.8	2.5	3.4
0.4	0.9	0.5	1.1	1	-0.2
0.7	1.5	1	2.1	1.8	-0.6
1	2.2	0.6	1.3	1.75	0.9
0.8	1.9	0.9	2.1	2	-0.2
1.4	3.6	1.2	3.1	3.35	0.5
0.6	1.6	0.5	1.3	1.45	0.3
1	2.5	0.9	2.2	2.35	0.3
JAMAR 5 kgf FDS(R)					

90 deg flexion day 1	Normalised length in percentage	90 deg flexion day 1	Normalised length in percentage	normalized mean	normalized diff
1.3	2.8	0.3	0.7	1.75	2.1
0.6	1.3	0.6	1.3	1.3	0
0.9	1.9	0.7	1.4	1.65	0.5
0.7	1.7	0.5	1.2	1.45	0.5
0.3	0.6	0.4	0.8	0.7	-0.2
0.6	1.3	0.6	1.3	1.3	0
0.4	0.9	0.6	1.3	1.1	-0.4
0.5	1.1	0.3	0.7	0.9	0.4
0.6	1.4	0.5	1.2	1.3	0.2
0.8	2.1	0.4	1	1.55	1.1
0.4	1.1	0.6	1.6	1.35	-0.5
0.2	0.5	0.4	1	0.75	-0.5
90 deg flexion FDS(L)					

Fist day 1	Normalised length in percentage	Fist day 1	Normalised length in percentage	normalized mean	normalized diff
1.2	2.6	1	2.2	2.4	0.4
1.3	2.7	1.1	2.3	2.5	0.4
1.4	2.9	1.4	2.9	2.9	0
1.5	3.6	1.5	3.6	3.6	0
0.8	1.7	1	2.1	1.9	-0.4
0.7	1.5	1	2.2	1.85	-0.7
1.6	3.4	1.5	3.2	3.3	0.2
0.7	1.5	0.8	1.8	1.65	-0.3
1.5	3.6	1.5	3.6	3.6	0
1.5	3.8	1.4	3.6	3.7	0.2
0.7	1.8	1.4	3.7	2.75	-1.9
1.5	3.7	1.6	4	3.85	-0.3
Fist FDS(L)					

JAMAR day 1	Normalised length in percentage	JAMAR day 1	Normalised length in percentage	normalized mean	normalized diff
0.4	0.9	0.7	1.5	1.2	-0.6
0.9	1.9	0.4	0.8	1.35	1.1
1.5	3.1	1.4	2.9	3	0.2
0.3	0.7	0.4	0.9	0.8	-0.2
1	2.1	0.7	1.5	1.8	0.6
0.4	0.9	1.1	2.4	1.65	-1.5
1.4	3	1.2	2.6	2.8	0.4
1.6	3.5	0.8	1.8	2.65	1.7
0.5	1.2	0.6	1.4	1.3	-0.2
0.8	2.1	0.8	2.1	2.1	0
0.6	1.6	1	2.6	2.1	-1
0.6	1.5	0.5	1.2	1.35	0.3
JAMAR 5 kgsFDS(L)					

90 deg flex day 1	Normalised length in percentage	90 deg flex day 1	Normalised length in percentage	normalized mean	normalized diff
1	2.2	0.6	1.3	1.75	0.9
0.4	0.8	0.5	1	0.9	-0.2
1.2	2.5	1.5	3.1	2.8	-0.6
0.1	0.2	1.1	2.6	1.4	-2.4
0.5	1	0.7	1.5	1.25	-0.5
0.4	0.9	0.4	0.9	0.9	0
0.1	0.2	0.5	1.1	0.65	-0.9
0.2	0.4	0.5	1.1	0.75	-0.7
0.5	1.2	0.5	1.2	1.2	0
0.5	1.3	0.7	1.8	1.55	-0.5
0.3	0.8	0.5	1.3	1.05	-0.5
0.2	0.5	0.3	0.7	0.6	-0.2
90 deg flexion FCU					

fist day 1	Normalised length in percentage	fist day 1	Normalised length in percentage	normalized mean	normalized diff
0.7	1.5	0.3	0.7	1.1	0.8
0.3	0.6	1.4	2.9	1.75	-2.3
2.3	4.7	1.8	3.7	4.2	1
0.9	2.1	0.8	1.9	2	0.2
2	4.2	1.5	3.1	3.65	1.1
0.8	1.7	1.1	2.4	2.05	-0.7
1.7	3.6	1.2	2.6	3.1	1
0.7	1.5	1.1	2.4	1.95	-0.9
1.5	3.6	1.4	3.3	3.45	0.3
1.3	3.3	1.5	3.8	3.55	-0.5
1	2.6	1	2.6	2.6	0
0.5	1.2	0.6	1.5	1.35	-0.3
Fist FCU					

JAMAR day 1	Normalised length in percentage	JAMAR day 1	Normalised length in percentage	normalized mean	normalized diff
0.5	1.1	0.8	1.7	1.4	-0.6
0.7	1.5	0.4	0.8	1.15	0.7
1.4	2.9	1.5	3.1	3	-0.2
0.5	1.2	0.5	1.2	1.2	0
0.4	0.8	0.9	1.9	1.35	-1.1
1	2.2	1.2	2.6	2.4	-0.4
0.9	1.9	0.8	1.7	1.8	0.2
0.5	1.1	0.7	1.5	1.3	-0.4
1.3	3.1	1.4	3.3	3.2	-0.2
1	2.6	0.8	2.1	2.35	0.5
0.6	1.6	1	2.6	2.1	-1
0.7	1.7	0.5	1.2	1.45	0.5
JAMAR 5kgf FCU					

90 deg flexion day 1	Normalised length in percentage	90 deg flexion day 1	Normalised length in percentage	normalized mean	normalized diff
	0		0	0	0
0.6	1.3	0.4	0.9	1.1	0.4
	0		0	0	0
	0		0	0	0
0.1	0.2	0.1	0.2	0.2	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
90 deg flexion FCR					

fist day 1	Normalised length in percentage	fist day 1	Normalised length in percentage	normalized mean	normalized diff
	0		0	0	0
0.6	1.3	1.1	2.3	1.8	-1
	0		0	0	0
	0		0	0	0
1	2.1	0.7	1.5	1.8	0.6
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
Fist FCR					

JAMAR day 1	Normalised length in percentage	JAMAR day 1	Normalised length in percentage	normalized mean	normalized diff
	0		0	0	0
0.5	1	0.7	1.5	1.25	-0.5
	0		0	0	0
	0		0	0	0
0.6	1.3	1	2.1	1.7	-0.8
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
	0		0	0	0
JAMAR 5kgs FCR					

Appendix 13:

a) Reliability:

90 degree finger flexion

Serial No.		FPL	FDS (I)	FDS (M)	FDS (R)	FDS (L)	FCU	FCR
1	Mean of normalized values[1]	1.1	1.85	1.95	1.3	1.75	1.75	N/A
	Difference of normalized values[2]	0	1.1	-0.5	0.4	2.1	0.9	
2	Mean of normalized values[1]	0.5	1.05	0.7	1.05	1.3	0.9	1.1
	Difference of normalized values[2]	0.2	0.5	0.6	0.5	0	-0.2	0.4
3		0.5	0.7	1.45	1.4	1.65	2.8	N/A

		0.6	0.2	-1.3	0	0.5	-0.6	
4		0.45 -0.5	2 0.2	1.65 -0.5	2.25 0.3	1.45 0.5	1.4 -2.4	N/A
5		0.6 -0.4	1.05 0.5	2.3 0.8	1.35 -1.1	0.7 -0.2	1.25 -0.5	0.2 0
6		0.3 0.2	0.75 0.7	1.2 0.2	0.75 0.3	1.3 0	0.9 0	N/A
7		0.3 -0.2	0.75 0.7	0.3 -0.2	1.4 0.2	1.1 -0.4	0.65 -0.9	N/A
8		0.75 0.7	1 -0.2	1 -0.2	1 -0.2	0.9 0.4	0.75 -0.7	N/A
9		1.1 -0.2	2 -0.2	1.9 0	1.55 -0.3	1.3 0.2	1.2 0	N/A
10		0.9 -0.8	2.45 -0.3	1.4 -0.2	2.2 0.8	1.55 1.1	1.55 -0.5	N/A
11		1.35 -0.5	0.95 0.3	1.85 1.1	1.3 0	1.35 -0.5	1.05 -0.5	N/A
12		0.75 0.5	0.45 -0.5	2 0	1.25 -0.5	0.75 -0.5	0.6 -0.2	N/A
Standard deviation of ND		0.481	0.48	0.644	0.509	0.749	0.766	0.115
Mean of ND		0.033	0.25	-0.017	0.033	0.267	-0.467	0.033

[1] **First Row** [2] **Second Row**

ND: mean of difference of normalized values (unit: percentage); SD: standard deviation of the difference of normalized values, N/A: tendon could not be tracked.

Fist

Serial No.		FPL	FDS (I)	FDS (M)	FDS (R)	FDS (L)	FCU	FCR
1	**Mean of normalized values**[1] **Difference of Normalized values**[2]	1.65 1.1	4 -0.2	3.8 -2.8	1.75 -0.9	2.4 0.4	1.1 0.8	N/A
2		1.05 0.9	1.25 -0.5	1.35 1.3	2.4 -0.2	2.5 0.4	1.75 -2.3	1.8 -1
3		0.9 -0.2	2.35 -2.3	3.1 -0.9	3 -0.2	2.9 0	4.2 1	N/A
4		1.05 -0.3	3.7 0.2	2.6 -1.5	3.8 0	3.6 0	2 0.2	N/A
5		2.2 -0.2	3.1 0	2.9 -1.4	2.6 -1.4	1.9 -0.4	3.65 1.1	1.8 0.6
6		2.05 0.3	2.15 1.7	2.35 2.1	2.8 0.8	1.85 -0.7	2.05 -0.7	N/A
7		1.5 1.2	0.6 0	0.4 1.5	2.9 0.6	3.3 0.2	3.1 1	N/A
8		1.95 1.3	2.75 -0.3	2.2 -0.4	1.95 0.9	1.65 -0.3	1.95 -0.9	N/A
9		2.65 -0.5	2.4 0	4.05 -1.3	3.45 0.3	3.6 0	3.45 0.3	N/A
10		2.2 -0.8	4.85 0.5	2.45 -2.3	4.85 0.5	3.7 0.2	3.55 -0.5	N/A
11		0.95 -0.3	3 1.8	2.75 -1.8	1.95 -1.3	2.75 -1.9	2.6 0	N/A

12		2.35	1.6	3.45	3.75	3.85	1.35	N/A
		0.3	0.2	0.5	0.5	-0.3	-0.3	
	Standard Deviation of ND	0.728	1.046	1.589	0.794	0.63	0.996	0.35
	Mean of ND	0.233	0.092	-0.583	-0.033	-0.2	-0.025	-0.033

[1]**First Row** [2]**Second Row**

ND: mean of difference of normalized values (unit: percentage); SD: standard deviation of the difference of normalized values; N/A: tendon could not be tracked.

JAMAR

Serial No.		**FPL**	**FDS (I)**	**FDS (M)**	**FDS (R)**	**FDS (L)**	**FCU**	**FCR**
1	**Mean of normalized values** [1]	3.9	1.1	1.95	1.95	1.2	1.4	N/A
	Difference of normalized values [2]	0.8	0.4	-0.5	0.5	-0.6	-0.6	
2		1.3	0.7	0.3	0.6	1.35	1.15	1.25
		0	0.2	0.2	0.8	1.1	0.7	-0.5
3		0.7	1	1.35	3.3	3	3	N/A
		-0.2	-0.4	1.1	-0.8	0.2	-0.2	
4		1.2	0.8	0.95	1.3	0.8	1.2	N/A
		0	0.2	-0.5	0.2	-0.2	0	
5		0.8	0.6	9.3	2.5	1.8	1.35	1.7
		0.4	-0.4	-14.8	3.4	0.6	-1.1	-0.8
6		0.85	1.15	1.7	1	1.65	2.4	N/A
		0.9	1.5	2.2	-0.2	-1.5	-0.4	
7		0.85	1.1	1.1	1.8	2.8	1.8	N/A
		-0.9	0.4	0.4	-0.6	0.4	0.2	
8		1.75	1.5	1.75	1.75	2.65	1.3	N/A

		0.9	0	-0.5	0.9	1.7	-0.4	
9		1.9	1.3	3.7	2	1.3	3.2	N/A
		0	-0.2	0.2	-0.2	-0.2	-0.2	
10		1.8	3.05	2.1	3.35	2.1	2.35	N/A
		-0.6	-0.5	0	0.5	0	0.5	
11		2.35	1.7	1.6	1.45	2.1	2.1	N/A
		-0.5	-0.2	0	0.3	-1	-1	
12		2.1	2.6	2.1	2.35	1.35	1.45	N/A
		-0.2	0.2	0.8	0.3	0.3	0.5	
	Standard deviation of ND	0.595	0.541	4.43	1.072	0.873	0.577	0.261
	Mean of ND	0.05	0.1	-0.95	0.425	0.067	-0.167	-0.108

[1]**First Row** [2]**Second Row**

ND: mean of difference of normalized values (unit: percentage); SD: standard deviation of the difference of normalized values; N/A: tendon could not be tracked.

Appendix 14:

Ethics approval letter

Keele University

RESEARCH AND ENTERPRISE SERVICES

22nd May 2014

Rani Sharma
19 Reedmace Walk
Newcastle
ST5 2GE

Dear Rani,

Re: Measurement of flexor tendon excursion during simple hand movement using 2D diagnostic ultrasound

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	Version	Date
Summary of Proposal	V1	08/05/14
Letter of Invitation	V1	08/05/14
Information Sheets	V1	08/05/14
Consent Form	V1	08/05/14
Edinburgh Handedness Inventory	V1	08/05/14
Poster	V1	08/05/14
Data Documentation Sheet	V1	08/05/14

If the fieldwork goes beyond the date stated in your application, you must notify the Ethical Review Panel via the ERP administrator at uso.erps@keele.ac.uk stating ERP2 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 ERP2 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 ERP2 in the subject line of the e-mail.

Yours sincerely

Dr Bernadette Bartlam
Chair – Ethical Review Panel

CC RI Manager
Supervisor

Research and Enterprise Services, Keele University, Staffordshire, ST5 5BG, UK
Telephone: + 44 (0)1782 734466 Fax: + 44 (0)1782 733740

Keele University

RESEARCH AND ENTERPRISE SERVICES

23rd June 2014

Rani Sharma
19 Reedmace Walk
Newcastle
ST5 2GE

Dear Rani,

Re: 'Measurement of flexor tendon excursion during simple hand movement using 2D diagnostic ultrasound'

Thank you for submitting your application to amend study 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	Version	Date
Letter of Invitation	2	11/06/2014
Information Sheet	2	11/06/2014
Data Documentation Sheet	2	11/06/2014
Protocol	2	11/06/2014

If the fieldwork goes beyond the date stated in your application you must notify the Ethical Review Panel via the ERP administrator at uso.erps@keele.ac.uk stating ERP2 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 ERP2 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 ERP2 in the subject line of the e-mail.

Yours sincerely

Dr Bernadette Bartlam
Chair – Ethical Review Panel

CC Supervisor

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