MRI EVALUATION OF FINGER FLEXOR TRAJECTORIES AS THEY ENTER, PASS THROUGH AND EXIT THE CARPAL TUNNEL AS A FUNCTION OF FOREARM ROTATION AND WRIST RADIAL AND ULNAR DEVIATION

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Abstract

Tendon displacement within the carpal tunnel has been suggested as a mechanism for wrist work-related musculoskeletal disorders. Tendon displacement has been examined during wrist flexion/extension, and forearm pronation/supination. The effects of radial/ulnar deviation, and how they interact with forearm rotation remain undocumented. The purpose of this study was to quantify linear and angular displacement of the finger flexor tendons during wrist radial/ulnar deviation in combination with forearm pronation/supination. The right distal forearms and wrists of 4 participants were scanned using magnetic resonance imaging. Analysis of the images enabled the measurement of linear and angular displacement. Tendons were displaced radially during radial deviation and pronation, and ulnarly during ulnar deviation and supination. The tendons were displaced furthest during radial-pronation and ulnar-supination. These findings support the results of previous researchers who found increased discomfort and median nerve contact pressure in these postures. These data further our understanding of potential mechanisms of injury.

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List of Abbreviations

ANOVA	Analysis of Variance
CT	Carpal tunnel
CTP	Carpal tunnel pressure
CTR	Carpal tunnel release
CTS	Carpal tunnel syndrome
FDP2,3,4	Flexor digitorum profundus, where the number represents the digit
FDS2,3,4	Flexor digitorum superficialis, where the number represents the digit
MP	Metacarpophalangeal
MR	Magnetic Resonance
NIOSH	National Institute for Occupational Safety and Health
NM	Neutral-mid-pronation
NP	Neutral-pronation
NS	Neutral-supination
RM	Radial-mid-pronation
RP	Radial-pronation
RS	Radial-supination
RST	Radial styloid
SDS	Standardized discomfort score
UM	Ulnar-mid-pronation
UP	Ulnar-pronation
US	Ulnar-supination
WRMSD	Work-related musculoskeletal disorder

Chapter 1: Introduction

In 2015, more than 50,000 workers across Canada, accounting for 21.6% of reported work-related musculoskeletal disorders (WRMSDs), experienced an upper extremity injury (AWCBC, 2015). According to the Bureau of Labor Statistics, upper extremity injuries result in a loss of productivity as they require a median of 32 days away from work (Bureau Of Labor Statistics, 2015). WRMSD's of the upper limb, otherwise known as repetitive strain injuries, cumulative trauma disorders or overuse injuries, is an umbrella term to cover injuries to tendons nerves or muscles created by common risk factors including awkward postures, force and/or repetition. In the forearm/wrist, specific injuries would include carpal tunnel syndrome, tendinitis or tenosynovitis of the finger flexors or myalgia to name the most common injuries. Among the risk factors linked to these injuries are forearm rotation (pronation/supination) and wrist deviation (radial/ulnar deviation). Epidemiological studies have suggested that forearm rotation (Sjögren and Grevsten, 1996; Hughes et al., 1987) and radial-ulnar deviation (Masear et al., 1986; Silverstein et al., 1987; Marras and Schoenmarklin, 1993) are related to increased incidence rate of upper extremity injuries. Increased discomfort has been suspected to be a precursor to more pain and future injury and has been used to assess the risk of injury in industrial tasks (Corlett & Bishop, 1976). A group of studies has been conducted that demonstrated that forearm rotation (O'Sullivan & Gallway, 2005; Mukhopadhyay et al., 2007) and radial-ulnar deviation (Khan et al., 2009) increases discomfort. Increased carpal tunnel pressure (CTP) is believed to collapse the capillaries surrounding the median nerve, leading to reduced nerve function. A number of studies have shown that CTP is increased with forearm rotation (Rempel et al., 1997, Werner 1997) as well as radial-ulnar deviation (Weiss et al., 1995; Werner et al., 1997; Keir et al., 1997, Rempel et al., 2007). The displacement of the finger flexor tendons may be a mechanism that increases discomfort via increased frictional work on the tendon. The displacement of the tendons may also be a mechanism for increased carpal tunnel pressure. The current body of knowledge would suggest that forearm rotation and radial-ulnar deviation are responsible for an increased risk of upper extremity injuries. However, there is a lack of research that has investigated the combined effects of these postures. Thus, the goal of this study is to quantify the displacement of the finger flexor tendons as a function of forearm and wrist posture. Equipped with this knowledge, we can begin to map out postures that are of less risk.

1.1. Epidemiological evidence of forearm and wrist postures and upper limb injuries

Epidemiological research suggests that adopting certain postures of the upper-limb are linked to upper-extremity injuries. In 1997, Hughes et al. examined 104 workers from an aluminum smelter to determine the relationship between work-related factors and the prevalence of forearm/elbow and hand/wrist disorders. They conducted a multiple logistic regression analysis and discovered that years of forearm twisting was a significant predictor of the development of both elbow/forearm and hand/wrist WRMSDs. Their findings are summarized in Table 1 below. Grevsten & Sjogren (1996) also found that forearm rotation was related to increased rates of injuries. They observed forestry machine operators who used various tools and machinery. The workers had to adopt different postures to effectively handle the different machinery. Workers who spent more time on machines that required more forearm pronation resulted in higher rates of sick leave due to an upper extremity injury than those who used machinery that required less forearm pronation.

Epidemiological evidence also links radial-ulnar deviation of the wrist with higher incidence rates of upper-limb injuries. Masear et al. (1986) examined potential work-related factors to elucidate what was causing such a high-rate of carpal tunnel syndrome (CTS) among the workers of a meatpacking factory. 117 of 788 (14.8%) employees underwent carpal tunnel release surgery (CTR) between 1967 when the factory opened, and 1983. The authors interviewed the 117 workers who underwent CTR. It was determined that workers who worked in ham and picnic boning, and loin boning, had the highest incidence rates of CTR. These tasks require extreme ulnar deviation. This suggests that ulnar deviation is a likely contributor to the development of CTS. In another study, Tanaka et al. (1995) used the data obtained from the 1988 Occupational Health Supplement survey conducted by NIOSH to examine the relationship between certain risk factors and CTS. The list of risk factors included exposure to manual work, occupation/industry, race, and gender. The authors discovered that exposure to manual work, particularly the bending and twisting of the hands and wrists resulted in significantly higher rates of CTS. 70% of the medically-treated CTS patients reported that they were exposed to this type of manual work, suggesting that deviated wrist postures, such as wrist flexion/extension or radial-ulnar deviation of the wrist, and forearm rotation may contribute to the development of CTS.

Silverstein et al. (1987) aimed to establish what occupational factors can be used to determine the risk of being afflicted with CTS. They addressed repetitive motions and force as their primary risk factors, while also examining postures. Though not significant, they found that jobs associated with higher incidence rates of CTS spent more time in ulnar deviation.

Table 1: Summary of epidemiological evidence showing the effects of posture on the incidence rate of injury

		Epidemiology					
		Hughes et al., 1997	Sjögren and Grevsten, 1996	Masear et al., 1986	Tanaka et al., 1995	Marras and Schoenmarklin, 1993	Schoenmarklin et al, 1994
		Odd Ratios			Odd ratios	ANOVA	Odd ratios
Plane of movement	Radial and ulnar deviation			Jobs requiring extremes of ulnar deviation associated with a higher incidence of CTS	Associated with increased incidence of CTS (OR = 5.233)	ROM, average, min, max and maximum difference of velocity and acceleration are significantly different between low and high risk	ROM, average velocity and acceleration, and peak radial/ulnar deviation are significant predictors of injury (OR = 1.52, 2.44, 2.69 and 3.30 respectively).
	Wrist flexion and extension			Jobs requiring extremes of wrist flexion associated with a higher incidence of CTS	Associated with increased incidence of CTS (OR = 5.233)	Average, min, max and maximum difference of velocity and acceleration are significantly different between low and high risk	ROM, average velocity and acceleration, and peak wrist flexion/extension are significant predictors of injury (OR = 1.31, 3.80, 6.06, 5.03 respectively)
	Pronation and supination of the forearm	Years of forearm twisting was a significant predictor of hand/wrist disorders (OR = 9.3), and elbow/forearm disorders (OR = 37)	Pronation was associated with increased sick leave due to an upper extremity injury			Average, min, max and maximum difference of velocity and acceleration are significantly different between low and high risk	Average velocity and acceleration significant predictors (OR = 1.95 and 2.96 respectively)

Expanding on these findings, Marras & Schoenmarklin (1993) aimed to quantify what type and how much wrist motion is present in industrial jobs, and which variables could differentiate between industrial jobs with a low and high risk of WRMSD development. The independent variables observed were the average, minimum, maximum, and the difference between the minimum and maximum values of position, velocity and acceleration across three planes of wrist and forearm motion (radial-ulnar deviation, flexion and extension of the wrist, pronation, and supination of the forearm). Their individual analyses of variance identified that the range of motion (the difference between the maximum and minimum of position) of radial-ulnar deviation was significantly different between low- and high-risk jobs. In addition, velocity and acceleration variables for all wrist and forearm motion were significantly different between jobs of low- and high-risk. This would indicate the tasks that require extreme radial or ulnar deviation would increase the risk of developing an injury. Likewise, jobs that require workers to quickly move between different wrist and forearm postures pose a higher risk of injury development.

A continuation of this study was conducted by Schoenmarklin et al. (1994). They aimed to determine if the same independent variables used by Marras & Schoenmarklin (1993) could be used to predict WRMSD incidence rates. They conducted a multiple logistic regression and demonstrated that while the range of radial-ulnar deviation and pronation/supination could predict the incidence rates of WRMSDs, the velocity and acceleration measurements in these planes were better predictors. This would suggest that jobs that require workers to move quickly between different wrist and forearm postures would be at the highest risk of developing a WRMSD.

The previous studies show that pronation and supination of the forearm are significant predictors of elbow/forearm and hand/wrist injuries, as well as low- and high-risk jobs. Prior studies have also linked forearm rotation to increased rates of upper limb injury, and the amount of forearm rotation has been shown to be significantly different between low-and high-risk jobs. Radial-ulnar deviation of the wrist has also been shown to be significant predictors of CTS and low- and high-risk jobs. The amount of radial-ulnar deviation has also been found to be significantly different between low- and high-risk jobs. This plane of movement has been linked to increased rates of injury, particularly for CTS. The epidemiological evidence provides us with the basis of knowledge that these postures are either linked to elevated rates of injury and demonstrate that spending time in these postures is a predictor of injury. Additional research regarding the underlying causes and mechanisms of injuries due to these postures will provide more information for future injury prevention strategies.

1.2. Biomechanical evidence of wrist and forearm postures affecting injury rates

1.2.1. Forearm and wrist postures affect discomfort

Increased discomfort has been suspected to be a precursor to more pain and injury and has been used to assess the stress involved in industrial tasks (Corlett & Bishop, 1976). Various studies have illustrated that deviated forearm and wrist postures have been linked to increased discomfort.

Standardized discomfort scores (SDS) were obtained after subjects completed isometric torque exertions in both directions at varying forearm rotation angles (O'Sullivan & Gallwey, 2005). It was shown that the further the subjects rotated their forearm from mid-pronation, the more discomfort they experienced (Table 2). Significantly higher standardized discomfort scores were obtained in pronation with respect to supination. A continuation of this study was conducted in 2007 when Mukhopadhyay et al. assessed discomfort scores as a function of elbow angle, normalized forearm rotation torque in both directions, frequency of exertion, and the angle of the forearm. The team of authors discovered that at every angle of the elbow, discomfort increased as the forearm rotated in either direction from mid-pronation. As in the previous study, greater discomfort scores were reported in pronated postures than supinated ones. Khan et al. (2009) added to this body of work by assessing wrist deviation in addition to forearm rotation and how these postures affected discomfort scores. The wrist deviation and forearm rotation angles were significant in predicting discomfort scores. Discomfort scores increased the further the subjects moved away from the neutral position in either direction. High discomfort scores were found at the combination of the extremes of planes of movement – ulnar deviation combined with supination, as well as radial deviation combined with pronation. These studies demonstrate that discomfort changes as a function of wrist deviation and forearm postures.

Table 2: Summary of evidence from discomfort and carpal tunnel pressure studies. Highlighted values indicate the highest value found in their study

		Discomfort (Standardized Discomfort Score)				CTP (mmHg)					
		Khan et al., 2009		Mukhopadhyay et al., 2007	O'Sullivan and Gallwey, 2005	Werner et al., 1997		Rempel et al., 2007	Rempel et al., 1997	Weiss et al., 1995	Keir et al., 1997
Pronation	Radial Deviation	6.6				17.5		3.6			
	Neutral	4.1	6.033	4.167	6.86	14.1	15.066	2.4	21.67		
	Ulnar Deviation	7.4				13.6		2.7			
Mid-pronation	Radial Deviation	2.8				12.5				90	
	Neutral	1.8	2.933	2.408	5.09	10.5	11.66		22.67	10	
	Ulnar Deviation	4.2				12				105	
Supination	Radial Deviation	5.7				15.8					9
	Neutral	3.7	5.7	3.025	5.63	15	16.867		47.66		8
	Ulnar Deviation	7.7				19.8					22

1.2.2. Increased carpal tunnel pressure associated with the development of carpal tunnel syndrome

Increased carpal tunnel pressure (CTP) can result in reduced blood flow to the median nerve, which leads to reduced median nerve function. Lundborg et al. (1982) applied compressions to the palmar side of the wrist which resulted in a complete loss of motor and sensory function of the median nerve. Subjects reported numbness and tingling, symptoms consistent with CTS. Recovery was prompt upon the release of the compression. This may suggest that increased carpal tunnel pressure is a contributor to CTS. Studies have shown that carpal tunnel pressure can be changed as a function of different forearm and wrist postures.

Keir et al. (1997) examined 8 cadaveric hands to assess how wrist flexion and extension, radial-ulnar deviation, and tendon loading affected CTP. They also examined how different hand grip postures affected CTP. CTP measurements were obtained using 2 techniques – a catheter, and a bulb. Each forearm was supinated and fixed horizontally, while the wrist joint was centred at the axes of the testing jig and the elbow flexed at 90º. The finger flexor tendons were attached via a cord to a ball-bearing pulley to apply a force of 9.8 N. Nine angles between 45º of extension to 45º flexion were examined. Six angles in the radial-ulnar plane from 20º of radial deviation to 30º of ulnar deviation were observed. Significant differences in CTP were found between deviated and neutral postures in both the flexion-extension ($F = 6.50$, $p = 0.0008$) and radial-ulnar plane ($F = 9.61$, $p = 0.0001$). These findings are summarized in Table 2. The authors discovered a parabolic pattern for CTP measurements with radial-ulnar deviation angles. CTP increased as subjects deviated further from a neutral wrist. A similar pattern was found for wrist flexion and extension. CTP was greater in ulnar deviation than radial deviation, and the neutral wrist. An interaction effect between finger-loading and radial-ulnar deviation angle was also found (F = 48.45, $p<.0.0001$). The presence of finger-loading further exacerbated CTP. This study presented that CTP increases the more the wrist deviates from neutral.

Werner et al. (1997) documented the changes in CTP in various positions of the wrist (flexion-extension, and radial-ulnar deviation), fingers (4 positions – closed, relaxed, straight, and pinched), and forearm in-vivo. The authors conducted a multiple linear regression analysis to predict CTP based upon these postures. A fluid-filled catheter was inserted into the carpal tunnel to measure CTP. Electrogoniometers were used to measure the change in angles throughout the experimental protocol. Seven healthy volunteers without symptoms of numbness, tingling or pain in the hand or wrist had their CTP continuously measured. The hand and forearm postures were fixed at the beginning of the trial, while subjects completed active wrist extension/flexion and radial/ulnar deviation. Their results showed increases in CTP when subjects rotated their forearms away from mid-pronation. When examining the radial-ulnar deviation angle alone, the neutral posture elicited the lowest CTP. Small increases in CTP were seen when deviating in either direction.

Rempel et al. (1997) conducted a similar study where they examined the effects of pronation and supination of the forearm and the angle of the metacarpophalangeal (MP) joint on CTP. Seventeen healthy subjects were recruited for this study. The subjects' arms were to their side with the elbow held at a 90º angle. Starting with a neutral wrist, subjects slowly flexed their fingers to achieve 0º, 45º or 90º of the MP joint. Once the desired MP angle was achieved, subjects rotated their forearm to full supination, then to full pronation before returning to a mid-pronated forearm. A saline-filled catheter inserted at the carpal tunnel was used to measure CTP. Across all MP joint angles, the lowest CTP was found at 45º of forearm pronation. Their results indicated that CTP increased as the subject rotated their forearm away from 45º of pronation in either direction, with full supination having significantly higher CTP than full-pronation across all MP angles. A Tukey post-hoc test revealed that the interaction effect of pronation/supination and MP joint angle was significant ($F = 4.0$, $p = 0.0003$). The increase in CTP as the forearm is rotated away from 45º of pronation suggests that extremes of forearm rotation place people at a higher risk of developing CTS.

Weiss et al. (1995) studied which radial-ulnar and flexion-extension angles would elicit the lowest CTP. They compared the average CTP of 4 CTS patients against 20 controls. A saline-filled catheter was inserted into the carpal tunnel and was attached to an in-line pressure transducer to continuously monitor CTP. The subjects were seated and had their arms at their side, and their elbow flexed to 90º. Subjects slowly moved their wrists through the full range of motion of radial-ulnar deviation and flexion-extension. Motions were repeated until the position resulting in the lowest CTP was identified. Average values of pressure for all positions of the wrist were reported. The lowest CTP (8 ± 4 mm Hg) amongst the controls was found in 2 ± 9º of wrist extension and 2 ± 6º of ulnar deviation. A parabolic pattern between CTP and wrist angle was observed; CTP increased as the angle of deviation from a neutral wrist in either plane increased. A similar posture (2 ± 9º of flexion and 1 ± 9º of ulnar deviation) was associated with the lowest pressure in the CTS patients. However, the lowest CTP of CTS patients was more than twice that of the controls. This study provides more evidence that radial-ulnar deviating the wrist increases CTP, which can increase the risk of developing CTS.

Keyboarding often requires very awkward postures. Traditional keyboard layouts require users to pronate their forearms and to extend and ulnar deviate their wrists in order to type. Rempel et al. (2008) examined the wrist postures during typing tasks and how they affect CTP. The authors aimed to study how radial-ulnar deviation and wrist flexion and extension affected carpal tunnel pressure. 20 experienced touch typists volunteered for the study with no evidence of CTS based on history, physical examination, and nerve conduction tests. The keyboards were adjusted so that one plane of movement was held constant while the other was varied. The wrist flexion and extension angles observed were 15º, 0º, -15º, -30º and -45º, where the negative values represent wrist extension. 0º and 15º each of radial and ulnar deviation were observed. Both planes of movement resulted in significantly different carpal tunnel pressures. 15º of radial deviation resulted in greater CTP than a neutral wrist and 15º of ulnar deviation. This keyboarding task further demonstrates that deviated wrist postures increase CTP and CTS risk.

These studies, with the exception of Rempel et al. (1997), consistently showed that CTP increased as subjects moved away from the neutral wrist, and the mid-pronated forearm. It would suggest that adopting postures away from this position would increase the risk of injury development.

While discomfort studies consistently show that pronation is more likely to cause injury than supination (O'Sullivan & Gallwey, 2005; Mukhopadhyay et al., 2007; Khan et al., 2009), the findings from the carpal tunnel pressure studies would suggest that supination is more harmful (Werner et al., 1997; Rempel et al., 1997). Likewise, the two areas of research do not agree upon whether radial or ulnar deviation is more injurious. Few studies have examined the combination of pronation and supination of the forearm with radial and ulnar deviation. Two studies that examined both planes of movement agree that the most injurious postures occur at the extremes of the combination of both postures. Khan et al. (2009) and Werner et al., (1997) found that at the extremes of radial deviation with pronation, and ulnar deviation with supination are the postures that pose the highest risk of injury development. Additional work must be completed to definitively identify the worst postures. Also, the interaction of forearm rotation with radial-ulnar deviation is understudied and further research is required.

1.2.3. Forearm and wrist postures affect contact stress

Another proposed mechanism of CTS development is increased contact stress of the finger flexor tendons against other tissues in the carpal tunnel, or direct compression of the median nerve. Ochoa et al. (1972) demonstrated in baboons that direct mechanical compression applied to the popliteal nerves caused a complete block of nerve conduction at the site of compression, while distal excitability persisted. Observing the nerves under an electron micrograph, it was apparent that there was demyelination of the nerves at the site of compression. Similar physiological changes at the median nerve would suggest decreased median nerve function and the presence of CTS symptoms. Furthermore, when pressure was applied to the tibial nerve of rabbits, the nerve became ischemic. After four hours of pressure-induced ischemia, edema develops in the epineurium. The lack of lymph vessels in this space causes the fluid to be resorbed into the endoneurial space. Edema in this space reduces blood flow to the nerve, which in turn leads to reduced nerve function (Lundborg, 1975). These studies show that mechanical pressure applied to peripheral nerves reduces their function. Mechanical pressure applied to the median nerve should show similar reductions in function and may elicit symptoms of CTS.

Models presented by Armstrong & Chaffin (1979) have likened the tendon sliding over the surface of either the flexor retinaculum or the carpal bone as a belt wrapped around a pulley. The contact force between the tendon and an articulating surface is related to the tendon force and inversely related to the radius of curvature. Magnetic resonance imaging (MRI) has been used in a previous study to observe changes in the radius of curvature as a function of wrist angle

(Keir & Wells, 1999). They observed that the radius of curvature decreased with wrist flexion, resulting in increased contact stress. This would suggest that the wrist posture affects the magnitude of contact stress.

Tendon displacement coupled with tendon loading at non-neutral postures is a contact stress related mechanism that can affect the development of injury. Force needs to be applied to accelerate the wrist and forearm from posture to posture. This force is transmitted through the tendons, which pass through the wrist (Schoenmarklin et al., 1994). As tendons are displaced, some of the tendon force is lost through friction as they rub against other structures in the wrist such as the carpal bones, or the flexor retinaculum. Moore et al. (1991) demonstrated that frictional work is the best predictor of injury. Furthermore, as tendons are displaced, they may come into direct contact with the median nerve, increasing the direct compression of it. Both increased frictional work and compression of the median nerve would likely increase the rate of injury. Previous studies have shown that finger flexor tendons are displaced as a function of forearm and wrist postures (Keir & Wells, 1999; Salas, 2016). Keir & Wells (1999) were able to show that the tendons were displaced in the palmar direction in flexion relative to the neutral wrist. They also described that the tendons were displaced dorsally in wrist extension. Salas (2016) had similar findings regarding wrist flexion and extension. It was suggested that the volar displacement may cause increased contact stress with the median nerve. Salas (2016) also observed the finger flexor displacement during forearm rotation in combination with wrist flexion and extension. The results show that the tendons were displaced ulnarly in supination, and radially in pronation with respect to the mid-pronated forearm.

1.3. Medical Imaging and Anatomical Reference Frames

In order to quantify wrist kinematics, such as the trajectory of the finger flexor tendons, anatomical reference frames are required. Various forms of medical imaging, such as MRI (Keir & Wells, 1999; Salas, 2016) and computed tomography (Miranda et al., 2010; Halilaj et al., 2013) have been used to segment bones and tendons to understand their relative motion with respect to anatomical reference frames created from anatomical landmarks. To create the reference frames, 3-dimensional models must be created by segmenting continuous images of the bones of interest. Then bony landmarks can be identified from these models to create the orthogonal axes for the reference frames. Dang et al., (2016) examined the inter- and intra-rater reliability of manually identifying landmarks on 3D models of carpal bones generated from MRI scans to measure joint angles. The average displacement between raters was 2.97 ± 1.49mm, while the difference in joint angle ranged from 3.46º to 3.88º. Halilaj et al. (2013), used 3D models generated from computed tomography and a mathematical algorithm to automatically identify landmarks and had similar magnitudes of error. Their mean difference in location was 0.9 ± 0.4mm and their difference in orientation ranged from 2.8º to 3.5º.

1.4. Purpose

Epidemiological evidence provides a foundation of knowledge that links deviated wrist and forearm rotation postures as likely causes of upper limb injuries. Previous studies regarding discomfort, carpal tunnel pressure, and contact stress have explained some plausible mechanisms for injury development. They have all showed that these postures may increase the likelihood of developing an upper limb injury. Currently. There is a lack of evidence about the effects of pronation and supination of the forearm and radial and ulnar deviation on injury rates, and even less so about the interaction effect of these movements. The literature that is available is unable to conclude which of these postures is most injurious. The studies that have examined tendon trajectories have mainly looked flexion and extension of the wrist and pronation and supination of the forearm, while radial and ulnar deviation remains understudied.

The purpose of this study is to assess the trajectory of the finger flexor tendons as a function of radial-ulnar deviation postures (20º ulnar deviation, neutral wrist, 10º radial deviation), and forearm rotation postures (40º pronation, mid-pronation, 40º supination). The interaction effect of these movements is also observed. This was accomplished by obtaining magnetic resonance (MR) images of the wrist and distal forearm to assess the locations of the tendons. The objective of this research is to quantify the linear and angular displacements of the finger flexor tendons with respect to a radial coordinate system as the tendons enter and exit the carpal tunnel.

1.5. Hypothesis

Previous research found that the tendons were primarily displaced in the sagittal plane during wrist flexion and extension, and in the frontal plane during forearm pronation and supination. There was also a lack of interaction effects (Salas et al., 2016). Based on these findings, we expect that a majority of the tendon movement will occur in the frontal plane. Therefore, we hypothesize that there will be a main effect of wrist and forearm posture on the following measurements: (1) linear displacement of the tendons in the frontal plane at the level of the radial styloid (RST), (2) linear displacement of the tendons in the frontal plane 15mm proximal to the RST, (3) angular displacement of the tendons in the frontal plane proximal to the carpal tunnel, (4) angular displacement of the tendons in the frontal plane distal to the carpal tunnel. We also hypothesize that there will not be a significant main effect of wrist and forearm posture on the following measurements: (5) linear displacement in the sagittal plane at the level of the a RST, (6) linear displacement in the sagittal plane 15mm proximal to the RST, (7) angular displacement of the tendon in the sagittal plane proximal to the carpal tunnel, and (8) angular displacement of the tendon in the sagittal plane distal to the carpal tunnel. Finally, we hypothesize (9) that there will be an interaction effect between the wrist and forearm postures on the linear and angular displacements of the finger flexor tendons in the frontal plane.

Chapter 2: Methods

2.1. Participants

Four healthy participants (2 male, 2 female) with no history or current upper limb injury were recruited for this study by word of mouth. The participants' demographic data are presented in Table 3. Participants gave informed consent in accordance with the Human Participants Review Committee at York University prior to the study. The participants completed a questionnaire regarding demographic information and musculoskeletal health. Participants were screened for current upper limb injury, current pain or discomfort, implanted metal, and implanted medical devices. This study was reviewed and approved by the Human Participants Review Committee at York University.

Table 3: Participants' demographic data

	Average (SD)
Age	23.25 (2.2)
Height (m)	1.62 (0.05)
Weight (kg)	56.75 (6.20)
BMI (kg/m^2)	21.60 (1.85)

2.2. MRI acquisition parameters

High-resolution 3D VIBE images of the wrist were acquired using a 3T Siemens TIM Trio MRI scanner. The MRI parameters include the following: TR = 12.8 ms, TE = 5.29 ms, FOV = 100 mm, voxel size = 0.3x0.3x0.8, and flip angle = 10.

2.3. Participant set-up

Prior to scanning, each participant had their wrist posture randomly selected using a custom MATLAB (The MathWorks Inc., Natick Massachusetts, United States) script. Then, the forearm postures were chosen in random order within each wrist posture. Participants were scanned in nine postures, requiring re-bracing after each scan. Prior to scanning, their wrist was braced into the desired posture using a custom MRI-safe wrist brace. The participant then laid on the bed of the scanner on their right side, placing their elbow into a V-shaped mold to secure it in place, before rotating their forearm into the desired posture. Once both desired wrist and forearm postures have been achieved, the participant was sent into the bore of the scanner. The participants were asked to push against a hand-grip dynamometer whilst scanning.

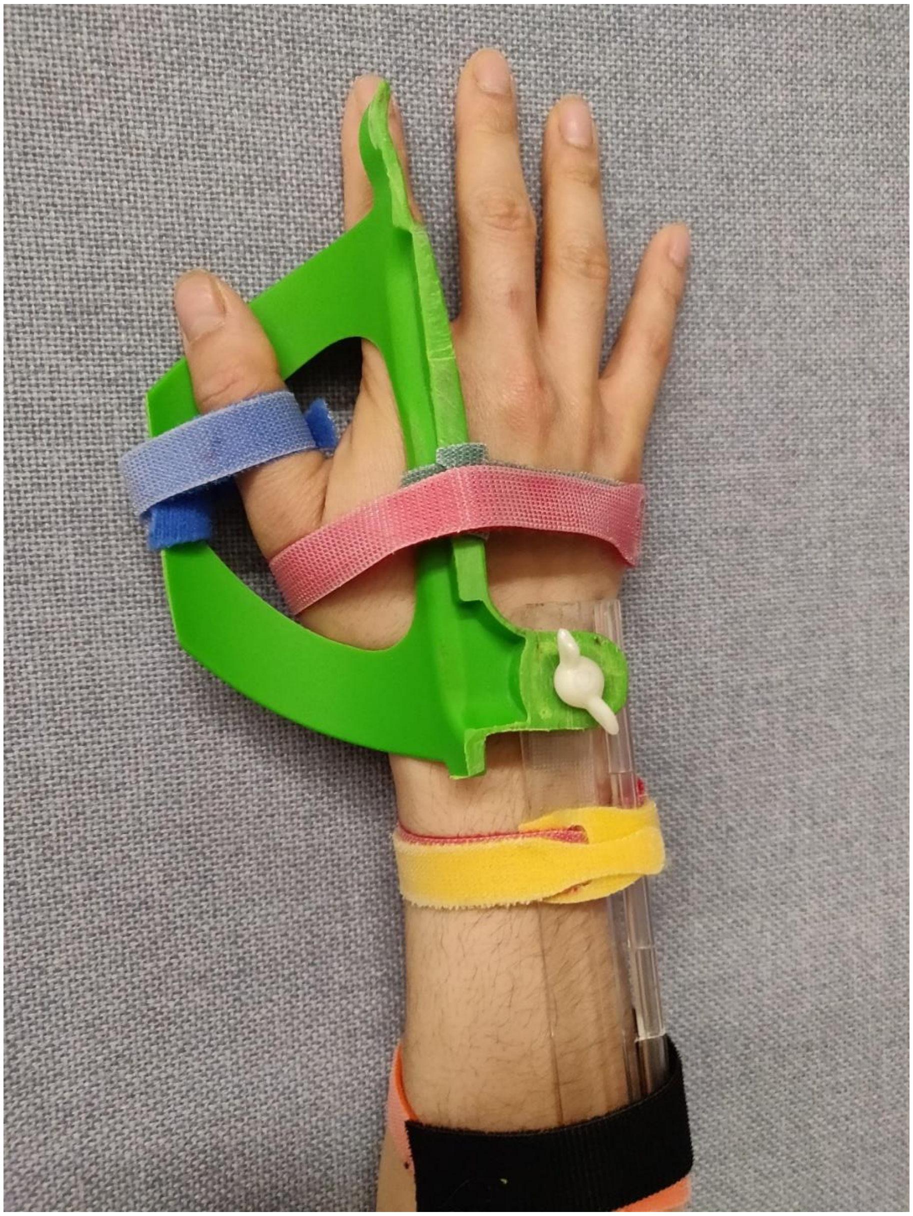

Figure 1: Participant’s wrist braced in a neutral wrist using a custom wrist brace.

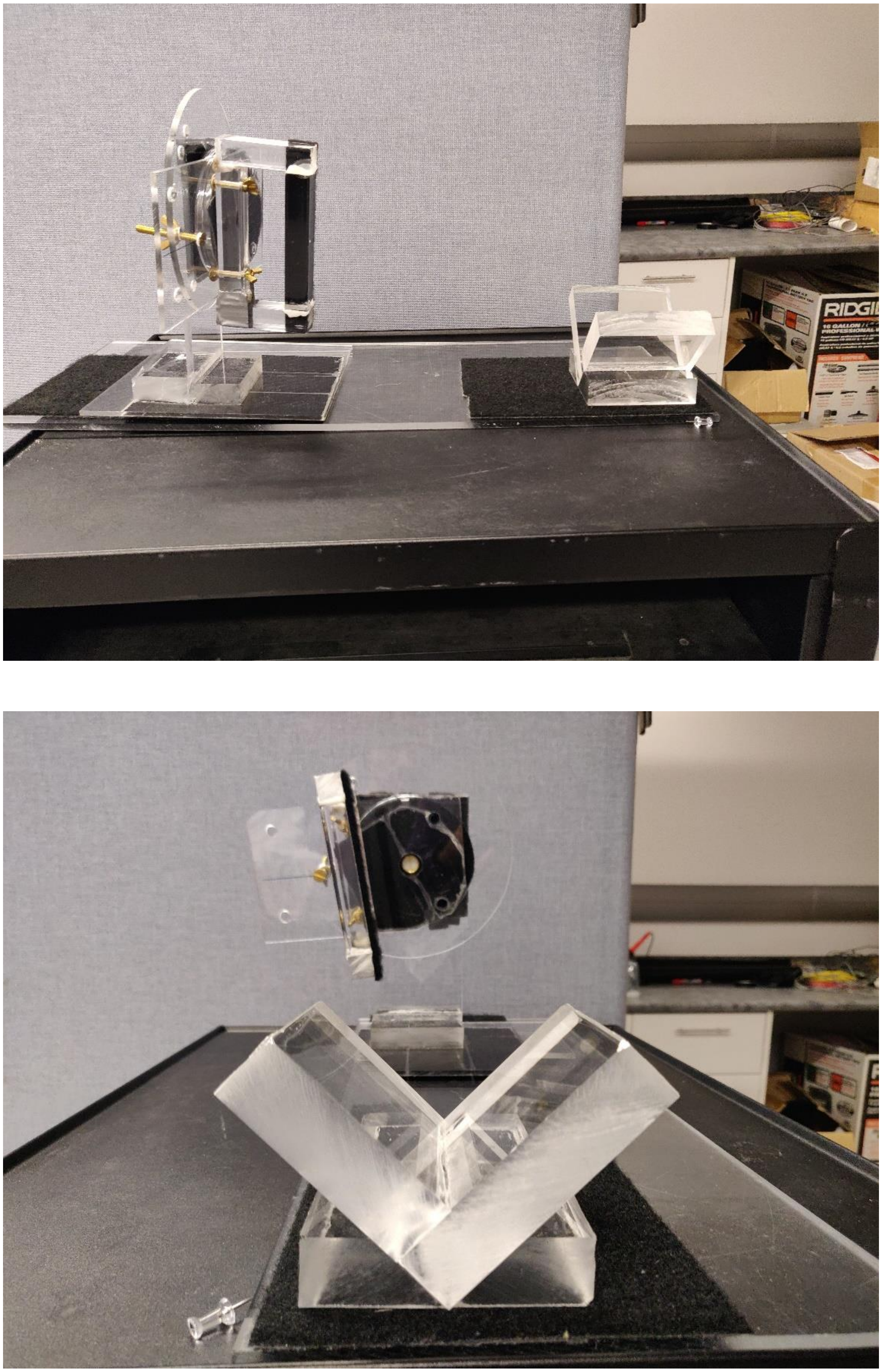

Figure 2: Side (above) and front (below) view of the forearm brace. The plastic v-mould is designed to secure the participant's elbow in place during scanning.

2.3. MRI analysis

2.3.1. Segmentation

The MRI images were imported into Mimics (Materialise, Leuven, Belgium), a medical imaging processing software. There, various anatomical structures were segmented (Table 3). Segmentation involves outlining the contours of the anatomical structures of interest in the software, which allowed for the creation of 3D models of these structures. These 3D models are required for 3D quantitative analysis.

Table 4: List of segmented structures and the anatomical landmarks of interest

Segmented Structure	Anatomical landmarks of Interest
Radius	Dorsal edge of ulnar notch Palmar edge of ulnar notch Radial styloid (RST) (digitized)
Ulna	Ulnar styloid Radio-distal prominence across from styloid (digitized)
3rd Metacarpal	Metacarpal styloid Dorsal-ulnar corner of the head Proximal and distal centroids (digitized)
Forearm	Proximal and distal centroids (digitized)
Flexor Digitorum Superficialis (FDS) (2nd – 4th digits) Flexor Digitorum Profundus (FDP) (2nd – 4th)	Centrelines (calculated)

The structures were segmented using various functions within Mimics. The first step was to use the threshold function, which highlighted pixels that fell within the desired range of intensity. This created the initial mask. Then, the masks underwent additional editing using the mask erosion, smart expand, fill holes, and smooth mask functions.

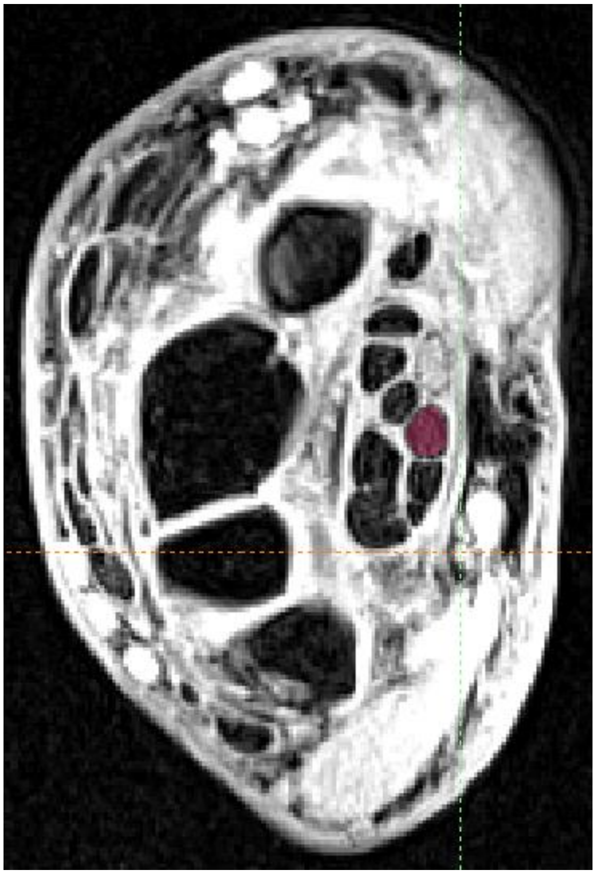

Figure 3: Axial view of segmentation of FDS3 tendon (purple) in Mimics.

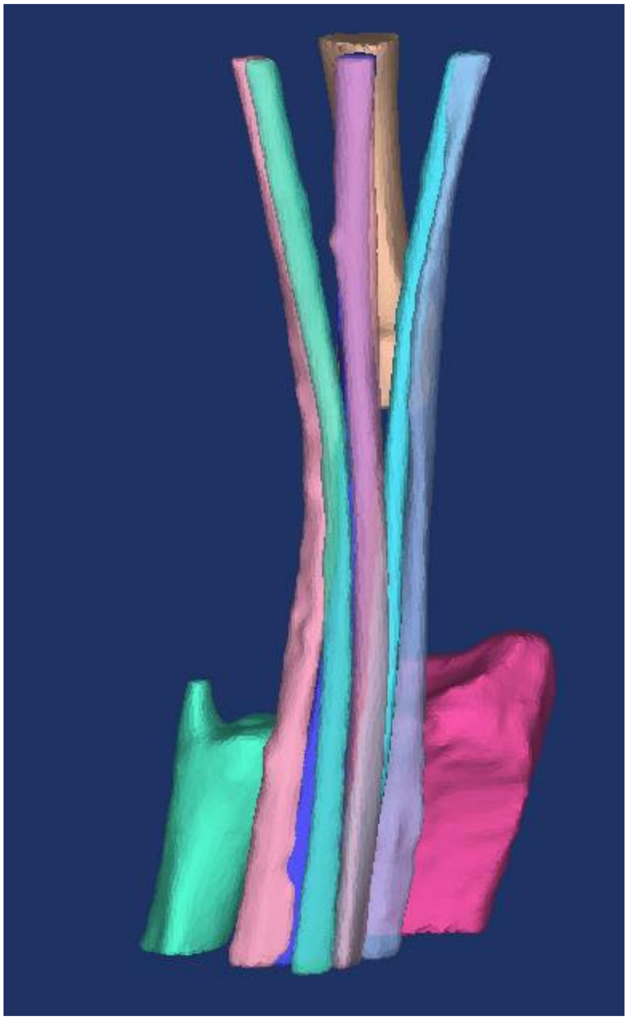

Figure 4: Palmar view of 3D models created from the segmented MR images. Seen above are the tendons of the 2nd, 3rd, and 4th digits, and the radius, ulna and third metacarpal.

2.3.2. Digitization and Registration

After segmentation, the segmented 3D models of the bones were imported into 3matics (Materialise, Leuven, Belgium), another medical imaging processing software. The anatomical landmarks of interest were identified and digitized in the neutral-mid (NM) posture. These landmarks were registered (superimposed) onto the same bones in the other eight postures. Registration maintains the spatial relationship between landmarks on the same bone for each participant to more accurately calculate the local or anatomical coordinate systems.

The registration process involved two steps. The first step was n-point alignment, which translated and rotated the bones of the NM posture onto one of the other postures. This type of registration was used for gross alignment of the structures. The second step, global alignment, was used for finer adjustment of the bones. This process was performed iteratively until the location and orientation error were minimalized. The digitized landmarks on NM and the registered landmarks on the other eight postures of each subject were exported as text files to be used in the calculation of the anatomical coordinate systems.

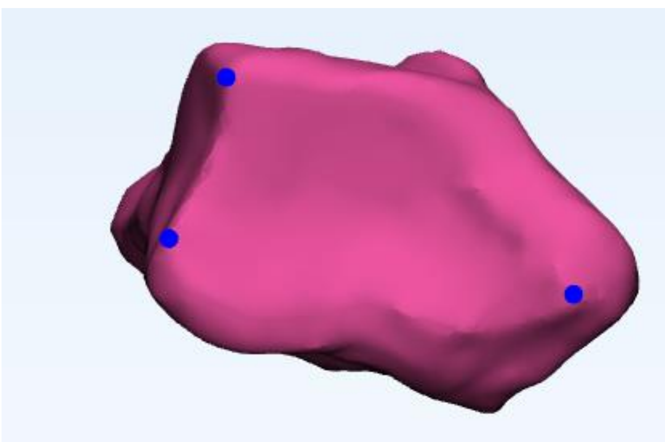

Figure 5: Digitization of the radial styloid, and the palmar and dorsal corners of the ulnar notch on the radius in 3matic.

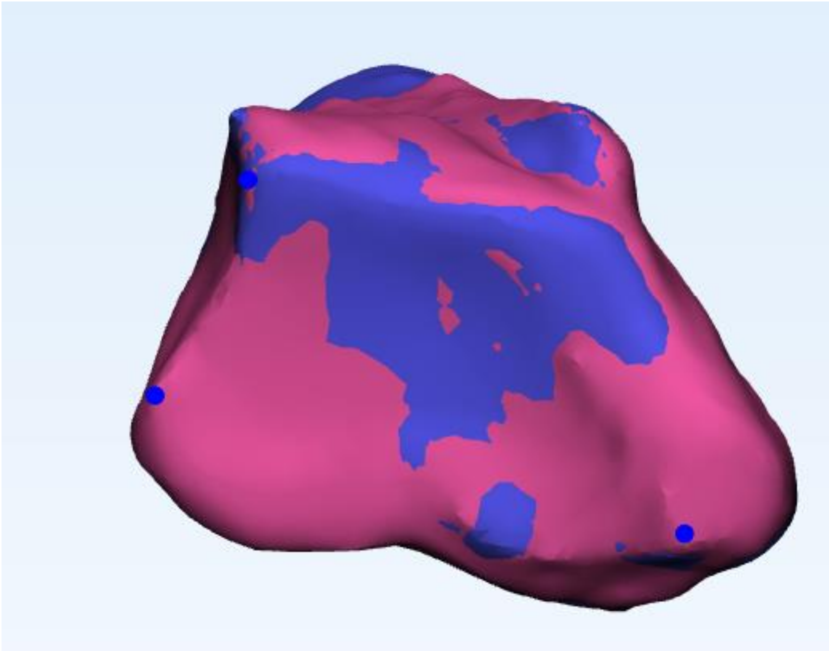

Figure 6: Result of registration of the RP radius onto the NM radius.

2.3.3. Fitting centrelines

The FDP and FDS tendons, as well as the 3rd metacarpal, were fit with centrelines using a Mimics function. The centreline followed the geometric centre along the longitudinal axis of the segmented structure. The XYZ coordinates of the metacarpal and tendon centrelines were exported as text files to be used in the calculation of local coordinate systems, and calculation of linear and angular displacement respectively.

2.4. Creating local coordinate using anatomical landmarks

In order to calculate the displacement of tendons, local coordinate systems first needed to be created. Coordinate systems of the radius, ulna, and third metacarpal were created. The previously exported anatomical landmarks were imported in a custom MATLAB script in order to calculate the local coordinate systems. These coordinates are expressed in the global coordinate system. This method of creating local coordinate systems was used in a previous study (Salas, 2016).

The radial coordinate system was created by first determining the interim mediolateral axis. The z'_r axis was calculated by subtracting the coordinates of the midway point between the dorsal and palmar edge of the ulnar notch, from the coordinates of the RST. The longitudinal axis, y_r, was calculated by subtracting the coordinates of the distal forearm centroid from the coordinates of the proximal forearm centroid and then normalized, y_{rNorm}. The anteroposterior axis, x_r, was created by calculating the cross product of the mediolateral and normalized longitudinal axis, and then normalized, x_{rNorm}. As the z'_r axis and y_{rNorm} axes are not necessarily orthogonal to each other, the normalized x- and y-axes were crossed to obtain an orthogonal z-axis. The final orthogonal coordinate system had an x-axis pointed dorsally, a y-axis pointing proximally, and the z-axis pointed ulnarly. A 3x3 rotation matrix to rotate the global CS to the radial CS, with the origin located at the RST, was then calculated.

The ulnar CS was created using a similar approach. The ulna shared a common long axis with the radius, y_{rNorm}. The interim mediolateral axis, x'_u, was created by subtracting the coordinates of the ulnar styloid from the coordinates of the radial-distal prominence and then normalized, x'_{uNorm}. The anteroposterior axis, z_u, was calculated as the cross product of x'_{uNorm}, and y_{rNorm}, and then normalized. In order to create an orthogonal coordinate system, the cross product of the normalized z- and y-axes was calculated. The final ulnar CS had the x_{uNorm} pointed radially, y_{rNorm} pointing proximally, and z_{uNorm} pointed dorsally. This CS was expressed as a 3x3 rotation matrix.

The final local coordinate system created was the metacarpal, created in a similar fashion as the previous two. The interim mediolateral axis z'_m was created by subtracting the coordinates of the dorsal-ulnar corner of the metacarpal head from the coordinates of the metacarpal styloid, and then normalized, z'_{mNorm}. The longitudinal axis, y_m, was created by subtracting the coordinates of the distal metacarpal centroid from the coordinates of the proximal metacarpal styloid, and then normalized, y_{mNorm}. The anteroposterior axis, x_m was determined by calculating the cross product of the normalized z' and y-axes. This axis was then normalized, x_{mNorm}. The final orthogonal axis was calculated by taking the cross product of the normalized x- and y-axes. This metacarpal CS was expressed as a 3x3 rotation matrix.

2.5. Posture Calculations

The posture of the wrist was calculated as the orientation of the third metacarpal with respect to the radial CS. A rotation matrix was calculated to rotate and align the metacarpal to the radial CS, and Euler angles were calculated using an XYZ sequence, according to Winter (2005). Wrist radial-ulnar deviation angle was defined as theta1 and wrist flexion/extension angle as theta3.

The forearm rotation angle was calculated as the orientation of the ulnar CS with respect to the radial CS. This was accomplished by calculating the product of their respective matrices. Euler angles were obtained using the XYZ sequence. The rotation of the ulna with respect to the radius was defined as theta2. The x and z-axes of the ulnar CS were not aligned with the radial CS, so forearm rotation angles were normalized to the NM trial of each participant.

2.6. Tendon displacement calculations

The exported tendon centrelines coordinates were with respect to the MRI scanner, which is the global coordinate system. The origin of the scanner can change position from scan to scan, which can introduce some error when calculating displacement. Thus, to ensure more accurate calculations, the coordinates of the tendon must be expressed in a local coordinate system. Each tendon centreline was translated and rotated into their respective radial coordinate system. This was completed by a custom MATLAB script which subtracted the coordinates of the RST in the global coordinate system from the coordinates of the tendon centreline and then multiplied the translated centrelines by the radial rotation matrix.

In order to calculate the linear and angular displacements of the tendons, each transformed tendon had to be defined as a line. Using a custom MATLAB script (Salas, 2016), a 3D line of best fit was calculated to pass from the tendon location at the RST to 15 mm proximal this location along the longitudinal axis at the proximal end. Similarly, at the distal end, a line of best fit was calculated to pass from the tendon location at the level of the metacarpal styloid, and 15 mm distal to the metacarpal styloid.

Changes at the level of the RST (y=0), as well as 15 mm proximal to this point (y=15) were used to estimate the linear displacement of the tendons proximal to the carpal tunnel as a function of wrist and forearm posture. Frontal linear displacement was determined by changes in the tendon's z-coordinate of the tendon, whereas changes in the x-coordinate represented displacement in the sagittal plane.

A similar process was used to estimate the displacement of the tendons at the distal end. Changes in the tendons position at the level of the metacarpal styloid and 15mm distal to this point were used to determine the linear displacement of the tendon. Changes in the z-coordinate of the tendon represented displacement in the frontal plane, whereas changes in the y-coordinate represented displacement in the sagittal plane.

The proximal angles of each tendon were measured with respect to the longitudinal y-axis in both the frontal and sagittal planes (Eq. 1 and 2). The distal angular displacements were measured in a similar fashion. The distal angles were measured with respect to the long axis of the 3rd metacarpal.

$$\theta_{yz} = Tan^{-1}\left(\frac{prx_z - prx_z}{prx_y - prx_y}\right) - Tan^{-1}\left(\frac{prx_z - prx_z}{15}\right) \quad (Eq.1)$$

$$\theta_{yx} = Tan^{-1}\left(\frac{prx_x - prx_x}{prx_y - prx_y}\right) - Tan^{-1}\left(\frac{prx_x - prx_x}{15}\right) \quad (Eq.2)$$

Where:

Θ_{yz} is the angle between the centreline and the long axis of the forearm in the frontal plane

Θ_{yx} is the angle between the centreline and the long axis of the forearm in the sagittal plane

Prx_z and dit_z are the z-coordinate of the proximal and distal points of the tendon centreline

Prx_x and dit_x are the x-coordinate of the proximal and distal points of the tendon centreline

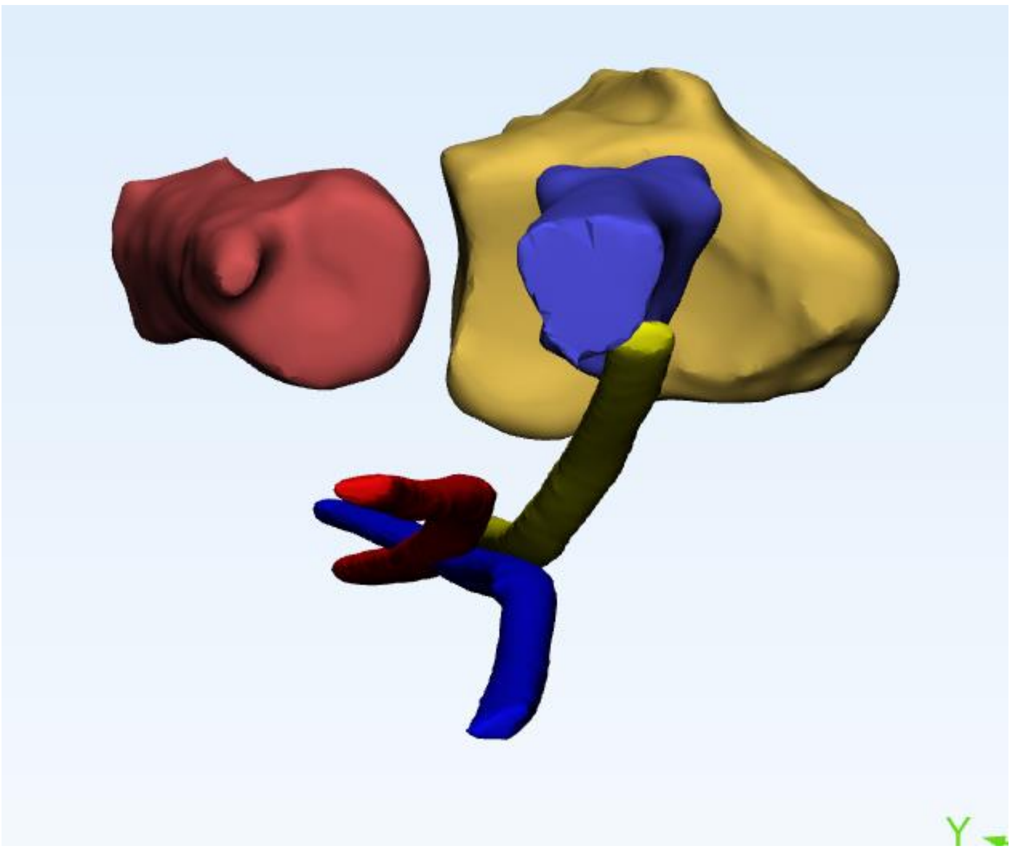

Figure 7: View from the distal end of the FDS4 tendon in three different postures: NM (red), US (blue), and RP (yellow)

2.7. Statistical Analysis

Separate two way repeated measures ANOVAs for each tendon were used to analyze the effect of wrist and forearm posture on the following variables: (1) linear displacement in the frontal plane at the level of the a RST, (2) linear displacement in the frontal plane 15mm proximal to the RST, (3) angular displacement of the tendon in the frontal plane proximal to the carpal tunnel, (4) angular displacement of the tendon in the frontal plane distal to the carpal tunnel, (5) linear displacement in the sagittal plane at the level of the a RST, (6) linear displacement in the sagittal plane 15mm proximal to the RST, (7) angular displacement of the tendon in the sagittal plane proximal to the carpal tunnel, and (8) angular displacement of the tendon in the sagittal plane distal to the carpal tunnel. Significant differences were further evaluated with Bonferroni-correct multiple corrections.

Chapter 3: Results

3.1. Proximal results

3.1.1. Frontal plane variables

3.1.1.1 Linear displacement of tendon at the radial styloid

Separate two-way ANOVA analyses were conducted on each tendon and revealed that there was a significant main effect of wrist posture on the tendon displacement at the level of the RS for FDP2 ($F(2, 6) = 8.082$, $p = 0.02$), FDS2 ($F(2, 6) = 27.934$, $p = 0.001$), and FDS3 ($F(2, 6) = 43.287$, $p = 0.001$). The mean displacement of the tendons in each posture can be found in Table 6. Post-hoc analysis for FDP2 using the Bonferroni correction suggest that ulnar deviation ($M = -2.313$, $SE = 0.683$) resulted in the tendon being displaced further in the ulnar direction than the neutral wrist ($M = -0.288$, $SE = 0.332$). Post-hoc analysis using the Bonferroni correction conducted on FDS2 and FDS3 showed similar patterns that suggest that ulnar deviation ($M = -4.444$, $SE = 0.934$ and $M = -3.877$, $SE = 1.015$, respectively) resulted in tendons being displaced significantly more in the ulnar direction than both radial deviation ($M = 0.197$, $SE = 0.318$ and $M = 0.861$, $SE = 0.457$, respectively) and the neutral wrist ($M = -0.246$, $SE = 0.461$ and $M = 0.861$, $SE = 0.457$, respectively).

The ANOVA analyses also revealed that there was a significant main effect of forearm posture on the linear displacement of the tendon of the RST in the frontal plane for FDS2 ($F(2, 6) = 21.182$, $p = 0.002$), FDS3 ($F(2, 6) = 17.934$, $p = 0.003$) and FDS4 ($F(2, 6) = 25.848$, $p = 0.001$). The post-hoc analyses using the Bonferroni correction indicated that across the three tendons, the tendons were displaced significantly more in the ulnar direction than radial deviation, and the neutral wrist (Table 5).

Table 5: Mean linear displacement (mm) of tendons in the frontal plane at the level of the radial styloid as a function of wrist and forearm posture

	Mean linear displacement of the tendon in the frontal plane at the level of RST (-ve is ulnar)					
	Wrist posture			Forearm posture		
Tendon	Radial Deviation	Neutral	Ulnar Deviation	Pronation	Mid	Supination
FDP2	0.13[a,b]	-0.29[a]	-2.31[b]	-0.40	-0.99	-1.08
FDP3	0.82[a,b]	-0.36[a]	-1.84[b]	-0.08	-0.14	-1.15
FDP4	0.71	-0.25	-1.40	0.02	-0.11	-0.85
FDS2	0.20[a]	-0.25[a]	-4.44[b]	0.57[a]	-0.68[a]	-3.24[b]
FDS3	0.86[a]	-0.24[a]	-3.88[b]	0.10[a]	-0.47[a]	-2.87[b]
FDS4	0.80	-0.29	-3.12	0.16[a]	-0.29[a]	-2.48[b]

Table 6: Mean linear displacement (mm) of tendons in the frontal plane at the level of the radial styloid in each combination of wrist and forearm posture

Frontal linear displacement at the level of the RST (-ve is ulnar)	
Posture	Average
RP	1.29
RM	0.91
RS	-0.44
NP	0.42
NM	0.00
NS	-1.25
UP	-2.09
UM	-2.25
US	-4.15

3.1.1.2. Linear displacement of the tendon proximal to the radial styloid

The results of the ANOVA tests indicated that there was a significant main effect of wrist posture on the linear displacement of the tendon proximal to the RST for FDS2 ($F(2, 6) = 31.798$, $p = 0.001$) and FDS3 ($F(2, 6) = 34.062$, $p = 0.001$). A significant interaction effect was found for FDP2. The mean displacement of the tendons can be found in Table 8. Post-hoc analysis using the Bonferroni correction revealed that for FDS2 and FDS3, the tendons were displaced significantly more in the ulnar direction relative to radial deviation and the neutral wrist (Table 7). The simple main effects for FDP2 revealed that across all forearm postures, ulnar deviation resulted in the tendon being displaced more in the ulnar direction than the neutral wrist. Within mid-pronation, the tendons were significantly deviated in the ulnar direction in ulnar deviation relative to radial deviation. There was no difference between ulnar deviation and radial deviation in the pronated or supinated forearm (Table 7).

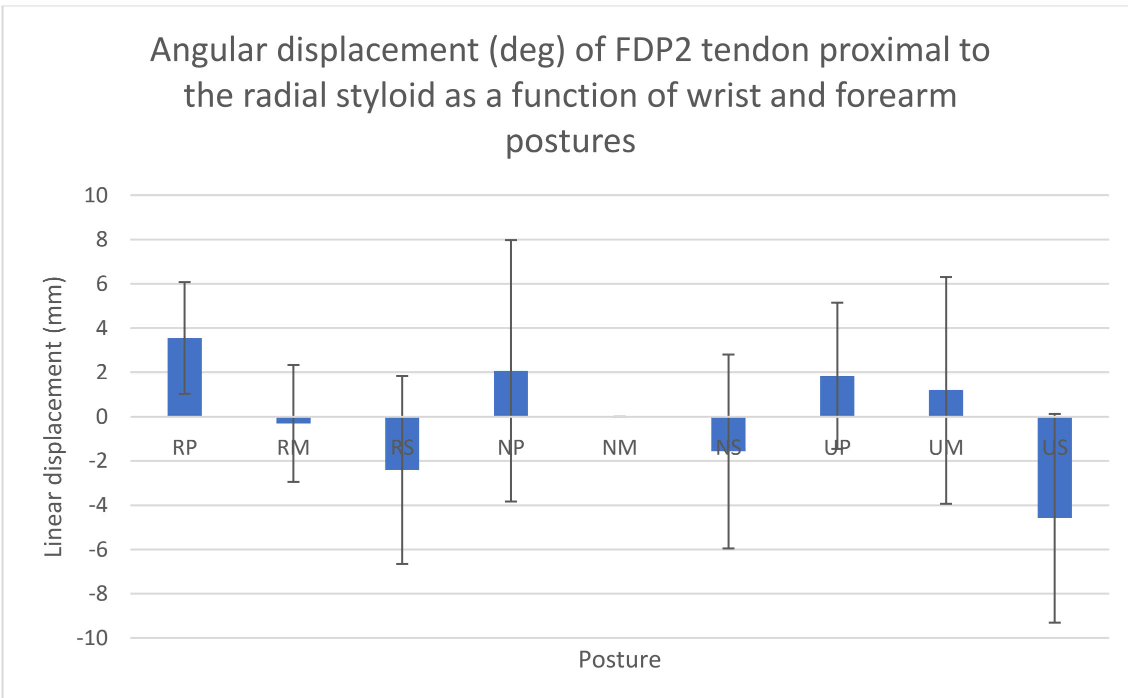

Figure 8: Linear displacement of FDP2 (mm) proximal to the radial styloid as a function of wrist and forearm posture. Wrist postures are (1) radial deviation, (2), neutral wrist, (3) ulnar deviation. Forearm postures are (1) pronation, (2) mid-pronation, (3) supination. The y-axis represents linear displacement in mm.

The ANOVA analyses also revealed that there was a significant main effect of forearm posture on the linear displacement of the tendon for FDS2 ($F(2, 6) = 28.806$, $p = 0.001$), FDS3 ($F(2, 6) = 30.550$, $p = 0.001$), and FDS4 ($F(2, 6) = 25.848$, $p = 0.001$). For these three tendons, the Bonferroni post-hoc analysis suggests that the tendons were displaced significantly more ulnarly than pronation and mid-pronation (Table 6).

Table 7: Mean linear displacement (mm) of tendons in the frontal plane proximal to the radial styloid as a function of wrist and forearm posture

	Mean linear displacement of the tendon in the frontal plane 15mm proximal to the RST (-ve is ulnar)					
	Wrist posture			Forearm posture		
Tendon	Radial Deviation	Neutral	Ulnar Deviation	Pronation	Mid	Supination
FDP2	0.12*	-0.38*	-2.19*	-0.46*	-1.09*	-0.90*
FDP3	1.12	-0.19	-1.77	0.90	-0.02	-1.11
FDP4	1.07	-0.12	-1.27	0.58	-0.11	-1.01
FDS2	0.83[a]	0.32[a]	-3.57[b]	0.40[a]	-0.19[a]	-2.62[b]
FDS3	0.85[a]	-0.09[a]	-3.32[b]	0.59[a]	-0.18[a]	-2.97[b]
FDS4	0.80	-0.29	-3.12	0.16[a]	-0.29[a]	-2.48[b]

Table 8: Mean linear displacement (mm) of tendons in the frontal plane proximal to the radial styloid in each combination of wrist and forearm posture

Frontal linear displacement proximal to the RST (-ve is ulnar)	
Posture	Average
RP	1.90
RM	1.03
RS	-0.49
NP	0.78
NM	0.00
NS	-1.13
UP	-1.57
UM	-1.82
US	-4.30

3.1.1.3. Angular displacement of the tendon proximal to the carpal tunnel

The ANOVA analyses revealed that there was a significant main effect of forearm posture on the angular displacement of the tendon in the frontal plane proximal to the RST for FDS4 ($F(2, 6) = 15.857$, $p = 0.004$). The mean displacement of the tendons in each posture can be found in Table 9. Post-hoc analyses using the Bonferroni correction (Table 9) revealed that supination (M = -2.859, SE = 1.729) resulted in the tendon rotated more in the ulnar direction than the pronated forearm (M = 2.49, SE = 1.872).

Table 9: Mean angular displacement of tendons (deg) in the frontal plane proximal to the radial styloid as a function of wrist and forearm posture

	Mean angular displacement of the tendon in the frontal plane 15mm proximal to the CT (-ve is ulnar)					
	Wrist posture			Forearm posture		
Tendon	Radial Deviation	Neutral	Ulnar Deviation	Pronation	Mid	Supination
FDP2	-0.02	-0.34	0.49	-0.23	-0.34	0.69
FDP3	1.15	0.62	0.27	1.45	0.45	0.15
FDP4	1.37	0.46	0.48	2.09	0.81	-0.60
FDS2	2.42	2.17	3.32	3.68	1.86	2.36
FDS3	-0.06	0.56	2.09	1.90	1.09	-0.40
FDS4	0.28	0.17	-0.52	2.49[a]	0.29[a,b]	-2.86[b]

Table 10: Mean angular displacement (deg) of the tendons in the frontal plane proximal to the carpal tunnel in each combination of wrist and forearm posture

Frontal angular displacement of the tendon proximal to CT (-ve is radial)	
Posture	Average
RP	2.31
RM	0.45
RS	-0.19
NP	1.37
NM	0.00
NS	0.45
UP	2.01
UM	1.64
US	-0.59

3.1.2. Sagittal plane variables

3.1.2.1 Linear displacement of the tendon at the level of the radial styloid

The results of the ANOVA tests revealed there was a significant main effect of forearm posture on the linear displacement of the tendon in the sagittal plane for FDP4 ($F(2, 6) = 12.089$, $p = 0.008$). The mean displacement of the tendons in each posture can be found in Table 12. Post-hoc analysis using the Bonferroni correction revealed that supination (M = -0.218, SE = 0.313) resulted in the tendon being displaced more in the ulnar direction than the pronated forearm (M = 0.789, SE = 0.326).

Table 11: Mean linear displacement (mm) of tendons in the sagittal plane at the level of the radial styloid as a function of wrist and forearm posture

	Mean linear displacement of the tendon in the sagittal plane at the level of RST (-ve is palmar)					
	Wrist posture			Forearm posture		
Tendon	Radial Deviation	Neutral	Ulnar Deviation	Pronation	Mid	Supination
FDP2	0.38	0.10	0.78	0.54	0.44	0.29
FDP3	0.45	0.09	0.04	0.60	0.24	-0.26
FDP4	0.84	0.09	0.14	0.79[a]	0.47[a,b]	-0.22[b]
FDS2	0.60	-0.08	0.21	0.46	0.59	-0.33
FDS3	0.39	-0.15	0.55	0.48	0.55	-0.26
FDS4	0.65	0.06	-0.05	0.67	0.47	-0.48

Table 12: Mean linear displacement (mm) of tendons in the sagittal plane at the level of the radial styloid within each combination of wrist and forearm posture

Sagittal linear displacement of the tendon at the level of RST (-ve is palmar)	
Posture	Average
RP	0.99
RM	0.63
RS	0.02
NP	0.39
NM	0
NS	-0.34
UP	0.39
UM	0.76
US	-0.31

3.1.2.2. Linear displacement of the tendon proximal to the radial styloid

The results of the ANOVA tests showed there was a significant effect of forearm posture on the linear displacement of the FDP4 ($F(2, 6) = 25.984$, 0.001) and FDS4 ($F(2, 6) = 8.766$, $p = 0.016$) tendons. The mean displacement of the tendons in each posture can be found in Table 14. Post-hoc analyses using the Bonferroni correction on FDP4 revealed that supination ($M = -0.584$, $SE = 0.146$) resulted in the tendon being displaced significantly more in the ulnar direction than pronation ($M = 0.854$, $SE = 0.344$) and the mid-pronated forearm ($M = 0.543$, $SE = 0.240$). The post hoc-analyses conducted using the Bonferroni correction for FDS4 revealed that supination ($M = -0.614$, $SE = 0.572$) resulted in the tendon being displaced significantly more than the pronated forearm ($M = 0.619$, $SE = 0.423$).

Table 13: Mean linear displacement (mm) of tendons in the sagittal plane proximal to the radial styloid as a function of wrist and forearm posture

	Mean linear displacement of the tendon in the sagittal plane 15mm proximal to the RST (-ve is palmar)					
	Wrist posture			Forearm posture		
Tendon	Radial Deviation	Neutral	Ulnar Deviation	Pronation	Mid	Supination
FDP2	0.14	0.19	0.63	0.20	0.28	0.47
FDP3	0.36	0.09	0.18	0.56	0.26	-0.19
FDP4	0.82	0.04	-0.05	0.85[a]	0.54[a]	-0.58[b]
FDS2	0.33	-0.21	0.36	0.19	0.38	-0.09
FDS3	0.28	-0.08	0.43	0.24	0.32	0.07
FDS4	0.58	0.01	-0.12	0.62[a]	0.46[a,b]	-0.61[b]

Table 14: Mean linear displacement (mm) of tendons in the sagittal plane proximal to the radial styloid within each combination of wrist and forearm posture

Sagittal linear displacement of the tendon proximal to RST (-ve is palmar)	
Posture	Average
RP	0.80
RM	0.36
RS	0.09
NP	0.20
NM	0
NS	-0.18
UP	0.33
UM	0.76
US	-0.38

3.1.2.3. Angular displacement of the tendon proximal to the radial styloid

The ANOVA results showed that there was a significant interaction effect of wrist and forearm posture on the angular displacement of the FDS4 ($F(4, 12) = 4.235$, $p = 0.023$) tendon proximal to the RS in the sagittal plane. Within the supinated forearm, ulnar deviation resulted in the tendon being displaced significantly more in the ulnar direction than the neutral wrist (Figure 2).

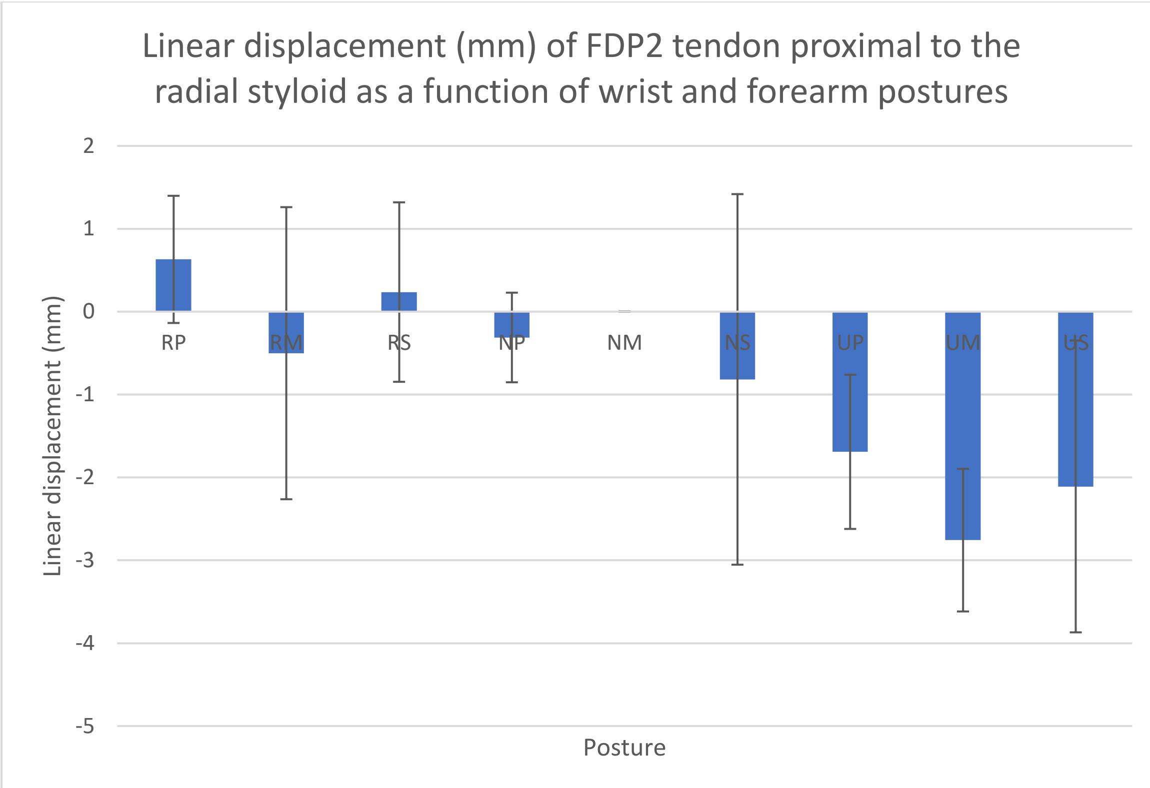

Figure 9: Angular displacement of FDS4 (deg) proximal to the radial styloid as a function of wrist and forearm posture. Wrist postures are (1) radial deviation, (2), neutral wrist, (3) ulnar deviation. Forearm postures are (1) pronation, (2) mid-pronation, (3) supination. The y-axis represents angular displacement in degrees.

Table 15: Mean angular displacement (deg) of the tendons in the sagittal plane proximal to the carpal tunnel as a function of wrist and forearm posture

	Mean angular displacement of the tendon in the sagittal plane 15mm proximal to the CT (-ve is palmar)					
	Wrist posture			Forearm posture		
Tendon	Radial Deviation	Neutral	Ulnar Deviation	Pronation	Mid	Supination
FDP2	-0.94	0.33	-0.59	-1.28	-0.63	0.72
FDP3	-0.34	0.03	0.52	-0.14	0.08	0.27
FDP4	0.03	-0.19	-0.73	0.25	0.26	-1.39
FDS2	-1.03	-0.47	0.57	-1.02	-0.81	0.91
FDS3	-0.41	0.26	-0.43	-0.93[a]	-0.87[a,b]	1.23[b]
FDS4	-0.26	-0.16	-0.30	-0.19	-0.04	-0.49

Table 16: Mean angular displacement (deg) of the tendons in the sagittal plane proximal to the carpal tunnel within each combination of wrist and forearm posture

Sagittal angular displacement proximal to CT (-ve is palmar)	
Posture	Average
RP	-0.72
RM	-1.01
RS	0.26
NP	-0.71
NM	0
NS	0.62
UP	-0.22
UM	0.003
US	-0.26

3.2. Distal results

3.2.1. Frontal plane variables

3.2.1.1. Angular displacement of the tendon distal to the carpal tunnel

The ANOVA results revealed there was a significant main effect of wrist posture for FDP2 ($F(2, 6) = 21.932$, $p = 0.002$), FDP4 ($F(2, 6) = 17.431$, $p = 0.003$), FDS2 ($F(2, 6) = 17.274$, $p = 0.003$), and FDS4 ($F(2, 6) = 16.349$, $p = 0.004$). There was no significant main effect of forearm posture. The mean displacement of the tendons in each posture can be found in Table 18. Post-hoc analyses using the Bonferroni correction for FDP2 revealed that ulnar deviation (M

= 15.799, SE = 2.315) resulted in the tendon rotating significantly more toward the ulnar direction than the neutral wrist (M = 1.175, SE = 1.980). Post-hoc analyses using the Bonferroni correction for FDP4 revealed that radial deviation (M = -7.719, SE = 1.733) resulted in the tendon being rotated significantly more in the radial direction than the neutral wrist (M = 0.064, SE = 1.622). Post-hoc analyses using the Bonferroni correction for FDS2 revealed that ulnar deviation (M = 12.137, SE = 2.441) resulted in the tendon being rotated significantly more in the ulnar direction than the neutral wrist (M = -0.513, SE = 1.197). Post-hoc analyses using the Bonferroni correction for FDS4 revealed that radial deviation (M = -6.645, SE = 1.251) resulted in the tendon rotating significantly more toward the radial direction than the neutral wrist (M = 0.929, SE = 1.166).

Table 17: Mean angular displacement (deg) of the tendons in the frontal plane distal to the carpal tunnel as a function of wrist and forearm posture

	Mean angular displacement of the tendon in the frontal plane distal to CT (-ve is radial)					
	Wrist posture			Forearm posture		
Tendon	Radial Deviation	Neutral	Ulnar Deviation	Pronation	Mid	Supination
FDP2	-4.86[a,b]	1.18[a]	15.80[b]	2.63	1.89	7.59
FDP3	-5.93	-0.10	15.75	1.46	2.09	6.16
FDP4	-7.72[a]	0.06[b]	19.01[a,b]	2.66	2.14	6.56
FDS2	-4.79[a,b]	-0.51[a]	12.14[b]	1.24	1.58	4.02
FDS3	-4.19	0.58	15.16	2.56	2.84	6.15
FDS4	-6.65[a]	0.93[b]	18.71[a,b]	2.90	2.94	7.15

Table 18: Mean angular displacement (deg) of the tendons in the frontal plane distal to the carpal tunnel within each combination of wrist and forearm posture

Frontal angular displacement distal to CT (-ve is radial)	
Posture	Average
RP	-6.25
RM	-8.07
RS	-2.75
NP	-1.64
NM	0
NS	2.71
UP	14.62
UM	14.81
US	18.86

3.2.2. Sagittal variables

3.2.2.1. Angular displacement of the tendon distal to the carpal tunnel

Separate two-way analyses were conducted on the angular displacement of the tendons distal to the carpal tunnel. No significant differences were found.

Table 19: Mean angular displacement (deg) of the tendons in the sagittal plane distal to the carpal tunnel as a function of wrist and forearm posture

	Mean angular displacement of the tendon in the sagittal plane distal to CT (-ve is palmar)					
	Wrist posture			Forearm posture		
Tendon	Radial Deviation	Neutral	Ulnar Deviation	Pronation	Mid	Supination
FDP2	4.94	1.77	-4.25	0.86	-1.03	2.62
FDP3	2.81	0.46	-7.38	-0.86	-2.22	-1.04
FDP4	2.89	0.46	-11.35	-1.74	-3.38	-2.88
FDS2	5.08	0.61	-4.34	0.39	-1.00	1.97
FDS3	3.87	0.53	-5.29	-0.01	-1.37	0.49
FDS4	1.69	-0.12	-9.51	-1.86	-2.59	-3.49

Table 20: Mean angular displacement (deg) of the tendons in the sagittal plane distal to the carpal tunnel within each combination of wrist and forearm posture

Sagittal angular displacement of the tendons distal to CT (-ve is palmar)	
Posture	Average
RP	3.18
RM	3.29
RS	4.16
NP	0.92
NM	0
NS	0.94
UP	-5.71
UM	-9.08
US	-6.26

Chapter 4: Discussion

4.1. Revisiting the Hypothesis

This study was driven by eight hypotheses. The first four hypotheses are related to the measurements made in the frontal plane. The first (1) hypothesis stated that there would be a main effect of wrist and forearm posture on the linear displacement in the frontal plane at the level of the RST. This hypothesis was partially accepted. Of the six tendons examined, the displacement of four tendons (FDP2, FDP3, FDS2, FDS3) were significantly affected by wrist posture, while three tendons (FDS2, FDS3, FDS4) were affected by forearm posture. The second (2) hypothesis stated that there would be a significant main effect of wrist and forearm posture on the linear displacement of the tendons in the frontal plane 15mm proximal to the RST. This hypothesis was partially accepted. Two tendons (FDS2 and FDS3) were significantly affected by wrist posture, while three tendons (FDS2, FDS3, and FDS4) were significantly affected by forearm posture. The third (3) hypothesis stated that there would be a significant main effect of wrist and forearm posture on the angular displacement of the tendons in the frontal plane proximal to the carpal tunnel. For wrist postures, this hypothesis was rejected as none of the tendons were significantly affected by wrist posture. Only FDS4 was significantly affected by forearm posture. The fourth (4) hypothesis stated that there would be a significant main effect of wrist and forearm posture on the angular displacement of the tendons in the frontal plane distal to the carpal tunnel. This was partially accepted as there was a significant main effect of wrist posture on four tendons (FDP2, FDP4, FDS2, FDS4). There were no tendons significantly affected by forearm posture.

The next four hypotheses are related to the measurements made in the sagittal plane. The fifth (5) hypothesis stated that there would be no significant main effect of wrist and forearm posture on the linear displacement of the tendon in the sagittal plane at the level of the RST. This was partially accepted as no tendons were significantly affected by wrist posture, and one tendon (FDP4) was significantly affected by forearm posture. The sixth (6) hypothesis stated that there would be no significant main effect of wrist and forearm posture on the linear displacement of the tendon in the sagittal plane 15mm proximal to the RST. This hypothesis was also partially accepted. No tendons were significantly affected by wrist posture, however, FDP4 and FDS4 were significantly affected by forearm posture. The seventh (7) hypothesis stated that there would be no significant main effect of wrist and forearm posture on the angular displacement of the tendon in the sagittal plane proximal to the carpal tunnel. This was partially accepted as there were no tendons significantly affected by wrist posture, and one tendon was significantly affected by forearm posture. The eighth (8) hypothesis stated that there would be no significant main effect of wrist and forearm posture on the angular displacement of the tendon in the sagittal plane distal to the carpal tunnel. No tendons were significantly affected by either wrist or forearm posture, and so the hypothesis was accepted.

4.2. Linear displacement of tendons in the frontal plane

Proximal to the carpal tunnel, linear displacement of the tendons was calculated at the level of the RST, and 15mm proximal to the RST. The tendons are located in a more ulnar position in ulnar deviation than a neutral or radial deviated wrist. At the level of the RST, and 15mm proximal to it, the shift in the ulnar direction (-2.832mm, and -2.563mm respectively) is more pronounced than the radial direction (0.586mm, and 0.811mm respectively). This may be due to the wrist angle that was achieved by the participants. On average, participants were able to radial deviate 6.94^{o}. In comparison, the participants were able to ulnar deviate 16.27^{o}. The greater wrist joint angle achieved by the participants in the ulnar direction may explain why the tendon displacement was more pronounced in the ulnar direction. However, even accounting for the lower joint angle, the ratio of tendon movement to the joint angle would still be lower in the radial direction. Displacement of the tendons could result in the tendons pressing against the median nerve, increasing the contact forces upon the median nerve. It has been documented that increased contact forces upon the median nerve can elicit symptoms of carpal tunnel syndrome (Lundborg et al., 1981). Keir et al. (1997) demonstrated that at similar magnitudes of radial and ulnar deviation, there was more contact pressure on the median nerve in ulnar deviation. The results of this study suggest that the increased displacement of the tendons in ulnar deviation may be a mechanism for the increased contact pressure observed in this posture in their study.

When observing individual postures, tendons were furthest from neutral-mid-pronation in radial-pronation and ulnar-supination. These results support the findings of Khan et al. (2009), who found that their participants experience the most discomfort in these postures. Moore et al. (1991) demonstrated that frictional work was highly correlated with workplace upper extremity injury. As tendons are displaced further, the amount of frictional work done on the tendon increases. The increased displacement of the tendons in these postures may be a mechanism for the increased discomfort.

The results of this study are consistent with studies examining changes in carpal tunnel pressure. It is been documented that increased intracarpal canal pressure may collapse the capillaries supplying the median nerve, leading to symptoms consistent with carpal tunnel syndrome (Lundborg, 1982). Werner et al., (1997) examined changes in intracarpal canal pressure as a function of forearm and wrist postures. High pressures were noted in two combinations of forearm and wrist postures – pronation with radial deviation, and supination with ulnar deviation. The displacement of the tendons of the current study is greatest in these postures.

At the level of the RST, and 15mm proximal to the RST, a significant main effect was observed for forearm posture, however only on the superficial tendons. The tendons are located more ulnarly in supination, and more radially in pronation. Tendon displacement in the ulnar direction in supinated postures was more pronounced than pronation. These findings are supported by Salas (2016), who observed that the tendons tended to shift more ulnarly with supination (2.2mm) than radially with pronation (0.3mm).

The general lack of interaction effect of wrist and forearm postures suggest that the effect that wrist and forearm postures have on tendon location is additive rather than multiplicative.

4.3. Angular displacement proximal to the carpal tunnel

The angular displacement of tendons was not affected by wrist posture. The angular displacement of FDS4 was affected by forearm posture. Supination rotated the tendon in the radial direction, whereas pronation rotated the tendon in the ulnar direction. The lack of significance in the other tendons may suggest that proximal to the carpal tunnel when tendons displace in either direction, the longitudinal axis of the tendon shifted linearly instead of being wrapped around or against something. A biomechanical model of finger flexor tendons at the wrist has likened the motion of the tendons at the wrist to a belt wrapped around a pulley (Armstrong and Chaffin, 1979). The linear shift may increase the area of the tendon that experiences frictional work but may minimize the overall amount of frictional work done onto the tendon. A non-linear shift of the tendon may indicate the tendon wrapped against something. The wrapping of the tendon would indicate a smaller radius of curvature, and would thus increase the normal force exerted onto the tendon, resulting in increased frictional work and risk of injury. Furthermore, there could be more localized damage at the site of tendon wrap, which could lead to a faster rate of damage and injury relative to a linear shift of a tendon.

4.4. Angular displacement distal to the carpal tunnel

Angular displacement of the tendon was also calculated distal of the carpal tunnel. There was a significant main effect of wrist posture for the tendons of the 2^{nd} and 4^{th} digits. In general, the tendons were located more in the ulnar direction during ulnar deviation and found more radially during radial deviation. For the tendons of the second digit, which are located more radially in the hand, there was a significant difference between ulnar deviated and neutral wrist, but not between radial and ulnar deviated wrists, or radial and neutral wrists. Given that the tendons of the 2^{nd} digit are located radially, it may suggest that they are closer to the radial border of the carpal tunnel. Thus, anatomical structures such as the flexor retinaculum or the carpal bones are preventing the tendons from moving further in the radial direction. There would not be a physical border ulnar to these tendons, which may reflect why the tendons experience more movement in the ulnar direction. The same phenomenon can be seen on the ulnarly located tendons. FDP4 and FDS4 are close to the ulnar border of the carpal tunnel, and ulnar deviation is not significantly different from neutral wrists. This may indicate that the tendons are unable to move as far in the ulnar direction due to something restricting its movement.

4.5. Sagittal plane analysis

In the sagittal plane, FDP4 was affected by forearm posture at the level of the RST, and 15mm proximal to it. FDS4 was also affected by forearm posture 15mm proximal to the RST. Supination resulted in the tendon being displaced more dorsally, and pronation resulted in the tendon to be displaced more in the palmar direction. Despite there being significant differences in these tendons, the largest range that the tendons move is 1.43mm.

4.6. Comparison of deep and superficial tendon displacement

The results of this study demonstrate that proximal to the carpal tunnel, the superficial flexor tendons (1.97mm) experience more displacement than the deep tendons (0.92mm). The deep tendons are in closer proximity to the stiffer carpal bones, whereas the superficial tendons are closer to and enclosed by the flexor retinaculum. The stiffness of the carpal bones may restrict the motion of the deep tendons, resulting in a narrower range of displacement. The flexor retinaculum in comparison is comprised of bundles of fibrous soft tissue which may allow for a wider range of tendon displacement.

Table 21: Comparison of the deep and superficial tendon displacement (mm) from the neutral-mid-pronation posture

	Deep		Superficial	
Posture	At the level of RST	Proximal to the RST	At the level of the RST	Proximal to the RST
RP	1.12	1.56	1.46	2.24
RM	0.55	0.59	1.27	1.46
RS	0.01	0.16	0.87	1.14
NP	0.03	0.11	0.86	1.45
NM	0.00	0.00	0.00	0.00
NS	0.86	0.80	1.63	1.46
UP	1.55	1.25	2.64	1.88
UM	1.79	1.59	2.71	2.05
US	2.20	2.38	6.09	6.23
Average	0.92		1.97	

Given that the results of this study suggest that the superficial tendons experience more displacement, special considerations must be made for the FDS4 tendon. This tendon lies almost directly ulnar to the median nerve (Rotman and Donovan, 2002). Radial deviation of this tendon may result in increased contact stress on the median nerve. Compression of the median nerve has been shown to reduce its function and elicit numbness and tinging, symptoms consistent with carpal tunnel syndrome (Lundborg, 1975). The findings from this study would suggest to avoid radial deviation and forearm pronation over extended periods of time to reduce the potential of compressing the median nerve, particularly when there is tension in the FDS4 tendon, as would occur when grasping.

4.7. Intersection Angle

The path of the tendons was also examined by calculating the intersection angle, the difference between the angle of the tendon as it enters and exits the carpal tunnel. This measurement provides an estimate of what is happening inside the carpal tunnel. Tendon intersection angles were strongly correlated with the wrist joint angle (r^2 from 0.966-0.995). Examining the range of the wrist joint and tendon movement within each forearm posture, the intersection angles ranged from 91-95% of the joint angle. Keir and Wells (1999) examined intersection angles as a function of wrist flexion and extension and also found that intersection angle to be strongly correlated with joint angle ($r^2 = 0.81$-0.96), however, they reported a smaller ratio of intersection angle to wrist angle (50-65%). This may be due to the average carpal tunnel being wider (25mm at proximal end, 26mm at distal end) than it is deep (12mm at proximal end, and 13mm at distal end) (Rotman and Donovan, 2002). This may mean there is more space available to allow the tendons to move with the joint in the mediolateral plane than in the anteroposterior.

Table 22: Range of joint angle and intersection angle (deg) during radial-ulnar deviation within each forearm posture.

	Difference between postures	Joint angle	Intersection Angle	Ratio
Pronation	Radial-Neutral	4.61	5.55	1.21
	Ulnar-Neutral	-17.48	-15.62	0.89
	Radial-Ulnar	22.09	21.17	0.96
Mid-pronation	Radial-Neutral	9.27	21.68	2.34
	Ulnar-Neutral	-14.52	-13.17	0.91
	Radial-Ulnar	23.79	21.17	0.89
Supination	Radial-Neutral	8.00	4.81	0.60
	Ulnar-Neutral	-15.74	-17.19	1.09
	Radial-Ulnar	23.73	22.00	0.93

When observing individual combinations of wrist and forearm posture, it can be noted that both radial-pronation and ulnar-supination were the two postures where the intersection angle was greater than the wrist joint angle. This has a few implications. Firstly, a greater intersection angle may imply that within the carpal tunnel, there is greater relative movement between the bones and the tendon, leading to increased frictional work and risk of injury. Another implication is that in order to achieve a greater intersection angle, the tendon may have to be wrapped around something. This could lead to increased normal pressure on a localized area of the tendon, leading to a faster rate of injury development as friction is concentrated on a smaller area of the tendon rather than being distributed along the length of the tendon.

Chapter 5: Limitations

One limitation of this study was that the radial angle achieved by the participants was less than the desired radial deviation angle. The results of this study demonstrate that the direction of tendons' displacement is in line with radial and ulnar deviation. As most tendons were approaching significance, perhaps achieving a larger radial wrist angle would elicit more tendon displacement in the radial direction and lead to a more definitive answer with regards to the displacement of the finger flexor tendons as a function of wrist posture. It should be noted, however, that the radial deviation achieved was due to the lack of available range of motion particularly in supination and is a limitation of the anatomy of the hand.

Another limitation is that the displacement measurements were calculated through the analysis of static MR images. While it provides an estimate of tendon displacement in the range of wrist postures examined, and the results suggest that there is a linear relationship between displacement and wrist angle, it is unclear if this relationship remains true during the dynamic movement of the wrist joint.

Chapter 6: Future Directions

This study quantified the amount of tendon movement in the mediolateral plane as a function of wrist and forearm posture. Most models currently use changes in the wrist flexion/extension angle to estimate tendon displacement along the tendons' longitudinal axis to calculate frictional work. In the future, the data collected in this study could provide a basis to develop a model that uses changes in wrist radial-ulnar angle, as well as forearm angle, to estimate tendon displacement in the mediolateral plane. This will provide a more robust analysis of the amount of frictional work done on the tendon in various combinations of wrist and forearm postures.

The results of this study would suggest that there is a linear relationship between the tendon displacement and the wrist/forearm angle. Displacement was only calculated at three levels of wrist posture, and three levels of forearm posture. Future studies should examine if this linear relationship holds true for all postures by assessing displacement at smaller intervals of changes in wrist and forearm posture.

Chapter 7: Recommendations

Studies have found that ulnar-supination and radial-pronation are postures that could lead to injury due to increased discomfort (Khan et al., 2009), and increased contact stress placed upon the median nerve (Werner et al., 1997). The results of this study demonstrated that the tendons are displaced furthest from a neutral position (neutral-mid-pronation) in these two postures. The displacement of the tendons could perhaps be the mechanism that is responsible for these findings. As the displacement of the tendons increases, there is more frictional work done onto the tendon which may be experienced as discomfort. Likewise, the displacement of the tendons could result in the tendons coming into direct contact with the median nerve and adjacent synovial sheaths, increasing contact stress. With these findings, minimizing the time spent in these postures may reduce the risk of injury. Occupational tasks such as manual material handling, especially the lifting, carrying, and holding of boxes; and keyboarding and mousing may pose a high risk of injury. Manual material handling often involves pinch and/or grip force, which further increases the frictional load on the tendon, exacerbating the risk of injury in these postures. Radial-pronation of the wrist and forearm may be the more problematic of the two postures from a contact pressure point of view. The FDS4 tendon is almost directly ulnar to the median nerve. Radial displacement of this tendon could result in the tendon coming into direct contact, compressing the median nerve from the ulnar side, increasing pain, discomfort and the risk of injury. Designing workspaces and tools to minimize that time spent in these postures may reduce this risk.

Chapter 8: Conclusion

The goal of this study was to examine the trajectory of the tendons as they entered and exited the carpal tunnel in different combinations of wrist and forearm postures. This was completed by quantifying the linear and angular displacement of the finger flexor tendons as a function of wrist and forearm posture.

The tendons were displaced furthest in the combinations of ulnar-supination and radial-pronation. The magnitude of tendon displacement found in these two postures within this study suggests a mechanism for increased discomfort and contact stress placed upon the median nerve, both of which have been linked to increased rate of injury. With these findings, it may be suggested that tasks such as manual material handling, especially the lifting, carrying, and holding of boxes; and keyboarding and mousing may pose a high risk of injury. Manual material handling often involves pinch and/or grip force, which further increases the frictional load on the tendon, exacerbating the risk of injury in these postures. Designing workspaces and tools to minimize that time spent in these postures may reduce this risk.

The results of this study also suggest that superficial tendons experience a wider range of displacement than the deep tendons. This may be problematic for the FDS4 tendon, which is almost directly ulnar to the median nerve. With more movement available to the superficial tendons, there may be a higher likelihood that the FDS4 tendon comes into contact with the median nerve when it is displaced radially.

Finally, the angular displacement of the tendons proximal to the carpal was not affected by wrist or forearm posture, suggesting the tendons shifted over linearly. This may be protective in nature in terms of disorders at the wrist, as a linear shift would imply that the tendon is not experiencing a wrap or bend around an anatomical structure. This would minimize the overall frictional work done onto the tendon. However, it does mean there could be more movement proximal to the wrist in the forearm musculature itself. Distal to the carpal tunnel, the angular displacement of the tendons of the 2^{nd} and 4^{th} digits are affected by wrist posture. The results suggest that the FDS/FDP2 tendons are unable to displace radially, and the FDS4/FDP4 tendons are unable to displace ulnarly. We hypothesize that there is a physical boundary, namely the borders of the carpal tunnel, that prevents these tendons from displacing further.

This study quantified the linear and angular displacement of the tendons to examine the trajectory of the finger flexor tendons entering and exiting the carpal tunnel. The data obtained from this study is a necessary step for future modeling of the tendons and the development of better risk assessment tools.

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Appendices

Appendix A: Informed Consent form

Informed Consent Form

Date: August 2017

Study Name: MRI evaluation of wrist flexor tendon trajectories as they enter, pass through, and exit the carpal tunnel as a function of forearm rotation and ulnar and radial deviation postures.

Researchers: Faculty Member: Dr. Anne Moore

MSc. Candidate: Andrew Dang

Upper limb injuries are prevalent in the workplace and costly. Understanding of upper limb injury mechanisms that are associated with work tasks is of crucial importance to reduce their incidence in the workplace. Epidemiological evidence has shown that sustained pronated postures and repetitive pronation and supination have been associated with upper limb injury.

Previous studies have shown forearm rotation affects tendon movement exclusively in the frontal plane. This tendon movement occurs in the same plane of movement of radial and ulnar deviation. There is a strong possibility that the magnitude of tendon movement may be increased when forearm postures are combined with radial and ulnar deviation. However, this relationship is unclear. Thus, the purpose of this study is to examine forearm and wrist loading as a function of forearm rotation and wrist postures, by measuring the magnitude of the deviations of tendons passing through the wrist with different postures.

You will be asked to answer two questionnaires: In the first one, you will be asked questions to gather information on height, weight, handedness, and musculoskeletal health. In the second one, we will ask you questions to screen whether it is safe for you to access the MRI room. You will be asked to remove any metallic objects you may be carrying. The anatomy of your wrist will be imaged using MRI, while you sustain three forearm rotation postures in combination with three wrist radial and ulnar deviation postures. During this process, you will be required to lie completely still on the patient bed that slides into the bore of the MRI scanner. No dye will be required. You will be able to communicate with the MRI technologist and researchers through an intercom and will have an emergency bulb that you can squeeze at any time if you need to come out of the scanner during the procedure. During the collection, you will be required to wear a splint to hold your wrist in the desired posture. At the same time, you will be required apply a constant light grip force on a ball filled with water, connected to a water tank to give you feedback on the amount of force that you will need to keep constant during each sequence. Your estimated participation will take approximately 1.5 hours.

If the scans obtained are unclear and are too difficult to analyze, you may be asked to come in at another time to complete another session.

It is important to inform you that these images are not intended to reveal any disease state, in part because this MRI protocol is not designed for clinical diagnosis. Thus, your wrist images will not be routinely examined by a clinical radiologist. The personnel at the Neuroimaging Laboratory are not qualified to medically evaluate your images. However, if in the course of collecting the images we have any concerns, we may show your scans to a clinical radiologist, who may suggest that you obtain further diagnostic tests.

At the investigator's discretion, you may view your wrist images and receive digital copies of them. However, you should be aware that structural images within the normal population can be highly variable, and that it is difficult to draw any conclusions from your images; you should be aware of the potential distress or discomfort that may occur by viewing your own images. Do not rely on this research MRI to detect or screen for any abnormalities.

Risks

This study has been reviewed and approved by the Human Participants Review Sub-Committee, York University's Ethics Review Board, and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. The risks associated with this study involve the following:

Metal: The MRI scanner produces a constant strong magnetic field, which may cause any metal implants and/or clips within your body to shift position. The magnetic field may also cause any implanted medical devices to malfunction. Thus, if you have any implanted metal, clips or devices, it is hazardous to your health to participate in this study. Please provide us with as much information as you can, for example, if you had surgery in the past, so that we may decide whether it is safe for you to be a subject. Metallic objects brought into the MRI environment can become hazardous projectiles. Metal earrings, body piercings, and necklaces must be removed prior to the study.

Pregnancy: Exposure to MRI scanning might be harmful to a pregnant female or an unborn child. Although there are no established guidelines at this time about MR and pregnancy, you should be informed that there is a possibility of a yet undiscovered pregnancy-related risk. If you know or suspect you may be pregnant or if you do not want to expose yourself to this risk, we recommend that you do not participate in this study.

Inner ear damage: MRI scanning produces loud noises that can cause damage to the inner ear if appropriate sound protection is not used. Earplugs and/or headphones will be provided to protect your ears.

Claustrophobia: When you are inside the MRI scanner, the MRI scanner surrounds your body and your head will also be positioned inside a close-fitting scanning coil. If you feel anxious in confined spaces you may not want to participate. If you decide to participate and begin to feel claustrophobic later, you will be able to tell us via the intercom and we will discontinue the study immediately.

Burns: In rare cases, contact with the MRI transmitting and receiving coil, conductive materials such as wires or other metallic objects, or skin-to-skin contact that forms conductive loops may result in excessive heating and burns during the experiment. The operators of the MRI scanner will take steps, such as using foam pads when necessary, to minimize this risk. Tattoos with metallic inks can also potentially cause burns. Any heating or burning sensations during a scan in progress should be reported to the operators immediately and we will discontinue the scan.

Although functional MRI scanning has been used for more than 15 years, long-term effects are unknown. If new findings of the risks of the MRI technique become available within a year of your participation, we will let you know about them.

Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer will not influence the nature of your relationship with York University either now, or in the future.

You can stop participating in the study at any time, for any reason, if you so decide. If you decide to stop participating, you will still be eligible to receive the promised pay for agreeing to be in the project. Your decision to stop participating, or to refuse to answer particular questions, will not affect your relationship with the researchers, York University, or any other group associated with this project. In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible.

Your data will be safely stored in a locked facility and only research staff will have access to this information. Confidentiality will be provided to the fullest extent possible by law. In no case will your personal information be shared with any other individuals or groups without your expressed written consent. Your images will be stored on secured computer servers and will be archived indefinitely. The experimental data acquired in this study may, in an anonymized form that cannot be connected to you, be used for teaching purposes, be presented at meetings, published, shared with other scientific researchers or used in future studies. Your name or other identifying information will not be used in any publication or teaching materials without your specific permission.

If you have questions about the research in general or about your role in the study, please feel free to contact Dr. Moore or Andrew Dang by email.

This research has been reviewed and approved by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines.

Legal Rights and Signatures:

I________________________consent to participate in the MRI evaluation of wrist flexor tendon trajectories as they enter, pass through, and exit the carpal tunnel as a function of forearm rotation and ulnar and radial deviation postures conducted by Andrew Dang. I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by signing this form. My signature below indicates my consent.

Signature______________________ **Date____________________**

Participant

Signature______________________ **Date____________________**

Appendix B: Initial Questionnaire – MSK health and demographic information

Initial Questionnaire **Date**: ___________________

Participant #: __________

Demographic Information

1. Date of Birth (mm/d/yr): _____________________________________
2. Sex: Female ☐ Male ☐
3. Handedness: _____________________________________
4. Height: _________m __________cm or __________ft ___________in
5. Weight: ______________Kg or __________Lb

Health and Injury Information

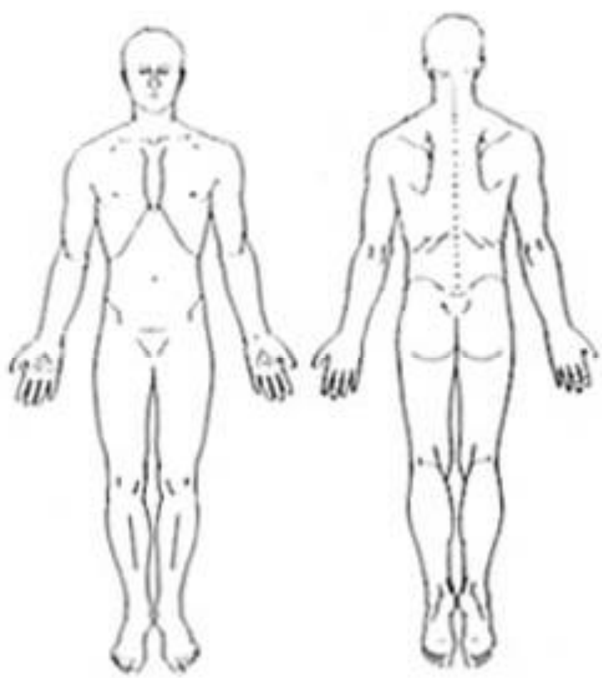
1. Do you currently have any health condition that could potentially be aggravated with physical activity (i.e. cardiovascular problems, high blood pressure, joint problems, etc.)?
   Y N ☐ ☐
   If yes, please explain: ____
2. Have you ever been diagnosed with neurological disorders (i.e. carpal tunnel syndrome, pronator teres syndrome)? Y ☐ N ☐
   - If yes, please explain: ____
   ____
3. Have you ever received treatment for any of the following, please specify:
   - Fractures - body part: ____
   - Dislocations –body part: ____
   - Muscle Strains or sprains - ____
   - Upper Back pain - ____
   - Lower back pain - ____

☐ Tendonitis/tenosynovitis - ____

☐ Other musculoskeletal disorder - ____

4. In the past year, have you had treatment for any musculoskeletal injury or disorder?
   Please specify:
   ____

5. Do you currently have any physical discomfort/pain? Y ☐ N ☐
   If yes, please indicate in the figure where you feel the discomfort/pain



Appendix C: MRI screening form

York University Neuroimaging Laboratory
Magnetic Resonance (MR) Safety Screening Form

Name ____ **Weight** __________
Last First MI **Height** __________

Date of Birth ______/______/______ ❑ Male ❑ Female
Month Day Year

Do you have: **Cardiac pacemaker or implantable cardioverter defibrillator (ICD)** ❑ **Yes** ❑ **No**
Aneurysm clip ❑ **Yes** ❑ **No**
Are you: Claustrophobic ❑ Yes ❑ No
Are you currently taking any medications? ❑ Yes ❑ No
List: ____

Have you ever had an injury to the eye involving a metallic object or fragment? ❑ Yes ❑ No
Have you ever worked in a metal shop? ❑ Yes ❑ No
Possibility of pregnancy? ❑ Yes ❑ No ❑ Not applicable

Brain/Head Surgery ❑ Yes ❑ No
List type/date
____

Artificial Implants/Mechanical Devices
List type/date ❑ Yes ❑ No
____

Heart/Chest Surgery ❑ Yes ❑ No
List type/date *Retained pacer wires* ❑ Yes ❑ No
____

Other Surgery
List type/date ❑ Yes ❑ No
____

Ear Surgery ❑ Yes ❑ No
List type/date
____

Eye Surgery ❑ Yes ❑ No
List type/date
____

Pierced body parts (earrings, etc.) ❑ Yes ❑ No
Hearing aid or cochlear implant ❑ Yes ❑ No
Permanent retainer or braces ❑ Yes ❑ No
Dentures or partials ❑ Yes ❑ No
History of bullets, shrapnel or BBs ❑ Yes ❑ No
History of seizures ❑ Yes ❑ No
Hair piece, wig or hair extensions ❑ Yes ❑ No
Medication or transdermal patch ❑ Yes ❑ No
Tattoo or permanent makeup ❑ Yes ❑ No
Stent, filter ❑ Yes ❑ No

WARNING: Certain implants, devices, or objects may be hazardous to you and/or may interfere with the MR procedure (i.e., MRI, MR angiography, functional MRI, MR spectroscopy). **Do not enter** the MR system room or MR environment if you have any questions or concerns regarding an implant, device, or object. Consult the MRI Technologist or Researcher BEFORE entering the MR system room. **The MR system magnet is ALWAYS on.**

I attest that the above information is correct to the best of my knowledge. I have read and understood the contents of this form and had the opportunity to ask questions regarding the information on this form and regarding the MRI procedure that I am about to undergo.

Signature of person completing form: ______________________________ **Date** ___/___/___
M D Y

Form completed by: ❑ MRI participant ❑ Other (specify)______________________

Reviewed by: ______________________ **PI of study** ______________________