The Variation of Median Nerve Functionality with Wrist Postures Typical of Computer Use and A Novel Ultrasound Technique for the Diagnosis of Carpal Tunnel Syndrome

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Abstract

Carpal tunnel syndrome (CTS) is an affliction that affects numerous people in an occupational and recreational environment. One area commonly linked to the development of this condition is computer use. This is due to the repetitive movements that occur while undertaking this task. However, a direct link between computer use and CTS development has not been established. Determining the cause and development of CTS will result in a greater understanding of the condition and its influence on the patient. This is necessary for adequate treatment and diagnosis of the condition. Knowing the physical responses or anatomical changes that occur will lead to identification of CTS at an earlier stage and a level of severity to be accurately determined.

Establishing a connection between CTS and computer use, involves breaking down computer activities into its individual components. One of these components is wrist posture. Deviation of the wrist from a neutral position has been shown to increase pressure within the carpal tunnel, leading to a reduction in nerve functionality. If this pressure is great enough, it will induce the development of CTS. However, investigations into the wrist postures frequented during computer use or the impact of these postures on the median nerve have been limited. During a computer activity wrist movements occur in extension/flexion and a radial/ulnar direction. However, previous studies have only documented these movements in one direction at a time.

To account for complete movement of the wrist, motion analysis techniques were adopted. This allowed for all wrist postures to be calculated and categorised. Once the most prevalent wrist postures were determined, their influence on median nerve functionality was investigated. This was carried out utilising electrodiagnostic techniques. This involved maintaining the most common wrist postures for an extended duration of time and recording the change in nerve response to electrical stimulation. This determined that nerve functionality decreased enough to indicate a significant pressure increase within the carpal tunnel. Even though testing was only conducted on healthy individuals, changes to NCS data occurred. This highlights the possibility of false diagnosis. To overcome this problem an alternative diagnostic modality, which is not influenced by this would be beneficial. One suitable method is sonography.

Sonography has previously been investigated for diagnosing CTS, but the accuracy of it has varied significantly in literature. However, the benefits of viewing the carpal tunnel contents and the potential of sonography in CTS diagnosis are evident. For sonography to develop further in the diagnosis of CTS, a new diagnostic criterion needs to be created. This would overcome the variation and problems associated with other criteria. The method proposed in this study is median nerve volume ratio.

To calculate median nerve volume, a 3-D model of the median nerve in the forearm and through the carpal tunnel was constructed. This is done from a number of B-scans of the median nerve. Image orientation was calculated using photogrammetric techniques and allowed for alignment of the images to occur. A total of four volumes along the median nerve were calculated. This resulted in three volume ratios, comparing the nerve volume in the carpal tunnel to areas in more proximal locations. The results display a substantial difference between controls and patients for two of the volume...
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ratios calculated. These volume ratios also show a strong trend for severity with better $R^2$ values than current diagnostic methods.

To understand the discrepancies in previous sonographic diagnostic criteria, the impact of the sonographer was reviewed. This focused on the transducer force applied during an ultrasound examination. It was found that force had the capacity to alter values used in diagnosis such as flattening ratio. However, it was also noted that area measurement did not alter significantly due to the applied force. Therefore, volume measurement from 3-D models would not be affected.

The experimental investigations undertaken revealed a link between computer use and decrease in nerve functionality. This was not simply beneficial in determining how CTS can develop, but also in showing the possibility of incorrect diagnosis occurring. The new sonographic methods presented here show great promise in diagnosing CTS and tackled the problem of false diagnosis associated with NCS.
DECLARATION

November, 2011

The substance of this thesis is the original work of the author and due reference and acknowledgement has been made, when necessary, to the work of others. No part of this thesis has been accepted for any degree and is not being concurrently submitted for any other award.

Maurice Donoghue
(Candidate)

Dr. Michael Walsh
(Supervisor)
Acknowledgements

So I’ve finally reached that stage of my thesis that I can write down whatever it is that I want. It’s a pity that once you actually reach this stage, you no longer have anything you want to say. But ignoring that and sticking with tradition I’ll go through all the thank yous that have been well deserved since I blindly started this final (thank God) stage of college. My family seems like an obvious place to start. I’d like to thank my parents, P.J. and Leish, for the support they gave me, not just during my Ph.D. but up until this point of my life. I was never stuck for anything and I always knew that I only needed to ask if I needed help in any area. To Bryan, Pat and Orna, I’m still not sure if I should be thanking you all or cursing you. Being the youngest in the family means that you are always compared to those that have gone before and ye didn’t half set the bar high. With that in mind it gave me some bit of drive and a standard to try and reach. One of these days I might actually reach it (if it stops rising).

To the men in charge who started me on this road of academia, thank you is most definitely warranted. Mikah, you have somehow managed to guide me to complete this while still giving me the freedom to do the type of research I wanted. I’m still not sure how you managed it, but I hope you do it for many more. Tim, you’ve always been there for a helpful bit of advice when needed or a pint at a conference. Long may it continue. And for those who have recently joined the high ranks of CABER (Eamonn, Philip), seemingly papers are important! Ye have been warned.

To those at BeoCare that gave me a foothold in research, I will be forever grateful. Who knows where I’d have ended up otherwise. Mr Finbarr Condon and Prof. Dominic Harmon, without the input and assistance you provided this journey would have been a lot more difficult. I hope it benefitted you too and you gained as much from it as I did.

To all of those who have worked alongside me over the years, it was an absolute pleasure. Molony, you always managed to turn up with the most random stories after nights out and they never failed to entertain. I’ll admit they did usually involve you ending up in the middle of nowhere, but they were epic. Aine, I’ve probably known you the longest out of all the people in CABER and I can’t think of one bad moment
through the lot of it. It would make it easier to take the mick out of you if I did, but
since I can’t I just hope I know you for many more years to come. Dave, you’ve been
getting through this thesis lark at the same rate as me for the last while and knowing
someone else dealing with the same problems helps no end. Now we can just
concentrate on celebrating and forget about any more early starts in the hospital. Steve,
you’ve had to endure more rants about testing and computer programs not working than
most and somehow always manage to see a solution. Many thanks for the input and
being someone to bounce ideas (or inappropriate jokes) off of.

Laura and Claire (aka Frank and Beans), you were always a welcome source of
distraction. Always up for anything and would head out for any excuse. I’ll be trying
to come up with a few more excuses in the future so don’t worry. Aidan (The Magpie)
Cloonan, you always knew where to find…..well everything. If I ever need anything,
you’ll be the man I’ll contact. Alex and Edel, I can just wish you the best of luck. You
are both in the final stages and will no doubt be handing up soon. It may seem like a
long time but it’s well worth the wait. John, you may no longer be postgrad rep but I
think you should take up a new calling of being an organiser. You’ve organised
everything at some stage and most recently it involved us shooting each other. Couldn’t
ask for anything more. Lynchie, you’re going to have to stop breaking your model for
testing and get on with finishing this thesis thing. Just add loads of pictures and it will
all look good. Will, you should be well able to help him on the picture front. And
while you’re helping him you can teach him that karate kick you perfected while
playing with CABER United.

Moving on to the oldies and the newbies. Bazz, Barry, Anto, Farmer and Grainne, ye
have been about UL in some way for God knows how many years at this stage and
acted as mentors to all who joined since. This extends far beyond helping in the work
place and I don’t see it stopping any time soon. Rory and Niall, ye fit into the middle of
these groups. More for the fact that ye have been there done that but still manage to fit
a few drinks at Nancy’s into your week. The newbie’s’ ranks has grown a bit recently.
Aoife and Eoghan, you are both included in this since ye managed to be honorary
members of CABER before officially joining up this year. And since I’ve not really got
to know the rest who started this year, the newbies still include Jen. Sarah, Len and
Siobhan. Ye’ve added a lot to the group since joining and are still keeping up the
reputation we have for winning best dressed table at BINI. Just keep the house parties coming and I’ll still be about!!

I’d like to thank all my friends from both home and around Limerick who have helped to keep me sane over the last few years. Dave, Toomey, Richie, Mike, Joe, Staff and Ted, it was great to live with ye, even if ye did manage to take most of my money off me at poker. Sharon, you have read more of my thesis than most and I appreciate it no end. It’s possibly the only area I knew a small bit more about than you at the start but figure you know as much as me at this stage. I hope to repay the favour soon. Fiachra, you’ve managed to keep the CABER vs. Stokes rivalry going strong for a long time. At least Fat Frank ended up in the right place in the end. Daithi, you may also be on the Stokes side but have definitely earned a mention. Between mountain biking and gyming it up I was usually too tired to think about the PhD and happy out about it. Brian, Francis, Sarah, Kev and Sean, you always gave me options for doing things at weekends and that always helped to keep my mind off college, which was badly needed at times.

To all those who I’ve not got to mention (and there are a lot of you) I’d also like to say thanks. Getting to know you all during this was an experience in itself and I will forever be indebted to the nights out and friendship that ye had no trouble being a part of.

“We keep moving forward, opening new doors, and doing new things, because we're curious and curiosity keeps leading us down new paths.”

Walt Disney
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<td>Aetiology</td>
<td>The cause of a disease.</td>
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<td>Anthropometric data</td>
<td>Data concerning the sizes and proportions of the human body.</td>
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<td>Bursae</td>
<td>Closed fluid-filled sacs that functions to provide a gliding surface to reduce friction between tissues of the body.</td>
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<td>Demyelination</td>
<td>A degenerative process that erodes away the myelin sheath that normally protects nerve fibres resulting in impaired nerve function.</td>
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<tr>
<td>Effector organ</td>
<td>An organ that produces an effect in response to nerve stimulation.</td>
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<tr>
<td>Epineurium</td>
<td>The outermost layer of connective tissue surrounding the peripheral nerve.</td>
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<tr>
<td>Fibro-osseous</td>
<td>Composed of bony and fibrous tissue.</td>
</tr>
<tr>
<td>Hyperextension</td>
<td>Extension of a joint beyond its normal range of motion.</td>
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<tr>
<td>Hypertrophy</td>
<td>Enlargement or overgrowth of an organ or part due to increase in size of its constituent cells.</td>
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<td>Lumbrical muscles</td>
<td>Any of four muscles whose origins are from the flexor digitorum profundus, with insertion into the extensor tendon on the dorsum of each of the four fingers; with nerve supply from the median and</td>
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ulnar nerves; and whose actions flex the proximal phalanges and extend the middle and distal phalanges.

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<thead>
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<td>Malalignment</td>
<td>A failure of parts of the body to align normally.</td>
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<td>Photogrammetric techniques</td>
<td>Calculating precise measurements by means of photography.</td>
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<td>Pronator quadrates muscle</td>
<td>A square shaped muscle on the distal forearm that acts to pronate the hand.</td>
</tr>
<tr>
<td>Radiologic imaging</td>
<td>The use of imaging to both diagnose and treat disease visualized within the human body.</td>
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<td>Radioulnar</td>
<td>Pertaining to the radius and ulna.</td>
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<td>Thenar muscles</td>
<td>The muscles that comprise the intrinsic musculature of the thumb and include the abductor pollicis brevis, adductor pollicis, flexor pollicis brevis, and opponens pollicis.</td>
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<td>∆CSA</td>
<td>Difference in nerve cross sectional area</td>
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<tr>
<td>AAA</td>
<td>Abdominal aortic aneurysm</td>
</tr>
<tr>
<td>AAEM</td>
<td>American Association of Electrodiagnostic Medicine</td>
</tr>
<tr>
<td>BMI</td>
<td>Body mass index</td>
</tr>
<tr>
<td>BCTQ</td>
<td>Boston carpal tunnel questionnaire</td>
</tr>
<tr>
<td>CMAP</td>
<td>Compound muscle action potential</td>
</tr>
<tr>
<td>CSA</td>
<td>Cross sectional area</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>CTP</td>
<td>Carpal tunnel pressure</td>
</tr>
<tr>
<td>CTS</td>
<td>Carpal tunnel syndrome</td>
</tr>
<tr>
<td>DICOM</td>
<td>Digital imaging and communications in medicine</td>
</tr>
<tr>
<td>DML</td>
<td>Distal motor latency</td>
</tr>
<tr>
<td>DSL</td>
<td>Distal sensory latency</td>
</tr>
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<td>EMG</td>
<td>Electromyography</td>
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<td>Extension</td>
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<td>Flex</td>
<td>Flexion</td>
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<tr>
<td>GIMP</td>
<td>GNU image manipulation program</td>
</tr>
<tr>
<td>LE/F</td>
<td>Left extension/flexion</td>
</tr>
<tr>
<td>LR/U</td>
<td>Left radial/ulnar deviation</td>
</tr>
<tr>
<td>MATLAB</td>
<td>Matrix laboratory</td>
</tr>
<tr>
<td>MCP</td>
<td>Metacarpophalangeal</td>
</tr>
<tr>
<td>MCV</td>
<td>Motor conduction velocity</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic resonance imaging</td>
</tr>
<tr>
<td>MSDs</td>
<td>Musculoskeletal disorders</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>NCS</td>
<td>Nerve conduction studies</td>
</tr>
<tr>
<td>NPV</td>
<td>Negative predictive value</td>
</tr>
<tr>
<td>NVCT</td>
<td>Nerve volume of the segment immediately proximal to the carpal tunnel</td>
</tr>
<tr>
<td>NVP1</td>
<td>Nerve volume of the segment immediately proximal to NVCT</td>
</tr>
<tr>
<td>NVP2</td>
<td>Nerve volume of the segment immediately proximal to NVP1</td>
</tr>
<tr>
<td>NVP3</td>
<td>Nerve volume of the segment immediately proximal to NVP2</td>
</tr>
<tr>
<td>PPV</td>
<td>Positive predictive value</td>
</tr>
<tr>
<td>Rad</td>
<td>Radial deviation</td>
</tr>
<tr>
<td>RE/F</td>
<td>Right extension/flexion</td>
</tr>
<tr>
<td>RR/U</td>
<td>Right radial/ulnar deviation</td>
</tr>
<tr>
<td>SCV</td>
<td>Sensory conduction velocity</td>
</tr>
<tr>
<td>Sens</td>
<td>Sensitivity</td>
</tr>
<tr>
<td>SNAP</td>
<td>Sensory nerve action potential</td>
</tr>
<tr>
<td>Spec</td>
<td>Specificity</td>
</tr>
<tr>
<td>SPSS</td>
<td>Statistical package for the social sciences</td>
</tr>
<tr>
<td>T</td>
<td>Trained</td>
</tr>
<tr>
<td>TMM</td>
<td>Tissue mimicking material</td>
</tr>
<tr>
<td>U</td>
<td>Untrained</td>
</tr>
</tbody>
</table>
Chapter I

Introduction
Chapter I Introduction

1.0 Introduction

Musculoskeletal disorders (MSDs) are widespread throughout the general population and are a cause of discomfort for the sufferer. These afflictions impact on the body’s muscles, joints, tendons, ligaments, cartilage, bursae and nerves. This encompasses all upper limb neuropathies, of which the most common is carpal tunnel syndrome (CTS). MSDs are commonly occupation related and are a leading type of work related injury. A substantial percentage of these injuries are directly contributed to CTS. Among the activities which have been related to the onset of this condition is computer use. This is due to the numerous repetitive activities that are undertaken during a typing or data inputting task. These tasks can be further broken down into singular aspects that incorporate finger tip forces, speed and wrist posture. Each of these variables has been shown to affect the carpal tunnel or its contents, which in most cases results in an increase in carpal tunnel pressure (CTP). An increase in pressure will inevitably damage the median nerve, if it is substantial enough or over a great enough period of time, resulting in CTS. However, a definitive connection between CTS development and computer use remains elusive.

Although it is necessary to determine and understand the factors that initiate CTS development, correct diagnosis of this condition is also essential. Clinical and electrodiagnostic means are currently the most common and successful methods of confirming CTS, with a majority of cases requiring a positive diagnosis from both modalities prior to surgical intervention being undertaken. However, not all cases are evident using these methods. A number of cases can be overlooked due to such things as condition severity and symptom duration. False positives may equally be obtained which could result in unnecessary or incorrect treatment being recommended. Patients suffering from CTS often experience discomfort during diagnosis. This is most common during electrodiagnostic examination where stimulation of the nerve is required to obtain a corresponding reaction or response. It is due to these drawbacks that alternative diagnostic means have been investigated. One of the most common of these is sonography.
Sonography is an imaging technique used to define the outline of blood vessels, tendons, muscle and nerves to name but a few. It has the capability of displaying real time images of the specified area, allowing for the subcutaneous results of movements to be illustrated. In terms of diagnosing CTS, it has experienced varied success utilizing numerous diagnostic criteria. Although a number of studies have indicated high sensitivity and specificity using certain methods and measures, a mutual agreement on the most suitable conditions has not been reached. This has led to sonography being overlooked as a viable diagnostic method for CTS on a larger scale. However, the potential for this method is undisputable as it is not just capable of diagnosing the condition but also indicating the anatomical changes that have occurred.

Sonography can be used to diagnose CTS by taking measurements, such as median nerve flattening ratio or median nerve area, within the carpal tunnel. These criteria have been the most successful for indicating CTS. However, cut off values to indicate this condition vary between the populations tested. This results in the need for a new criterion that can transcend these shortcomings. This criterion should be capable of accounting for subject variations including body mass index (BMI) and wrist size.

Another area that must be accounted for is the dependence upon user skill and technique. To get an accurate undeformed image, it is necessary for the angle of the ultrasound transducer to be accounted for and a minimal amount of contact force to be applied to the measuring site. Transducer angle can increase or decrease the visible cross sectional area at the region of interest while an application of force will deform or compress the soft tissue in that area. Even though it is vital to account for these variables in 2-D measurements, it is also essential in the creation of 3-D models from a number of B-scans. This is particularly applicable to the carpal tunnel and the median nerve due to their superficial locations. These variables could highly impact measurement values taken for CTS diagnosis. However, the extent of this impact at the location of the carpal tunnel has not previously been investigated.

The wrist postures frequented and the effect of wrist posture on CTP in one plane of motion has previously been investigated. However, this has not been extended to include postures of extension/flexion and simultaneous radial/ulnar deviation. The first section of this study aims to account for these postures and subsequent impact on CTP
by electrodiagnostic means. The subsequent sections of this investigation focus upon the use of an alternative diagnostic tool to electrodiagnostic testing for CTS and a novel criterion which could be applied.

The literature review presented in Chapter II focuses on CTS and the activities that can increase CTP. The most common diagnostic methods for determining CTS and this increase in CTP are also reviewed. This includes a detailed analysis of the uses of sonography in this area. The main objectives of this study are stated in the conclusion of this section.

Chapter III shows the findings of a motion analysis study to determine the most common wrist positions frequented during a computer task. This included positions in one plane of motion and the combination of motion in two planes. This led to a representation of wrist posture during a sample computer activity.

The study in Chapter IV deals with the impact of these postures on median nerve conduction values. This involved recording compound muscle action potential (CMAP) data and monitoring the changes that occurred to these values over an extended period. This gives an indication of the CTP within the carpal tunnel and how it affects nerve functionality.

Chapter V concentrates on the methods used and the results seen for a novel diagnostic criterion. This encompasses a comparison noted between the new criterion and nerve conduction values. A determination on the usefulness of this novel criterion and the method used to obtain it is also discussed.

The influence of transducer force on the median nerve is stated in Chapter VI. This section investigated how force could influence the current criteria which are used to confirm CTS in patients. The level of force which is required to alter these values to a significant level is also examined.

The final chapters of this thesis are comprised of the discussion, conclusions and future work of this project. This includes the benefits and limitations of this research and methods which would lead to further advancements in this area.
Chapter II

Literature Review
2.0 Literature Review

2.1 Introduction

Upper limb neuropathies are extremely common among the working population and individuals with existing medical conditions such as inflammatory arthritis and thyroid disorders. They are caused by mechanical dynamic compression of a short segment of an individual nerve at a specific site. This is often evident as the nerve passes through a fibro-osseous tunnel, or an opening in fibrous or muscular tissue [1]. The most prevalent of these is carpal tunnel syndrome (CTS) [2, 3]. This is induced by an increase in pressure placed on the median nerve within the carpal tunnel.

Wrist movement and position have previously been shown to increase carpal tunnel pressure (CTP) to greater values than those seen in the neutral position [4, 5]. This occurs in patients with CTS and also in healthy subjects. However, the values obtained vary from study to study. This may be due to the test protocols or testing conditions employed, making it difficult to determine a conclusive wrist position which leads to the development of CTS. However, establishing such a wrist position would lead to the limits of safe wrist movement being ascertained. Although pressure change due solely to wrist motion has been investigated, it is also necessary for the activities undertaken in these positions to be accounted for.

One of the most common activities involving abnormal wrist posture is computer use. It involves movement of the wrist from the neutral position and an application of pressure on the palms and fingers. The accumulated effect of these actions has been shown to increase CTP to a greater extent than any individual activity [6]. If these activities increase the pressure within the carpal tunnel to above the pressure threshold of 30 mmHg (≈4 kPa) stated by Lundborg et al. (1983) [7] and Keir et al. (2007) [8], the median nerve may become damaged. If this occurs over an extended period of time, it is likely that the symptoms of CTS will develop. However, there has been much debate as to whether computer use causes CTS or simply exacerbates its symptoms.
Chapter II Literature Review

The most widely used method for confirming CTS is electrodiagnostic testing. This method is considered the gold standard in diagnosing CTS and has also shown promise in grading the severity of this condition [9, 10]. Changes in electrodiagnostic results can occur due to nerve demyelination, stretching, crushing and an increase in pressure on the median nerve. This pressure increase can be caused by chronic conditions, such as CTS, or acute disorders. However, wrist posture alone has also led to impairment of nerve function as indicated by electrodiagnostic testing [11]. This demonstrates the versatility of this method in determining significant pressure changes within the carpal tunnel. Even though this method is the foremost procedure for establishing the presence of CTS, false positives and false negatives are common [12, 13]. This has led to alternative diagnostic methods being investigated.

Electrodiagnostic testing, clinical evaluation and radiographic imaging have all been investigated and used for diagnosing CTS. Each method has advantages in comparison to the others. However, the reliability of these methods can be seen to differ from study to study. One area which has been focused on as a diagnostic tool is sonography. This technique has shown promise in determining the presence of CTS, but an agreement on the specific criteria for defining its presence is required. However, the benefit of sonography as a diagnostic application or an application of a similar premise is evident [14-16]. Clear distinctions in the anatomical structures of the carpal tunnel are apparent between healthy subjects and those with CTS. Sonography can identify these variations and may also be capable of defining the severity of the condition [17, 18].

Although sonography has the potential to become a prominent diagnostic tool for the detection of CTS, the technique applied can be highly user dependent. This is most evident using the freehand ultrasound method. This is conducted by a clinician manually guiding the ultrasound transducer over the area of interest, resulting in a sonographic image being captured. However, this image may not give a true indication of the anatomical state of the area. This is due to the orientation of the transducer and also the necessary contact force that is applied between the transducer and skin to get a clear image [19]. These variables would also have a large impact on the creation of 3-D models. The range of forces and image planes would lead to misalignments between a succession of sonographic scans if not accounted for. To do this, the influence and effects of such variables must first be understood.
2.2 Carpal Tunnel Syndrome

The carpal tunnel is a narrow passageway that is made up on three sides by the carpal bones and on the palmar side by the flexor retinaculum or transverse carpal ligament. Within the tunnel lie nine flexor tendons and the median nerve which is usually located at the anterior of the hand against the flexor retinaculum (Figure 2.1). The median nerve innervates the majority of the flexors of the forearm and the thenar and lumbrical muscles in the hand. It also controls sensation to the thumb, index, long and one-half of the ring finger. Due to the composition and sensitivity of the nerve, it is the most likely component in the carpal tunnel to adversely suffer from an increase of pressure within the tunnel. This increase in pressure on the median nerve is known as CTS.

![Figure 2.1](image-url)  
**Figure 2.1** Anatomy of the carpal tunnel (Britannica Online Encyclopedia) [20].

The pressure increase that induces CTS can be as a result of an increase in the volume of the carpal tunnel components or a decrease in the size of the tunnel. These anatomical changes are due to such things as edema, muscle hypertrophy and bone malalignment. Although the aetiology of CTS may be multifactorial, it often occurs in people suffering from diabetes or rheumatoid arthritis, pregnant women or those
performing highly repetitive tasks [2, 3, 21]. However, numerous types of activities have been shown to increase CTP [22-24]. The activities involving repetitive movements are most commonly linked to the development of CTS [25, 26], but static positioning of the wrist can also increase CTP to levels great enough to cause median nerve damage [24, 27].

The prevalence of CTS in the general population has been shown to be quite large [21, 28]. However, a substantial number of cases have been associated with particular types of occupation. This is indicated in surveys carried out in the United States by the Bureau of Labour Statistics [29] that determined the majority of cases occurred in the manufacturing and service providing industries. The total number of CTS cases in private industry led to an annual average of 26,972 cases involving days away from work between the years 1992 and 2006 inclusive. Since CTS is attributed with one of the largest number of median days away from work (≈29), it is a leading reason for work absenteeism in the United States. This has led to numerous studies being conducted to determine the contributing factors involved in the development of CTS. Many of these investigations have focused on the areas of wrist posture and computer use. However, a conclusive verdict on the major contributing factor of CTS has not yet been determined.

### 2.3 Carpal Tunnel Pressure

The median nerve can be subjected to both hydrostatic and contact pressure within the carpal tunnel. Changes in these pressures can have a large impact on the development and severity of CTS. These pressures can vary due to motion of the wrist and placement of external forces on the hand, wrist or fingers [8, 22, 30]. For the majority of the time, the pressure generated within the tunnel is not great enough to damage the median nerve. This is because the hand is often left in a relatively neutral position. The mean CTP generated while the hand is in a neutral position varies from study to study. However, none of the values recorded in healthy subjects, exceeds the CTP threshold of 30 mmHg used by Keir et al. (2007) [7, 8]. This is considered a suitable CTP threshold as decreased blood flow occurs at 20 and 30 mmHg with an impairment of nutrient transport to the nerve axon evident at 30 mmHg [7, 31]. Initially, intraneurial edema and ultimately, axonal degeneration and demyelination will also be evident at this
pressure [32]. The position associated with the lowest CTP was determined by Weiss et al. (1997) [33]. This study found a position of 2±9 degrees of flexion and 2±6 degrees of ulnar deviation led to a CTP of only 8±4 mmHg (1.07±0.53 kPa). These results are supported by Werner et al. (1997) [34] who considers the neutral position to lie between 0±20° of flexion or extension and 0±10° of radial or ulnar deviation. However, the large standard deviation and range in the studies by Weiss et al. (1997) [33] and Werner et al. (1997) [34], indicate that the wrist position with the lowest CTP is largely subject dependent.

The CTPs of CTS patients have also been recorded and have been found to be greater than those of healthy subjects (Table 2.1). While the hand is in the neutral position, CTPs as high as 43.8 mmHg have been recorded [24]. This can be quite severe as constant pressures of 30 mmHg and above have been shown to significantly reduce nerve functionality [35-38]. This is evident for pressures applied for a maximum of 6 hours or until nerve conduction block was reached by Szabo and Sharkey (1993) [38] and for up to 14 hours by Hargens et al. (1979) [37]. Diao et al. (2005) [35] maintained a constant pressure until a change in conduction velocity of 15% or greater was evident for two consecutive weeks. These studies found that the constant application of pressure inevitably led to axonal degeneration and demyelination of the nerve fibres. Greater nerve deterioration was noted with increased pressure and duration. A reduction in nerve functionality was also seen at the time of testing as pressure and duration were increased.

2.4 Wrist Posture

Numerous studies have measured the effects of extension, flexion, radial deviation and ulnar deviation of the wrist on CTP [6, 8, 23, 27, 33, 34, 39, 40]. In general, these studies have indicated that movement of the wrist from a resting position or an angle of 0° flexion/extension and radial/ulnar deviation (neutral position) results in an increase in CTP. Subjects suffering from CTS can once again be seen to have higher CTPs than healthy subjects for all wrist positions investigated. Although the pressure increase placed on the median nerve subsides on return of the wrist to the neutral position, the elevated pressure is maintained for a longer period of time in patients with CTS [5]. As seen in Table 2.1, these pressures are often greater than 30 mmHg. This is, therefore,
detrimental for peripheral nerves as chronic compression of nerves has been shown to cause pathological changes due to the development of edema, demyelination and axonal degeneration [41-43]. These pathological changes have been shown to occur to nerves which have been compressed for a prolonged period of time (up to 15 weeks) and also to nerves compressed for a relatively shorter duration [32, 44] resulting in the onset of numbness, pain and a reduction in nerve functionality [37].

### 2.4.1 Extension/Flexion

The greatest CTP seen due to wrist motion can be noted at the end range of motion for flexion and extension. Studies by Gelberman et al. (1981), Okutsu et al. (1989), Seradge et al. (1995) and Sanz et al. (2005) [24, 27, 39, 45] recorded the effects of maximum passive wrist motion on healthy subjects with the results from each study varying greatly. Sanz et al. found that the CTP of healthy subjects was as low as 14 and 16 mmHg in maximum flexion and extension respectively. These values are clearly below that of the threshold value and would not damage the nerve. However, alternative studies have seen these results rise as high as 143.9±65.76 and 157.8±65.22 mmHg [27]. This is a large variation and indicates a substantial variance in CTPs among the general population. A similar trend can also be seen for the maximum flexion and extension values obtained for CTS sufferers. Rojviroj et al. (1990) [46] and Sanz et al. (2005) [39] indicate that CTP values are relatively low and can even be at levels just below the CTP threshold (26.6±2.53 mmHg) [46]. These pressures are once again seen to increase dramatically in alternative studies where values ranging from 94±20 to 222.4±44.19 mmHg have been noted for flexion and extension [24, 27, 45].

Although maximal extension and flexion have been discussed previously, numerous investigators have only measured the CTP of the wrist at certain levels of extension/flexion or radial/ulnar deviation. Nakao et al. (1998) [47] measured the CTP of six cadavers at a position of 35° flexion and extension. In both postures an increase in the CTP in relation to the neutral position was noted. Similar findings were observed in studies by Keir et al. (1997) [48], Luchetti et al. (1998) [23], and Rempel et al. (1997) [49]. These studies recorded the CTP of wrist positions at 45° flexion and extension. In each of these investigations the CTP was also noted to be substantially higher at the point of maximal range of motion.
2.4.2 Radial/Ulnar Deviation

The effects of radial/ulnar deviation on the CTP of healthy subjects were also recorded in studies by Rempel et al. (1997) [49], Keir et al. (1997) [48], Werner et al. (1997) [34], Keir et al. (1998) [50] and Keir et al. (2007) [8]. These found that movement of the wrist away from either a neutral position or a position of 10° ulnar deviation resulted in increases in CTP, with the greatest values being 30.8 mmHg and 40.9 mmHg seen at 20° radial and 30° ulnar deviation respectively [50]. Although these values are greater than the CTP threshold, this was not the case in all studies. Results from Keir et al. (1997) [48] indicated that pressures did not exceed 20 mmHg for an equivalent set of wrist positions tested. These low CTP values are also indicated by Werner et al. (1997) [34] where a mean value of 15.2 mmHg was not exceeded for either radial or ulnar deviation.
Table 2.1  Mean CTPs and standard deviations of CTS patients and control subjects while the wrist is in neutral or maximum deviation in various positions. Values are given in mmHg.

<table>
<thead>
<tr>
<th>Study</th>
<th>No. of wrists</th>
<th>CTS Patients</th>
<th>Control Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Neutral Flex. Ext. Ulnar Radial</td>
<td>No. of wrists</td>
</tr>
<tr>
<td>Gelberman et al. (1981) [45]</td>
<td>15</td>
<td>32.0 (3.8) 94.0 (20.0) 110.0 (22.0)</td>
<td>12</td>
</tr>
<tr>
<td>Okutsu et al. (1989) [27]</td>
<td>62</td>
<td>43.0 (17.2) 191.9 (63.9) 222.4 (44.2)</td>
<td>16</td>
</tr>
<tr>
<td>Rojviroj et al. (1990) [46]</td>
<td>61</td>
<td>11.9 (12.2) 26.6 (19.8) 32.8 (25.1)</td>
<td>32</td>
</tr>
<tr>
<td>Seradge et al. (1995) [24]</td>
<td>102</td>
<td>43.8 (32.7) 98.0 (68.8) 119.4 (74.7)</td>
<td>21</td>
</tr>
<tr>
<td>Schuind et al. (2002) [51]</td>
<td>20</td>
<td>20.7 (20.7) 54.0 (68.4) 92.3 (51.7)</td>
<td>-</td>
</tr>
<tr>
<td>Sanz et al. (2005) [39]</td>
<td>103</td>
<td>23.0 (U) 38.0 (U) 59 (U)</td>
<td>25</td>
</tr>
<tr>
<td>Average</td>
<td>61</td>
<td>29.1 (U) 83.8 (U) 106.0 (U)</td>
<td>21</td>
</tr>
</tbody>
</table>

Note: Flex. and Ext. refer to flexion and extension respectively and (U) refers to unknown standard deviations.


2.5 Computer Use

Computer use has commonly been linked to the development of CTS. However, a consensus on computer use causing CTS has not been reached. A number of studies have stated that no relationship is evident [52, 53]. However, the studies that have reported a connection have generally been investigated from the viewpoints of wrist posture during keyboard use, typing and mouse usage. These areas have been looked at individually to conclude if any one aspect can lead to a substantial increase in CTP. If this is the case a direct link between CTS and computer use could be established. Knowing the actions that increase CTP to harmful levels will also lead to the correct preventative measures being employed.

2.5.1 Keyboard Usage

To the authors knowledge the resultant CTP of wrist postures generated during keyboard use have been directly measured in only one study [6]. However, the actual position of the wrist during keyboard use has often been recorded. The mean values found from previous studies for right extension/flexion, left extension/flexion, right radial/ulnar deviation and left radial/ulnar deviation using a conventional keyboard can be seen in Table 2.2. These results are further corroborated by Tittiranonda et al. (1999) [54] who found that the largest percentage of typing time was spent in an extension of 21-30° and an ulnar deviation of 11-20°. However, it is also worth noting that positions between 41-50° extension and 31-40° ulnar deviation were also frequented during typing [54]. By comparing these studies to those investigating CTP due to wrist posture, an indication of which typing postures lead to damaging CTPs can be established. The average positions of 15.3° extension and 13.9° ulnar deviation calculated from the mean wrist positions of previous studies result in a CTP that does not exceed 18.5 mmHg in healthy subjects [6, 49]. This is well below the CTP threshold. Values exceeding this threshold were not evident until positions of 40° extension or 30° ulnar deviation were reached [8]. Although these positions are attained during a typing task, it may not occur regularly enough for nerve damage to arise.
### Table 2.2

Mean wrist angles and standard deviations for right extension/flexion (RE/F), left extension/flexion (LE/F), right radial/ulnar deviation (RR/U) and left radial/ulnar deviation (LR/U) during computer use.

<table>
<thead>
<tr>
<th>Study</th>
<th>No. of Subjects</th>
<th>RE/F (Degrees)</th>
<th>LE/F (Degrees)</th>
<th>RR/U (Degrees)</th>
<th>LR/U (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cook et al. (2004a) [55]</td>
<td>13</td>
<td>-1.4 (5.8)(^1)</td>
<td>-0.7 (9.0)(^1)</td>
<td>14.8 (5.6)</td>
<td>13.6 (5.3)</td>
</tr>
<tr>
<td>Cook et al. (2004b) [56]</td>
<td>15</td>
<td>25.7 (12.2)</td>
<td>22.5 (13.5)</td>
<td>3.0 (7.9)</td>
<td>22.5 (7.9)</td>
</tr>
<tr>
<td>Fagarasamu et al. (2005) [57]</td>
<td>30</td>
<td>21.7 (5.8)</td>
<td>22.2 (5.3)</td>
<td>16.7 (4.0)</td>
<td>15.9 (2.8)</td>
</tr>
<tr>
<td>Rempel et al. (2007) [58]</td>
<td>100</td>
<td>13.1 (11.0)</td>
<td>12.8 (11.6)</td>
<td>15.2 (9.5)</td>
<td>16.3 (10.7)</td>
</tr>
<tr>
<td>Serina et al. (1999) [59]</td>
<td>25</td>
<td>19.9 (8.6)</td>
<td>23.4 (10.9)</td>
<td>18.6 (5.8)</td>
<td>14.7 (10.1)</td>
</tr>
<tr>
<td>Simoneau et al. (2003) [60]</td>
<td>15</td>
<td>12.2 (6.9)</td>
<td>12.8 (7.9)</td>
<td>9.1 (6.6)</td>
<td>12.7 (5.6)</td>
</tr>
<tr>
<td>Straker et al. (2008) [61]</td>
<td>36</td>
<td>13.9 (0.5)</td>
<td>16.5 (2.4)</td>
<td>14.5 (2.9)</td>
<td>7.5 (2.4)</td>
</tr>
<tr>
<td><strong>Average(^2)</strong></td>
<td><strong>33</strong></td>
<td><strong>15.0 (8.8)</strong></td>
<td><strong>15.6 (8.5)</strong></td>
<td><strong>13.1 (5.3)</strong></td>
<td><strong>14.7 (4.5)</strong></td>
</tr>
</tbody>
</table>

1. Negative values denote flexion or radial deviation.
2. The standard deviation for the average values was calculated from the mean values indicated for each study.
Although keyboard posture in one plane of motion increases CTP, it is unlikely that it will increase it significantly enough to cause CTS. However, the addition of typing to any wrist posture, further increases the CTP [6]. This is due to an increase in fingertip force while performing this task. Studies by Feuerstein et al. (1997) [62] and Rempel et al. (1994) [63] found the mean keyboard and fingertip forces to be within the range of 1.6-5.3 N. This value rises to above 6.5 N in a study by Szeto et al. (2005) [64]. This is significant, as fingertip forces of 6 N and greater on the index finger have been shown to increase the CTP to levels above the threshold CTP in an array of wrist postures, including the neutral position [49]. Pressures are also seen to increase with greater applications of force [22, 49] indicating that more vigorous typists would be at a greater risk of CTS development.

### 2.5.2 Mouse Usage

Mouse usage can also be related to an increase in CTP. This is principally due to the hand position and activity involved in using this hardware. Cobb et al. (1995) [30] showed that externally applied forces placed on the proximal aspect of the hand yield a large increase in CTP. Mouse usage may apply a similar force depending on the hand position of the user on the mouse. The wrist posture generated while using this device will also increase CTP as wrist positions are often found to be more extreme than during keyboard use, with mean extensions of 23.1° and 36.2° being recorded [40, 56]. The effect of ulnar deviation of the wrist varies far greater, with positions of -3.2° to 20° found, but this is largely dependent upon mouse location relative to the user. As stated previously, positions below 40° extension or 30° ulnar deviation will not induce a damaging CTP. Therefore, wrist posture during mouse usage alone does not generate a high enough CTP. However, as seen with keyboard use, the CTP can be further increased with the addition of mouse activity. Keir et al. (1999) [40] determined that a dragging and pointing task increased the CTP to above or close to the threshold level, across a range of mice. The values recorded for these activities are significantly greater than those seen for statically placing the hand upon the mouse.
2.6 Electrodiagnostic Testing

Electrodiagnostic testing is a non or minimally invasive method for determining loss of functionality or damage to muscles or nerves. The two most commonly used aspects of electrodiagnostic testing are electromyography (EMG) and nerve conduction studies (NCS). These two tests are often performed during a single examination to define the cause and extent of nerve or muscle damage.

EMG evaluates the functionality of the muscle by recording the electrical signal produced during muscle activation. This activation occurs due to a neuronal action potential supplied to the relevant muscles by a motor neuron. It is measured by either placing surface electrodes on or inserting a needle electrode into the required muscle. The surface electrodes are used to avoid any invasive procedure but only give a general indication of muscle activation. In contrast, needle electrodes give a localised indication of muscle activation requiring numerous samples to be taken before a clear image of functionality is obtained. A subject’s voluntary contraction of the muscle, in a controlled manner, is sufficient to register the require readings.

The efficiency of motor and sensory nerves at transmitting electrical signals within the body is regularly measured using NCS. Similar to EMG, this method may also be recorded by needle or surface electrodes. However, the limited amount of information obtained from a needle electrode makes it most suitable for cases with severe muscle wasting or deep muscle not suitable for surface electrodes [65]. NCS are performed by placing recording electrodes over the nerve or muscle for sensory or motor nerve conduction studies respectfully. The nerve is then stimulated by a stimulation bar or rod and the resultant response recorded. This leads to readings such as sensory nerve action potential (SNAP) data, compound muscle action potential (CMAP) data and F-wave data being recorded. With regard to the diagnosis of CTS, NCS is one of the most frequently used tools to confirm its presence.

2.6.1 The Impact of Nerve Compression on the Neuron and NCS

Acute and chronic nerve compressions have been shown to result in pathological changes to the median nerve [37, 42, 66, 67]. These changes largely affect the axons
and myelin sheaths of the neurons. The axons are long protrusions of nerve cells that conduct electrical impulses to other nerve cells or to effector organs from the terminal end of the axon. Myelin sheaths are electrically insulating layers that surround the neurons and allow for a rapid conduction of impulses from one nerve cell to the next (Figure 2.2). The compression endured by the nerve results in axonal loss and demyelination. This is inferred from the NCS results [12, 37, 68]. For motor NCS, axonal loss will result in smaller CMAP amplitude due to less functioning motor axons being connected to muscle fibres. As further motor axon loss occurs, it can be noticed that the distal motor latency can be prolonged by up to 120% the normal limit while conduction velocity can be reduced to 80% of the normal limit. During demyelination nerve conduction is slowed or in some cases completely blocked. However, the effects of demyelination depend greatly on the location and extent of myelin loss. The effects of demyelination can be observed by a reduction in CMAP amplitude or by abnormal F-waves. For sensory NCS, axonal loss and demyelination will both produce a smaller SNAP amplitude. However, a prolonged duration is also noticed with demyelination [65].

![Figure 2.2 Anatomy of a neuron [69].](image)
2.6.2 Wrist Temperature

External factors, such as temperature, have a large influence on the results of NCS [70-72]. This is clearly displayed in a study by Ashworth et al. (1998). This study found changes in sensory and motor nerve conduction parameters of CTS patients due to temperature change. It also noted clear differences between the rate of change of conduction parameters for the “diseased” median nerve and the control values obtained from the “normal” ulnar nerve. This indicates that nerves suffering from compression disorders react differently to temperature change than healthy nerves. Malik and Weir (2005) [65] also state changes occur to nerve conduction parameters due to temperature change with the fastest motor nerve conduction velocity being reduced by approximately 1 m/s per °C temperature fall. To combat variations such as these, conversion factors have been suggested to normalise the results [71, 73]. However, these factors were often calculated using the effects of temperature on healthy subjects and may not be suited for clinical studies [70]. If both control and patient groups were used to calculate conversion factors inapplicable data could still be attained. Variations between and within control and patient groups would have a large bearing on the conversion factor as numerous features, such as weight, sex and age, have been shown to influence NCS [74-76]. For these reasons it is recommended that temperature is monitored throughout testing and conversion factors not be used [77, 78]. For accurate and comparative readings to be obtained, it would be necessary to normalise testing temperature throughout a study.

2.6.3 NCS for Diagnosing CTS

The effectiveness of NCS for the evaluation of median nerve entrapment neuropathies at the wrist is a topic of some debate. Studies carried out by Mondelli et al. (2008) [79], Atrosi et al. (2003) [12] and El Miedany et al. (2004) [13] indicate the usefulness of NCS in determining the presence of disorders such as CTS. This is taken a step further by Ogura et al. (2003) [9], Wilder-Smith et al. (2008) [10] and Havton et al. (2007) [80] who state that NCS can be used as a method of grading the severity of this condition. Ogura et al. (2003) carried out testing on 37 subjects suffering from CTS to determine if a correlation between CTS and NCS could be established. To do this, CTS was clinically graded into three categories: mild, moderate and severe. It was determined
from the results that CMAP and SNAP amplitudes were sufficient for grading the severity of CTS. This investigation showed that SNAP was the preferred option due to the more linear relationship found between clinical grading and SNAP. The usefulness of NCS is further emphasized by Wilder-Smith et al. (2008) and Havton et al. (2007). However, in these instances it was determined that motor electrophysiological parameters of the median nerve were more suitable for grading CTS severity. Wilder-Smith et al. (2008) concluded that distal motor latency (DML), CMAP amplitude and median motor conduction velocity (MCV) are all good indicators of median nerve damage severity. A linear relationship was also evident when these motor electrophysiological parameters were compared to the data collated from clinical findings. In the study by Havton et al. (2007), a positive correlation between median MCV and CMAP amplitude and a negative correlation between median MCV and DML was found.

Although numerous studies have indicated the advantages of NCS, there are also problems associated with this method. It is possible for false positives and false negatives to occur [12, 79] and for patients with CTS not to exhibit any indications of the disorder during examination. However, these flaws are relatively small with the number patients showing no signs of the condition shown to be minimal in comparison to those confirmed to suffer from CTS [13]. Even with these failings, NCS is considered the most appropriate method of confirming CTS and is the gold standard of CTS diagnosis which all other diagnostic methods are compared to.

As previously discussed, NCS are commonly used in the diagnosis of CTS. However, the usefulness of the method, with respect to the carpal tunnel, does not end at CTS diagnosis. Chowet et al. (2004) [11] found that nerve function measured by NCS was significantly reduced due to wrist hyperextension and that nerve conduction block was exhibited in 83% of the subjects tested after 60 minutes. This indicates that CTP is increased to levels great enough to alter NCS due to wrist posture alone. Although carpal tunnel pressure was not recorded during this study, the effect on NCS express a CTP increase. This would be expected as the impact of wrist posture on CTP has previously been discussed in section 2.4. This is further verified in studies by Hargens et al. (1979) [37], Szabo and Sharkey (1993) [38] and Stecker et al. (2008) [68] which indicate the effect of a pressure increase on the nerve conduction result.
2.7 Sonographic Diagnostic Criteria

NCS is by far the most common method for confirming CTS. This is often carried out following a clinical diagnosis that indicates its presence. This condition has been shown to have a prevalence of 2.7% in the general population, when confirmed by clinical and electrodiagnostic means together. This figure rises to 3.8% when solely using physical signs and 14.4% when only considering CTS related symptoms [28]. Since CTS is not always detected with NCS, alternative diagnostic methods have been investigated. Radiologic imaging has previously been used to assess CTS [81-84]. This includes the use of computed tomography, magnetic resonance imaging and sonography. These methods may be used to determine the physical changes that occur to the carpal tunnel and its contents.

The imaging tool that has a great deal of promise in this area is sonography. This method is capable of obtaining a detailed display of the carpal tunnel anatomy [85, 86] and is considered a beneficial diagnostic tool for CTS [87, 88]. Changes to the median nerve area, flattening ratio and swelling ratio have commonly been associated with the development of CTS [89-91]. However, the diagnostic criteria that indicate the presence of CTS vary from study to study. To understand the reason for these variations and indicate the direction new techniques should aim, an in depth look at the previous criteria is necessary.

2.7.1 Median Nerve Cross Sectional Area

Numerous investigations have been carried out to determine the criteria that confirm the presence of CTS by means of sonography. These investigations have largely focused on median nerve area at various locations along the nerve and within the carpal tunnel. However, a consistent method or protocol of diagnosing CTS using sonographic area measurement has not yet been established. This can be first noticed in the positions that the cross-sectional images are taken. Some studies determine the level to measure cross-sectional areas (CSAs) of the median nerve by means of anatomical landmarks. This is generally carried out at three distinct locations: the radioulnar articulation (proximal level), pisiform bone (intermediate level) and hook of hamate (distal level) [89, 91-96]. However, other studies use the tunnel inlet and outlet, found by
sonographic means [15, 79, 97, 98]. External landmarks, such as the distal wrist crease, have also been used as locations where CSAs have been measured [15, 90, 99]. Although, these points are in similar locations, a direct comparison between results cannot be made. Agreement of anatomical landmarks in relation to carpal tunnel location is also not unanimous. Colak et al. (2007) [99] and Nakamichi and Tachibana (2002) [15] use the hook of hamate to define the mid carpal tunnel while other authors use this landmark to mark the outlet of the carpal tunnel [91, 94, 95]. However, this may be as a result of whether the image is taken at the proximal or distal aspect of the bone.

The method used to calculate the area of the nerve may contribute to variations in area being noted. The two methods that are commonly used to determine the CSA are the ellipse formula method and direct trace method. The ellipse formula method uses Equation 2.1, shown below, to calculate the area.

\[
\frac{\pi(d_1 \times d_2)}{4}
\]

Equation 2.1

In this instance, \(d_1\) and \(d_2\) are the lengths of the large and small diameters of the ellipse. The direct trace method is conducted by manually defining the circumference of the nerve by means of the sonographic equipment and the area being automatically calculated. Although both methods have been used to determine the area of the nerve, they result in different areas being obtained [89, 100]. Duncan et al. (1999) [97] determined that the direct tracing method had a greater diagnostic capability since the median nerve is not always elliptical in shape. Therefore, determining the presence of CTS due to area is dependent on the measuring technique used. This is also evident in a study by Sernik et al. (2008) [101] where a different CSA cut off point was selected for each method to indicate the presence of CTS. An alternative method which has been used for determining the area of the median nerve is the automated ellipse area measurement. This method can be employed on certain ultrasound machines and involves an ellipse being placed over the median nerve. The major and minor diameters of this ellipse are decided upon by the sonographer, in order for the best representation of the nerve to be portrayed. Although this would be expected to yield similar results to that of the formula method, distinct differences can once again be noticed [89].
The boundaries of the median nerve which are to be measured are a further source of variation between studies. In general, the area of the median nerve is calculated inside the hyperechoic rim (epineurium) [17, 92, 102, 103]. However, some studies include this rim in the area measurement [18, 95]. This would increase the area of the nerve measured and once again make a direct comparison between the results of these studies difficult. A comparison would also be problematic for studies that neglect to state the boundaries of the measured nerve [89, 91, 93] as the boundaries of the area measured are unknown.

The mean areas recorded for both CTS patients and healthy control subjects vary greatly from study to study (4.9-16.8 mm$^2$ for CTS patients and 4.8-11.5 mm$^2$ for healthy subjects). This is in part due to the reasons stated previously. However, when comparing the area of nerves measured at the same anatomical landmarks and in a similar manner, the range of results is decreased significantly (Table 2.3). The values for the CTS patients can also be seen to be greater than the controls at each image location throughout all studies. This is substantiated by the average values calculated from the studies. This indicates that an increase in area is evident due to the development of CTS. Variations between the recorded areas in each study are still noticeable. This may be due to the variations in severity of the CTS present. Several studies only included patients suffering from mild or moderate CTS [92], while others looked solely at subjects with CTS confirmed by NCS [93, 95]. The latter inclusion criterion may have led to patients with mild cases of CTS and normal NCS being excluded.
Table 2.3  Studies that calculated median nerve area and standard deviation for patients (Pat.) and controls (Cont.) at the radioulnar articulation, pisiform and hook of hamate by means of the direct trace and ellipse formula methods.

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>Altinok et al. (2004)</td>
<td>40 (40)</td>
<td>7.6 (1.6)</td>
<td>6.5 (1.2)</td>
<td>10.3 (2.4)</td>
<td>6.8 (1.5)</td>
<td>-</td>
<td>-</td>
<td>13.7 (4.0)</td>
<td>7.8 (2.0)</td>
<td>-</td>
<td>-</td>
<td>9.0 (2.0)</td>
<td>6.6 (1.4)</td>
<td></td>
</tr>
<tr>
<td>Bayrak et al. (2007)</td>
<td>41 (20)</td>
<td>-</td>
<td>-</td>
<td>10.4 (3.2)</td>
<td>7.3 (1.4)</td>
<td>-</td>
<td>-</td>
<td>14.5 (3.8)</td>
<td>8.1 (1.3)</td>
<td>-</td>
<td>-</td>
<td>15.5 (4.9)</td>
<td>8.3 (1.9)</td>
<td></td>
</tr>
<tr>
<td>Buchberger et al. (1992)</td>
<td>20 (28)</td>
<td>-</td>
<td>-</td>
<td>10.0 (2.0)</td>
<td>7.9 (1.1)</td>
<td>-</td>
<td>-</td>
<td>12.2 (4.5)</td>
<td>7.9 (2.5)</td>
<td>-</td>
<td>-</td>
<td>10.3 (2.5)</td>
<td>7.7 (1.1)</td>
<td></td>
</tr>
<tr>
<td>Kaymak et al. (2008)</td>
<td>34 (38)</td>
<td>12.5 (2.6)</td>
<td>10.6 (2.6)</td>
<td>15.6 (4.2)</td>
<td>11.5 (3.2)</td>
<td>-</td>
<td>-</td>
<td>12.2 (4.5)</td>
<td>7.9 (2.5)</td>
<td>-</td>
<td>-</td>
<td>13.3 (4.9)</td>
<td>8.6 (3.0)</td>
<td></td>
</tr>
<tr>
<td>Keles et al. (2005)</td>
<td>36 (40)</td>
<td>-</td>
<td>-</td>
<td>11.6 (4.2)</td>
<td>8.2 (2.6)</td>
<td>-</td>
<td>-</td>
<td>12.2 (4.5)</td>
<td>7.9 (2.5)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td>Koyuncuoglu et al. (2005)</td>
<td>319 (30)</td>
<td>-</td>
<td>-</td>
<td>8.8 (3.1)</td>
<td>7.6 (1.5)</td>
<td>8.5 (3.1)</td>
<td>7.7 (1.4)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
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<tr>
<td>Leonard et al. (2003)</td>
<td>20 (20)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11.6 (U)</td>
<td>7.8 (U)</td>
<td></td>
</tr>
<tr>
<td>Sarria et al. (2000)</td>
<td>64 (42)</td>
<td>-</td>
<td>-</td>
<td>13.2 (4.3)</td>
<td>10.4 (3.5)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11.1 (3.6)</td>
<td>-</td>
<td>-</td>
<td>14.2 (4.6)</td>
<td>10.8 (3.8)</td>
</tr>
<tr>
<td>Sernik et al. (2008)</td>
<td>103 (63)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15.1 (7.3)</td>
<td>8.1 (1.6)</td>
<td>14.8 (5.5)</td>
<td>8.0 (1.5)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Wang et al. (2008)</td>
<td>61 (40)</td>
<td>10.5 (4.7)</td>
<td>6.9 (1.3)</td>
<td>12.9 (4.2)</td>
<td>9.2 (1.8)</td>
<td>15.5 (9.9)</td>
<td>-</td>
<td>12.0 (3.7)</td>
<td>8.8 (1.7)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td>Yesildag et al. (2004)</td>
<td>148 (76)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>14.9 (4.7)</td>
<td>7.8 (1.6)</td>
<td>14.2 (4.2)</td>
<td>7.5 (1.8)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td>Average</td>
<td></td>
<td>10.2 (2.5)</td>
<td>8.0 (2.3)</td>
<td>11.3 (1.4)</td>
<td>8.4 (1.4)</td>
<td>12.9 (2.8)</td>
<td>8.5 (1.7)</td>
<td>13.1 (2.3)</td>
<td>8.2 (1.2)</td>
<td>8.5 (1.7)</td>
<td>7.7 (1.6)</td>
<td>13.3 (2.2)</td>
<td>8.9 (1.6)</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The standard deviation for the average area was calculated from the mean values indicated for each study and (U) denotes an unknown standard deviation.
Determining the diagnostic precision of sonographic area measurements of the median nerve is vital if implementation of this technique is to be considered for detecting CTS. This can be carried out by calculating the sensitivity (Sens.), specificity (Spec.), positive predictive value (PPV) and negative predictive value (NPV) within studies. The results of these will indicate the most suitable cut off value and location where area measurement should be taken. However, numerous variables are seen from study to study. To maintain continuity between studies, only those that implemented the direct trace method to calculate the median nerve area and considered the outer border of the nerve to be the inner boundary of the hyperechoic rim are accumulated in Table 2.4. These data show various standards of CTS identification, even when parameters remain similar. The sensitivity of the CSA at the level of the pisiform with a cut off value of >10 mm$^2$ is observed to vary from 52.5% to 85%. These contrasting results are echoed in other studies that use similar cut off values. Ideally the values for sensitivity and specificity would be close to 100% indicating good diagnostic capabilities. Although studies by Duncan et al. (1999) [97], Klauser et al. (2009) [103], Sernik et al. (2008) [101] and Yesiladg et al. (2004) [100] are close to a sensitivity and specificity of 100%, the remainder of the studies with low sensitivity and specificity cast doubt upon the capability and suitability of this technique.
Table 2.4 Sensitivity (Sens.), specificity (Spec.), positive predictive value (PPV) and negative predictive value (NPV) for cross sectional area (CSA) measurements to confirm the presence of CTS.

<table>
<thead>
<tr>
<th>Authors</th>
<th>No. of CTS Wrists (Controls)</th>
<th>CSA Location</th>
<th>CSA Cut Off Value</th>
<th>Sens. (%)</th>
<th>Spec. (%)</th>
<th>PPV (%)</th>
<th>NPV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altinok et al. (2004)</td>
<td>40 (40)</td>
<td>Pisiform</td>
<td>&gt;9 mm²</td>
<td>65</td>
<td>92.5</td>
<td>89.7</td>
<td>72.5</td>
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<tr>
<td></td>
<td></td>
<td>Pisiform</td>
<td>&gt;10 mm²</td>
<td>52.5</td>
<td>95</td>
<td>91.3</td>
<td>66.7</td>
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<td></td>
<td></td>
<td>Pisiform</td>
<td>&gt;11 mm²</td>
<td>30</td>
<td>95</td>
<td>85.7</td>
<td>57.6</td>
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<td>Duncan et al. (1999)</td>
<td>102 (68)</td>
<td>Pisiform</td>
<td>&gt;9 mm²</td>
<td>82.4</td>
<td>97.1</td>
<td>97.7</td>
<td>78.6</td>
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<td>Hobson-Webb et al. (2008)</td>
<td>44 (18)</td>
<td>Distal Wrist Crease</td>
<td>&gt;10 mm²</td>
<td>93.6</td>
<td>61.1</td>
<td>86.3</td>
<td>78.6</td>
</tr>
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<td>Klauser et al. (2009)</td>
<td>100 (93)</td>
<td>Max Nerve Shape Change</td>
<td>&gt;10 mm²</td>
<td>100</td>
<td>57</td>
<td>71.4</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max Nerve Shape Change</td>
<td>&gt;11 mm²</td>
<td>99</td>
<td>86</td>
<td>88.4</td>
<td>98.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max Nerve Shape Change</td>
<td>&gt;12 mm²</td>
<td>94</td>
<td>95</td>
<td>94.9</td>
<td>93.6</td>
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<td>Mondelli et al. (2008)</td>
<td>85 (28)</td>
<td>Proximal to CT Inlet</td>
<td>&gt;10.5 mm²</td>
<td>56.5</td>
<td>100</td>
<td>100</td>
<td>43.1</td>
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<td></td>
<td></td>
<td>Scaphoid Tubercle</td>
<td>&gt;12.2 mm²</td>
<td>29.4</td>
<td>100</td>
<td>100</td>
<td>31.8</td>
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<tr>
<td></td>
<td></td>
<td>Hook of Hamate</td>
<td>&gt;10.1 mm²</td>
<td>31</td>
<td>100</td>
<td>100</td>
<td>32.2</td>
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<tr>
<td></td>
<td></td>
<td>Abnormal at Any of the Three Locations</td>
<td>±2 SD of Controls</td>
<td>64.7</td>
<td>100</td>
<td>100</td>
<td>48.3</td>
</tr>
<tr>
<td>Nakamichi et al. (2002)</td>
<td>414 (408)</td>
<td>CT Outlet</td>
<td>&gt;13 mm²</td>
<td>57</td>
<td>97</td>
<td>96</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hook of Hamate</td>
<td>&gt;11 mm²</td>
<td>44</td>
<td>97</td>
<td>93</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distal Wrist Crease</td>
<td>&gt;14 mm²</td>
<td>43</td>
<td>96</td>
<td>91</td>
<td>62</td>
</tr>
<tr>
<td>Sernik et al. (2008)</td>
<td>40 (63)</td>
<td>Pisiform</td>
<td>&gt;10 mm²</td>
<td>85</td>
<td>92.1</td>
<td>87.2</td>
<td>90.6</td>
</tr>
<tr>
<td>Visser et al. (2007)</td>
<td>168 (137)</td>
<td>Distal Wrist Crease</td>
<td>&gt;10 mm²</td>
<td>78</td>
<td>91</td>
<td>91</td>
<td>77</td>
</tr>
<tr>
<td>Wong et al. (2002)</td>
<td>54 (70)</td>
<td>Proximal to CT Inlet</td>
<td>&gt;8.8 mm²</td>
<td>74</td>
<td>63</td>
<td>67</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CT Inlet</td>
<td>&gt;9.8 mm²</td>
<td>89</td>
<td>83</td>
<td>84</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CT Outlet</td>
<td>&gt;8.5 mm²</td>
<td>80</td>
<td>51</td>
<td>64</td>
<td>73</td>
</tr>
<tr>
<td>Yesiladg et al. (2004)</td>
<td>148 (76)</td>
<td>Pisiform</td>
<td>&gt;10.5 mm²</td>
<td>89.9</td>
<td>94.7</td>
<td>97.1</td>
<td>82.7</td>
</tr>
</tbody>
</table>
2.7.2 Median Nerve Flattening Ratio

The median nerve flattening ratio has also been measured in numerous studies and has often been considered a good diagnostic criteria for the presence of CTS using sonography [13, 93]. This is calculated by placing the best fit ellipse over the median nerve and determining the ratio between the large and small cross sectional diameters, by calculating the ratio between the maximal nerve dimension in a radial-ulnar and palmer-dorsal direction or by some other similar method. This is commonly carried out at the level of the pisiform but can be carried out throughout the tunnel. Studies that calculated the flattening ratio can be seen in Table 2.5. The average flattening ratio determined from these studies can be seen to be greater in patients with CTS at all levels investigated. The most significant differences are noted at the pisiform and the hook of hamate. However, not all studies indicate a correlation between flattening ratio and CTS. Sarría et al. (2000) found no significant differences between CTS patients and controls. Duncan et al. (1999) also reproached the usefulness of this method due to the high variability of results.
Table 2.5 Flattening ratios and standard deviations at various levels proximal to and throughout the carpal tunnel.

<table>
<thead>
<tr>
<th>Author</th>
<th>No. of Wrists</th>
<th>Radioulnar Articulation</th>
<th>Pisiform</th>
<th>Hook of Hamate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pat. (Cont.)</td>
<td>Patients</td>
<td>Controls</td>
<td>Patients</td>
</tr>
<tr>
<td>Altinok et al. (2004)</td>
<td>40 (40)</td>
<td>2.20±0.29</td>
<td>2.01±0.036</td>
<td>2.27±0.31</td>
</tr>
<tr>
<td>Bayrak et al. (2007)</td>
<td>41 (20)</td>
<td>2.20±0.40</td>
<td>1.90±0.40</td>
<td>2.50±0.60</td>
</tr>
<tr>
<td>Buchberger et al (1992)</td>
<td>20 (28)</td>
<td>2.70±0.40</td>
<td>2.70±0.30</td>
<td>2.70±0.40</td>
</tr>
<tr>
<td>Duncan et al. (1999)¹</td>
<td>102 (68)</td>
<td>3.17±0.90</td>
<td>2.72±0.73</td>
<td>-</td>
</tr>
<tr>
<td>El Miedany et al. (2004)²</td>
<td>96 (78)</td>
<td>2.65±0.52</td>
<td>1.75±0.15</td>
<td>-</td>
</tr>
<tr>
<td>Kotevoglu et al. (2005)</td>
<td>44 (27)</td>
<td>2.20±0.36</td>
<td>1.76±0.18</td>
<td>2.61±0.54</td>
</tr>
<tr>
<td>Sarría et al. (2000)</td>
<td>64 (42)</td>
<td>2.88±0.80</td>
<td>2.88±0.80</td>
<td>2.81±0.70</td>
</tr>
<tr>
<td>Yesildag et al. (2004)</td>
<td>148 (76)</td>
<td>-</td>
<td>-</td>
<td>2.90±0.40</td>
</tr>
<tr>
<td>Wong et al. (2002)¹</td>
<td>54 (70)</td>
<td>2.93±0.58</td>
<td>3.26±0.66</td>
<td>-</td>
</tr>
<tr>
<td>Average³</td>
<td></td>
<td>2.62±0.38</td>
<td>2.37±0.58</td>
<td>2.63±0.23</td>
</tr>
</tbody>
</table>

1. Values categorised under radioulnar articulation and the hook of hamate represent the values at the inlet and outlet of the carpal tunnel.
2. These values are an average of the flattening ratio seen at the inlet and outlet of the carpal tunnel.
3. The standard deviation for the average flattening ratio was calculated from the mean values indicated for each study.
2.7.3 Alternative Methods for Sonographically Defining CTS

Alternative sonographic criteria that have been investigated to define CTS include: swelling ratio, the variance in the CSA, palmar bowing of the flexor retinaculum, flexor retinaculum thickness and median nerve width. Swelling ratio is a term used by Altinok et al. (2004) [92] that compares the median nerve area at two distinct locations. This study determined a swelling ratio using the area of the nerve at the radioulnar articulation and the pisiform bone (40 symptomatic and 40 asymptomatic wrists). It found a noticeable difference between patients and controls (1.36±0.12 and 1.13±0.12 respectively) and concluded that a swelling ratio ≥1.3 would be helpful for verification of CTS. Hobson-Webb et al. (2008) [90] also compares the median nerve area at two distinct locations (18 symptomatic and 44 asymptomatic wrists). This study determined that a higher swelling ratio or wrist to forearm ratio of ≥1.4 was an indicator of CTS. However, this higher value was generated from a comparison between the nerve area at the distal wrist crease and a location 12 cm proximal to it. Although this study indicates a considerable difference between controls and patients (1.0±0.1 and 2.1±0.5 respectively), a study by Cartwright et al. (2009) [105] signifies that the cut off value may not be great enough for use in the general population. Cartwright et al. (2009) investigated the area of the median nerve in healthy subjects at six locations along the arm. The area recorded at the distal wrist crease (9.8±2.4 mm²) and at the mid-forearm (7.5±1.6 mm²) can be used to calculate a swelling ratio of 1.3. This value is greater than that seen for healthy subjects by Hobson-Webb et al. (2008) [90] and indicates that a larger number of controls may alter the mean area value for the control subjects.

Klauser et al. (2009) [103] used a similar method for detecting CTS. This study looked at the difference in nerve cross sectional area (ΔCSA) for 100 symptomatic and 93 asymptomatic wrists. The areas at the proximal third of the pronator quadratus muscle and at the maximal nerve shape change were used to determine this difference. Comparing controls to patients indicated large variations in the ΔCSA (0.25±0.43 mm² and 7.4±5.6 mm² respectively). Cut off values of 2 mm² and 3 mm² for the ΔCSA were found to be better indictors for CTS than median nerve area at the point of maximal nerve shape change. Sensitivity, specificity, PPV and NPV of 99%, 100%, 100% and 98.9% were calculated respectively. This surpasses all values seen in Table 2.4.
Although this diagnostic criterion looks promising, further testing of this technique is required if it is to be verified as an alternative to NCS. The cut off values of $2 \text{ mm}^2$ and $3 \text{ mm}^2$ for the $\Delta\text{CSA}$, used in this study are also equivalent to swelling ratios of $\geq 1.21$ and $\geq 1.31$ respectively. However, as previously stated this may be dependent on the number of controls used.

Palmar bowing of the flexor retinaculum is considered the distance from the palmar apex retinaculum to a straight line drawn between tubercle of trapezium and hook of hamate bone. Clear distinctions between patients and controls can once again be made for this criterion (Table 2.6). Comparing the average value from all studies indicates a 59% increase in palmar bowing for patients. Sarría et al. (2000) [95] found this method of determining the presence of CTS to be the most reliable in comparison to median nerve area and flattening ratio. However, this finding is not replicated in other investigations [91-93, 104].

Table 2.6: Studies that measured palmar bowing and standard deviation of the flexor retinaculum.

<table>
<thead>
<tr>
<th>Author</th>
<th>No. of Wrists</th>
<th>Patients (mm)</th>
<th>Controls (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altinok et al. (2004) [92]</td>
<td>40 (40)</td>
<td>2.94±1.10</td>
<td>1.40±0.58</td>
</tr>
<tr>
<td>Buchberger et al. (1992) [93]</td>
<td>20 (28)</td>
<td>3.70±1.10</td>
<td>2.10±0.80</td>
</tr>
<tr>
<td>Kotevoglu et al. (2005) [91]</td>
<td>44 (27)</td>
<td>3.90±1.05</td>
<td>2.18±0.35</td>
</tr>
<tr>
<td>Sarría et al. (2000) [95]</td>
<td>64 (42)</td>
<td>3.40±1.10</td>
<td>1.90±1.20</td>
</tr>
<tr>
<td>Wong et al. (2002) [104]</td>
<td>54 (70)</td>
<td>2.72±0.68</td>
<td>2.37±0.54</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>54 (70)</strong></td>
<td><strong>3.33±0.50</strong></td>
<td><strong>1.99±0.37</strong></td>
</tr>
</tbody>
</table>

**Note:** The standard deviation for the average palmar deviation was calculated from the mean values indicated for each study.

The flexor retinaculum may also be capable of determining CTS due to an increase in its thickness. This is usually measured at the middle (or as close as possible to the middle) of the flexor retinaculum. This method has varied success. Although Wong et al. (2002) [104] determined that flexor retinaculum thickness was not a useful discriminatory factor, El Miedany et al. (2004) [13] and Sernik et al. (2008) [101] saw noticeable changes in thickness (1.05±0.2 mm in patients and 0.85±0.46 mm in
controls, and 0.88±0.23 mm in patients and 0.75±0.1 mm in controls respectively). El Miedany et al. (2004) also found a correlation between CSA and flexor retinaculum thickness which agreed to data obtained from personal correspondence with orthopaedic surgeons.

An alternative method which has been examined is median nerve width at the level of the pisiform. Yesildag et al. (2004) [100] and Duncan et al. (1999) [97] both recorded this measurement to determine its effectiveness as an indicator of CTS. Although some correlations were noticed in the data obtained, it was not as significant as CSA. Irrespective of this, the use of this measurement should not be ignored, as Duncan et al. (1999) also found that a combination of median nerve width and CSA improved the diagnostic capability for CTS.

### 2.8 Diagnostic Accuracy

To emphasize the range of accuracy between diagnostic criteria and cut off values, and to demonstrate the array of studies reviewed, a funnel plot (Figure 2.3(a)) was created. This depicts the average percentage of incorrect diagnosis and the upper and lower limits of two (≈95% prediction limit) and three (≈99.7 prediction limit) times the standard deviation for all suitable studies available to the author (Appendix A). This considered each test criterion as a separate investigation, even if numerous criteria, such as median nerve area, flattening ratio or swelling ratio, were examined in each study. A number of investigated criteria are seen to fall outside both sets of limits. Although those approaching zero percent indicate an increase in diagnostic accuracy, the validity of these results is in question due to the degree in which they fall outside the limits. Many of the outlying studies can be explained by the methods used while performing the studies. Mondelli et al. (2008) [79] only investigated subjects which had mild symptoms of CTS (Figure 2.3). This would reduce the number of correct diagnoses as more severe cases would have clearer indicators and symptoms evident. The study by Klauser et al. (2009) [103] may also be explained by the methods used (Figure 2.3 (b)). In this instance, area change of a subject’s nerve by 2 mm$^2$ and 3 mm$^2$ was the diagnostic criterion. This was a unique technique which used the change in area of a subject’s nerve as the diagnostic criterion as opposed to a predetermined value. Although these outlying values can be explained, the weight and contribution of these
results needs to be assessed as the methods vary so greatly. To validate new diagnostic methods further studies using these criteria need to be conducted.

Extracting the diagnostic criterion with the greatest sensitivity and specificity from each study reveals the benefits of sonography in diagnosing CTS (Figure 2.3 (b)). The mean percentage of incorrect diagnoses or incorrect diagnoses value (Figure 2.3) can be seen to reduce dramatically from 23.5% to 11.1% with the majority of the data falling within the limits of two and three standard deviations. Data outside this area can once again be explained by the methods used for diagnosis. However, the most suitable diagnostic evaluation is still debatable as different diagnostic methods have been shown to be the most capable of diagnosing CTS in independent studies.

Figure 2.3 A funnel chart indicating the level of incorrect diagnosis from (a) studies regarding each investigated criterion separately and from (b) the most accurate criterion investigated in each study. The 99% and 95% confidence interval are indicated. The mean incorrect diagnosis from all data were also calculated and displayed in the figures.

2.9 Defining Severity Using Sonography

The use of sonography to define the severity of CTS is an area that has only been substantially investigated since 2004. In general, the severity of this condition is determined by either NCS [17, 18, 79, 92, 103] or clinical methods [16, 99, 106]. To determine if a correlation exists between severity defined by NCS or clinical means and sonographic indicators, both sets of results must be compared. This will indicate if sonography can be used as an alternative method for defining severity. Sonographic
means of determining the severity of CTS are usually based around CSAs, indicating
the degree of severity of the condition. However, alternative methods such as palmar
displacement, flattening ratio and swelling ratio have also been divided into severity
grades to determine if a correlation exists [13, 92]. With regard to CSA, a comparison
between studies is difficult. The position of the CSA varies from study to study and in
some cases is an average of the area seen at two separate locations [18]. The levels of
severity also vary, but the majority of studies indicate four grades; normal, mild,
moderate and severe.

A number of studies indicate a positive correlation between the mean CSA values of the
nerve and severity [13, 16-18, 92, 106-108]. However, this is not always the case.
Colak et al. (2007) [99] and Visser et al. (2008) [16] showed a decrease in mean nerve
area for severe cases when compared to moderate cases. Colak et al. (2007) attributed
this to prolonged axonal degenerative changes, which resulted in a serious decrease in
the CSA of the nerve. It is worth noting that both of these studies graded CTS severity
based upon clinical findings. These defined CTS severity in similar ways with healthy
subjects indicating no symptoms, mild CTS indicated by sensory loss on clinical
examination, moderate CTS indicated by sensory loss, muscle weakness and permanent
or transient pain and, severe CTS indicated by a loss of sensory and/or motor function
and thenar atrophy. All studies that compared the results of NCS to CSA indicated a
positive correlation. Even though a relationship can be made, this does not indicate that
it is suitable for determining CTS severity. A number of grades have ranges for NCS
which overlap. This suggests that if a stated area range is associated with a severity,
incorrect grading of a patient’s condition may occur. This may result in unsuitable
treatment being recommended.

2.10 Variables in Sonographic Imaging

Although sonography has been shown to be a beneficial tool in confirming CTS,
numerous variables must be considered. During a sonographic examination, the impact
of the user on the resultant image can be quite large. The transducer orientation in
relation to the test site can lead to a number of uncertainties. When determining CSA,
altering transducer angle would result in variations of the recorded area, even if images
were taken at the same location. This would also influence the mean area values
calculated from a number of subjects if a consistent angle was not maintained during examinations. A comparison between different modalities, such as magnetic resonance imaging (MRI), would also be difficult if an equivalent angle was not used while obtaining sonographic images [109].

The effect of contact force between the transducer and the skin is also an issue which has been widely investigated [19, 110, 111]. These studies have determined that relatively small forces cause substantial deformation of the soft tissue under the examining site and propose methods to combat these errors. This is necessary for accurate measurements to be taken from the sonographic scans as diagnostic criteria, such as flattening ratio, would be effected. However, neither these nor any other studies have specifically investigated the influence of contact force on the median nerve within the carpal tunnel.

2.11 3-D Sonography

A number of methods have been developed to create 3-D models from sonographic images. These include 3-D sonographic transducers, mechanically swept transducers and freehand sonography. Freehand sonography is the most convenient modelling technique as it does not require specifically designed transducers or the addition of a motorised device for transducer repositioning. For these reasons freehand sonography is commonly utilised. It requires the implementation a positioning system to be used in conjunction with a conventional transducer. These generally employ positioning sensors such as electromagnetic sensors or optical sensors [112]. Electromagnetic sensors operate by emitting a magnetic field in a working volume that is recorded by a receiver. This gives both positional data and also the angles produced [113]. Optical sensors operate by determining the position of markers placed on the transducer. The markers are picked up by multiple cameras focused on the transducer during testing. The data collected from the cameras is then used to calculate the coordinates of these markers in 3-D space. From this information, the position of the transducer and the resultant sonographic images can be computed.


2.12 Discussion

The effect of wrist posture and computer use on the CTP has been well documented, as have the diagnostic methods utilizing sonography. Within these areas discrepancies between previous studies are evident. In relation to CTP this is evident in the values recorded for wrist positions. The range of values seen in the neutral position for both control subjects (2.5-24 mmHg) and CTS patients (20.7-43.8 mmHg) is quite large and this is echoed through movements of flexion and extension. The reasons for these variations often depend on the methods and techniques used to perform these investigations. Although large differences are not seen within test methods, they may still be significant enough to cause varying results.

One aspect that may alter the neutral CTP values is the position of the wrist while in this posture. The neutral posture is one of 0° extension/flexion and 0° radial/ulnar deviation. However, CTP is not always recorded with the hand in this position. Numerous reports record the CTP with the hand in a resting position [27, 39, 46] and use this value as the neutral pressure. In some studies this is considered to be the wrist position with the lowest CTP [22]. Even though this position would not be far from the neutral posture, it would still produce a change in CTP. This change may be further emphasised by an adjustment in finger position. Rempel et al. (1998) [114] and Keir et al. (1998b) [50] showed that by adjusting the metacarpophalangeal (MCP) joint angles from 0°-90°, changes in CTP were once again noticed. MCP angles of 0° and 90° generally saw the highest pressures indicating that studies requiring extended fingers or other extreme finger postures would encourage greater CTPs. The study by Rempel et al. (1998) [114] also indicated that supination and pronation varies CTP with 45° pronation resulting in the lowest value. A majority of pressures in alternative studies were recorded with the forearm in a supinated position, as CTP is commonly measured prior to surgery with the arm in the required surgical position. However, the pressure is not always measured with the arm in this position [8] which makes a comparison between studies difficult.

Variations in results can be due to numerous other reasons. Catheter placement and condition severity have also been shown to impact CTP. Luchetti et al. (1998) [23] measured the pressure of the carpal tunnel at five different locations along the tunnel.
These measurements were taken while the wrist was in a position of flexion, extension or the neutral position. This study found that the pressure varied depending on the location of the catheter. Therefore, for a direct comparison to be made between studies and in the same study, consistency and accuracy in catheter placement would be vital. Severity of the condition in CTS patients must also be taken into account when comparing results. Sufferers of CTS that exhibit more acute symptoms may have a higher CTP than those with only mild or moderate symptoms. The level of severity was not accounted for in the majority of studies with only the duration of symptom onset being noted. Although subjects did fit the required criteria for CTS, symptom duration alone does not indicate condition severity.

One aspect that is common to all studies is that CTP increases the more extreme the wrist posture becomes. Although this is the case, these studies only calculated the mean wrist position in one direction at a time. The mean position of extension/flexion and the coinciding radial/ulnar deviation have not yet been assessed. This is also the case for positions recorded during computer use. However, the mean extension/flexion and radial/ulnar values noted in these studies do not increase CTP to harmful levels (Table 2.2). The impact of extending or flexing the wrist while it is not in a neutral radial/ulnar position has not been investigated. Positions of this nature may increase CTP to above the threshold at lower levels of wrist deviation due to the accumulative pressure created by movement in two directions simultaneously. Therefore, if wrist posture alone can increase CTP significantly during computer use, the most common wrist postures in extension/flexion with the corresponding radial/ulnar deviation must be identified.

A reduction in nerve functionality can be measured by NCS. This may be as a result of nerve damage or an increase of pressure placed on the nerve. NCS is a common method for detecting CTS and detecting abnormalities in nerve functionality. The results seen for CMAP and SNAP data indicate the drop in nerve functionality if pressure placed on the nerve increases. However, this drop in functionality is not only generated by the occurrence of neurological disorders. Wrist posture in healthy subjects has also led to variations in NCS and resulted in complete nerve blockage in a number of subjects. This highlights the effectiveness of NCS at representing a reduction in nerve functionality due to wrist position.
Once these positions have been established, it would also be advantageous to calculate the CTP or variations in nerve functionality due to performing computer related activities in such postures. The effect of fingertip forces applied in an array of wrist positions have been recorded [49], but this is once again only carried out with the wrist in a position of either extension/flexion or radial/ulnar deviation and not both. Rempel et al. (2007) measured the impact of wrist position during typing on CTP. However, the positions recorded are the mean angles of extension/flexion or radial/ulnar deviation throughout the task and not a combination of the two.

The numerous studies examining wrist posture have indicated that changes in wrist position alter CTP. The degree of these CTP changes vary greatly from one study to the next but can be explained, at least in part, by the methods and subjects used. The data collated indicate that large movements are required to increase CTP to harmful levels. However, an accumulation of movement in two directions simultaneously may induce higher CTP. The inclusion of computer tasks or related activities has also been shown to increase CTP further. To determine if nerve functionality is impacted by an increase in pressure, wrist posture or for any other reason NCS can be utilised. This will indicate if functionality deteriorates or if nerve damage has occurred.

Understanding the causes of CTS, and how such a condition develops, will in turn aid in the diagnosis of it. Sonography has been shown to have numerous advantages in this area. It is a non-invasive, time efficient method that is readily accessible in a majority of hospitals. Although initial purchase of equipment may be higher than that for NCS, examination costs are less. Wong et al. (2004) stated that a sonographic examination cost under one fifth that of electrodiagnostic testing and took only half the time [87]. This method is not just beneficial in determining CTS but also in finding the cause of symptoms such as entrapment neuropathy, inflammatory conditions, traumatic injury and masses [115]. Although a contradiction over the extent of sonographic advantages exists, it is considered a beneficial tool in the diagnosis of CTS and may surpass NCS as the gold standard. However, if this is to be the case, a confirmed set of criteria that indicate CTS needs to be established.

Median nerve area is one of the most commonly investigated sonographic criteria used for determining the presence of CTS. All studies reviewed indicated a noticeable
change in the median nerve area of patients when compared to controls within the respective studies. However, similar findings are not denoted when comparing study to study. Two studies indicate mean areas of over 11 mm$^2$ for healthy subjects at the level of the pisiform [95, 116]. These values are greater than the cut off values (9-10 mm$^2$) suggested by numerous authors at the same location [13, 92, 97, 101]. This implies that a number of healthy subjects would be graded as having CTS using this criterion. Therefore, determining a definitive median nerve area that can indicate the presence of CTS may not be possible. Ziswiler et al. (2005) [106] recommends sonography be used to either rule in or rule out CTS. Cut off values of <8 mm$^2$ and $\geq$12 mm$^2$ were set to define patients with and without CTS. All subjects between these values could not be accurately assessed by means of nerve area alone and required further evaluation to determine if CTS was evident. This method may be helpful in determining CTS in the general population, but the benefits of using this technique may be limited, as suspected cases may have a median nerve area of 8-12 mm$^2$.

Using a method such as median nerve swelling may be a more reliable approach. This technique makes each diagnosis subject specific and rules out information taken from alternative sources. This may lead to a reduction in false positives due to abnormal nerve size as the swelling ratio would be equivalent. However, as discussed earlier, variations in an appropriate swelling ratio exist. For this method to be implemented correctly, an in-depth study on the relationship between the median nerve area at a suitable diagnostic location (for example the pisiform bone) and a location proximal to this should be carried out for both healthy subjects and patients.

The use of alternative sonographic diagnostic criteria, such as flattening ratio and palmar bowing of the flexor retinaculum, has also been investigated for determining CTS. The results seen for these are not as consistent as those for median nerve area. This does not mean that this information is irrelevant. The use of these results, in conjunction with additional findings, may confirm CTS. Altinok et al. (2004) [92] states that detection of at least two of the three indicators investigated in the study (median nerve area, swelling ratio and palmar displacement) may be helpful for verification of CTS. By requiring more than one criterion to be met, accurate diagnosis would be more probable as one unusual result would not indicate CTS. This sentiment is also seen in studies by Sarría et al. (2000) [95] and Kotevoglu et al. (2005) [91] that.
recommend clinical and sonographic confirmation together would be sufficient to establish the presence of CTS. This could remove the need for NCS to be performed.

There are numerous advantages evident with the use of sonography. However, variables do need to be considered when using this technique as either a diagnostic tool or in creating 3-D models. These include the impact of transducer angle and pressure on the captured images. Although solutions to these sources of error have been created, they may not be specifically applicable to the carpal tunnel and its contents. For this to be accounted for, an investigation into these aspects is required.

Although sonographic studies carried out to date have shown promise in relation to detecting CTS, the lack of a universal set of criteria reduces the use of this method. In order to improve this, it is necessary for the shortcomings on current criteria to be managed. Alternatively a new indicator for CTS by sonographic means will need to be created. This would need to be capable of accurately and efficiently determining the presence of CTS in the general population. It would also be beneficial if the severity of the condition could be determined, to ensure the most suitable treatment would be carried out.

2.13 Summary

It has been shown that deviations in wrist position from a neutral posture will lead to greater CTP. Increased pressure placed on the nerve has also been shown to cause ischemia and nerve degeneration. This may contribute to the development of CTS. However, these positions are not common in everyday computer use. To determine if computer use is associated with CTS development, the effects of wrist extension/flexion and a concurrent radial/ulnar deviation on nerve function should be investigated. The impact of these postures on the nerve can be determined using NCS and the methods employed for diagnosing CTS.

Although NCS and clinical diagnosis are the most common diagnostic methods for CTS, an alternative area under investigation is sonography. This has shown to be a useful tool in the detection of such a disorder. However, the full extent of sonographic capabilities and advantages has not yet been firmly established. For sonography to be
recognised as a practical method of diagnosis and be used on a larger scale, a suitable criterion needs to be ascertained. The variables associated with measurements at the carpal tunnel would also need to be identified and accounted for. This may result in sonography being used as alternative to NCS in the diagnosis of CTS.

2.14 Study Hypothesis and Objectives

Median nerve functionality can be altered due to a number of reasons. However, the effect of wrist postures on median nerve functionality has not previously been studied. Therefore, the hypothesis that wrist postures have a significant effect on median nerve functionality will be investigated. To address this, the current study evaluated the effects of postures reached during a typical computer task on the median nerve. This will determine if nerve functionality is hindered due to these postures being maintained for a prolonged period of time. The level of nerve function can be assessed by means of NCS. However, prior to this being investigated wrist postures frequented during a typical computer task must first be determined. This has previously been conducted using motion analysis equipment and is a proven method for calculating these postures.

A second hypothesis being investigated in the study is that sonography can be used as a diagnostic tool for CTS. With this in mind, the feasibility of a new diagnostic indicator for CTS using sonography was researched. This was focus around median nerve volume calculations within the carpal tunnel and at areas proximal to this. The suitability of this diagnostic indicator was assessed. The influence of transducer forces on the measuring site and, in turn, the volume measurements was also reviewed.

To investigate the two hypotheses proposed above, this research was broken down into the following objectives:

- Establishing the most common wrist postures frequented during a computer task
- Determining the effect of these wrist postures on nerve function by means of NCS
➢ Concluding if a link between wrist posture exhibited during computer use and CTS is evident

➢ Investigating new sonographic methods for confirming the presence of CTS

➢ Ascertaining the effect of transducer force on the carpal tunnel and the median nerve.
Chapter III

Computer Wrist Postures
3.0 Computer Wrist Postures

3.1 Introduction

One of the most commonly related activities to the onset of carpal tunnel syndrome (CTS) symptoms is computer use. Although the exact cause of CTS is unknown, it is widely believed that computer users are at a high risk of suffering from such a disorder. Studies carried out by Aydeniz et al. (2008) [117] and Conlon and Rempel (2005) [118] state that there is an increased risk of CTS with increased computer use. However, adjusting working conditions and equipment, changing the way tasks are performed or ceasing certain activities have been shown to improve comfort, reduce muscle activity and prevent or even treat CTS [3, 54, 58, 61, 119].

To determine the effects computer use has on the carpal tunnel, it is necessary to understand the movements involved in performing everyday tasks. The most common of these are typing and mouse usage. To do this, motion analysis techniques were adopted. Motion analysis is a common method of determining the movements involved in human activities. These techniques have been shown to be accurate in determining hand and finger motion [120] and were used by Tittiranonda et al. (1999) [54] to calculate wrist movements during computer use. This method records all movements carried out during a specific task and allows the level of extension/flexion and radial/ulnar deviation of the wrist to be calculated.

It has previously been proven that the pressure within the carpal tunnel can increase due to the activities undertaken. These include gripping, creating a fist and fingertip loading [23, 24, 49]. The effect of wrist positions on carpal tunnel pressure (CTP) has also been well documented [8, 33, 48]. However, in each of these studies only the influence of wrist position in one direction was investigated. The effect of wrist posture in a state of both extension/flexion and conjointly radial/ulnar deviation has not yet been examined. This is necessary to determine if these wrist positions create a CTP greater than the critical pressure threshold of 30 mmHg (∼4 kPa) stated by Werner et al. (1997) [34] and Keir et al. (2007) [48]. If this pressure threshold is exceeded for a prolonged period of
time, the median nerve will more than likely become damaged, resulting in the
development of CTS. These postures may also result in nerve functionality being
reduced, which may be a prelude to nerve damage occurring.

3.2 Materials and Methods

Twenty healthy participants performed a computer task involving both mouse and
keyboard use. Reflective markers were strategically attached to the participant’s arms
and hands to calculate the wrist angles created as a result of carrying out the task. The
resultant positions were recorded and categorised to determine the joint angles that are
most prevalent during computer use.

3.2.1 Participants

Twenty volunteers (12 male and 8 female), with no signs of CTS, were required to
perform a computer task in an experimental setting. Of this group, seven had previously
undertaken a typing course of some kind. The remaining participants had never
undergone computer training of any sort. Participants were required to be regular
computer users, with no selection bias given to those with previous training or
attendance at computer courses. Participants were of working age and spent a mean of
5.85±1.5 hours in front of a computer during an average working day. Before
participants were allowed to partake in testing they were required to fill out a subject
information sheet and perform a Phalen’s and Tinel’s test to determine if any signs of
CTS were evident. Phalen’s test was performed by pressing the dorsal aspect of the
hands against each other in a fully flexed position for 60 seconds. An onset of pain,
numbness or tingling indicated CTS was evident. Tinel’s test was performed by tapping
the palmar surface of the wrist. A positive indication in this case will result in
paraesthesias of the areas supplied by the median nerve [21, 121]. No subjects had a
history of CTS or showed signs of the disorder on the day of testing. One subject was
previously diagnosed with tenosynovitis but had not suffered from any symptoms in the
24 months prior to this study. All subjects taking part were required to sign a consent
form indicating they understood what was entailed in the task. This research method
was reviewed and approved by the University of Limerick Research Ethics Committee.
3.2.2 Workstation

The workstation consisted of an adjustable chair, a computer utilising a standard QWERTY keyboard and a three button mouse. No wrist or arm rests were provided while carrying out the computer task. Prior to participants commencing testing the adjustable chair was raised to its highest level. Participants were instructed to adjust the chair to a comfortable height to mimic their everyday working environment. Movement of the keyboard, mouse and monitor was also permitted prior to the commencement of testing. The keyboard was set to a slope of $+10^\circ$ which remained constant throughout testing. The article to be typed out was placed, by the participant, in a suitable position which allowed them to carry out the task in their most natural manner.

3.2.3 Motion Analysis

Motion analysis was carried out using a Hawk Digital RealTime System consisting of four Hawk Digital Cameras and Evart 5.0.4 software (Motion Analysis Corporation, Santa Rosa, California). This system measured and recorded the extension/flexion and radial/ulnar deviation of the wrist away from the neutral position during the specified computer task. The neutral position is defined as $0^\circ$ extension/flexion and $0^\circ$ radial/ulnar deviation. This was done by placing reflective markers at the knuckle of the middle finger, the wrist and the forearm as indicated in Figure 3.1. The markers were attached to both arms using mounts 10 mm high that were affixed to the skin by means of double sided adhesive pads. All subjects were required to wear sleeveless or short sleeve tops to preserve marker visibility and prevent marker displacement. Prior to beginning the test all jewellery, watches or any other type of reflective items were removed by the participant to prevent alternative objects being recorded during testing.

![Figure 3.1](image) Position of reflective markers on the arm.
The cameras were configured to give an optimal view of the computer task being performed. This consisted of two cameras being placed on either side of the workstation with the keyboard and mouse area being the main focus of attention. Two further cameras were placed to the fore of the participant’s position to obtain an unobstructed view of all movements performed.

### 3.2.4 Experimental Procedure

The experimental section consisted of the participants opening and closing a Microsoft Word document (Microsoft®, Washington, USA) using only the mouse and performing a typing task as per normal. The passage typed was an extract from an online short story (Appendix A) and remained constant for all volunteers. Once the participant was ready to commence the task the cameras began recording. Participants continued typing until the task was completed. The cameras stopped recording immediately following the completion of the task.

### 3.2.5 Data Analysis

The task was recorded at a rate of 200 frames per second and passed through a 10 Hz Butterworth filter in order to smooth data. To measure the angles created by the wrist, four planes were created; two to measure extension/flexion and two to measure radial/ulnar deviation. These planes were created from the markers using specifically designed matrix laboratory (MATLAB) programs (v. 7.3.0.267, Natick, Massachusetts) (Appendix B). The markers labelled A, B, and C created one plane and the markers B, C, and D created the second plane (Figure 3.1). These planes were used in order to calculate the flexion and extension undergone throughout the task. To create the planes used to measure radial/ulnar deviation, three phantom markers were created. One of these markers was created at the midpoint between B and C and the others 40 mm above A or D depending on the plane being created. The angles generated between the two planes were calculated using Equation 3.1 where the terms $a_1$, $b_1$, $c_1$, $a_2$, $b_2$ and $c_2$ were computed using Equations 3.2-3.7 respectfully. Equations 3.2-37 are graphically represented in Figure 3.2. The values for $x$, $y$ and $z$ are obtained from the coordinates recorded for the reflective markers and from the phantom markers which were created.
\[ \cos \theta = \frac{a_1a_2 + b_1b_2 + c_1c_2}{\sqrt{a_1^2 + b_1^2 + c_1^2} \sqrt{a_2^2 + b_2^2 + c_2^2}} \]  
Equation 3.1

\[ a_1 = y_1(z_2 - z_3) + y_2(z_4 - z_1) + y_3(z_1 - z_2) \]  
Equation 3.2

\[ b_1 = z_1(x_2 - x_3) + z_2(x_3 - x_1) + z_3(x_1 - x_2) \]  
Equation 3.3

\[ c_1 = x_1(y_2 - y_3) + x_2(y_3 - y_1) + x_3(y_1 - y_2) \]  
Equation 3.4

\[ a_2 = y_4(z_5 - z_6) + y_5(z_6 - z_4) + y_6(z_4 - z_5) \]  
Equation 3.5

\[ b_2 = z_4(x_5 - x_6) + z_5(x_6 - x_4) + z_6(x_4 - x_5) \]  
Equation 3.6

\[ c_2 = x_4(y_5 - y_6) + x_5(y_6 - y_4) + x_6(y_4 - y_5) \]  
Equation 3.7

**Figure 3.2** A graphical representation of Equations 3.2-3.7 are indicated to show how \( \cos \theta \) calculated.
The angles measured were collated in two ways. Firstly, the frequency of extension/flexion and radial/ulnar deviation was categorised independently of other movements. This allowed for frequency of each position in a single plane to be measured. The mean flexion/extension angle and radial/ulnar deviation for all subjects throughout the task were also calculated. Following this, the position of the wrist in two planes was also categorised. This allowed a true indication of wrist positions to be ascertained. The angles measured in one plane were divided into categories ranging from 0-50 degrees in increments of 5°. The categories were named after the highest attainable value in that range. A value of 17° flexion would go into the category of 20° flexion and so on. A similar method was used to categorise motion in two planes. In this instance the increments were extended to 10° to reduce the number of categories. For notation purposes a position of 17° extension and 12° ulnar deviation was categorised as Ext20°Ulnar20°. Positions of flexion and radial deviation were abbreviated to Flex and Rad respectively and used to categorise in a similar way. All measurements that exceeded 50 degrees were grouped together as their occurrence was minimal.

Computer based statistical analysis was carried out using Statistical Package for the Social Sciences (SPSS) software (v. 14.0, SPSS, Chicago, Illinois). This entailed a means comparison being conducted by way of an independent samples t-test. Levene’s test was used to determine if equal variance was assumed. Statistical significance between gender, left and right hands and trained and untrained subjects was investigated. For all comparisons statistical significance was set at p < 0.05.

3.3 Results

3.3.1 Posture in One Plane

The typing task had a mean time of 16 minutes and 38 seconds to complete. The most prevalent wrist positions during a computer task for all computer users were calculated. Throughout the duration of the task the position of flexion was seldom visited as can be seen from Figure 3.3. It can be noted that the positions of extension and ulnar deviation were the most common with 94% of extension/flexion and 67% of radial/ulnar deviation being in these areas respectively. The greatest percentage of extension occurred at 20°
with a high distribution of the task spread between 5° and 30°. A similar distribution is also seen for the radial and ulnar movements with 15° being the peak in both of these instances. Wrist positions denoted as ‘No Value’ are a result marker positions not being recordable.

These results can be broken down into movements that occur on the left and right wrists to determine if any correlation is evident between wrist position and a specific wrist (Figure 3.4 & Figure 3.5). These results indicate that flexion occurs most often in participants left wrist, with 5° being the most common position. The range of extension does not change greatly for either wrist with the majority of the movement still occurring between 5° and 30°. A contrast between the radial deviation of the left and right hand can be noticed. For the right hand a large amount of the movement occurs between 5° and 15°, where as the left hand shows radial deviation to occur mostly at 15° and 20°. There is also a notably larger amount of radial/ulnar deviation being radial in the right hand (39%) when compared to the left hand (27%). However, no statistical

**Figure 3.3** Percentage of time the wrist spent in a position of flexion, extension, ulnar deviation and radial deviation. The accumulated percentages of extension and flexion equates to 100% as does the accumulated percentages of radial and ulnar deviation (n=20).
significance was noted between the left and right hand for any of the wrist postures (p < 0.05). The mean angles and standard deviations for extension, flexion, radial deviation and ulnar deviation in both the right and left hand can be seen in Table 3.1. The mean value for the combined range of extension and flexion (extension|flexion) and radial and ulnar (radial|ulnar) deviation were also calculated.

Figure 3.4  Percentage of time the right wrist spent in a position of flexion, extension, ulnar deviation and radial deviation. The accumulated percentages of extension and flexion equates to 100% as does the accumulated percentages of radial and ulnar deviation (n=20).
Figure 3.5  Percentage of time the left wrist spent in a position of flexion, extension, ulnar deviation and radial deviation. The accumulated percentages of extension and flexion equates to 100% as does the accumulated percentages of radial and ulnar deviation (n=20).

Table 3.1  Mean wrist positions (°) obtained for the left, right and a combination of the left and right hand.

<table>
<thead>
<tr>
<th>Wrist Position</th>
<th>Left Wrist</th>
<th>Right Wrist</th>
<th>Left and Right Wrist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion(^1)</td>
<td>3.8±3.4</td>
<td>7.2±5.5</td>
<td>2.5±4.2</td>
</tr>
<tr>
<td>Extension(^1)</td>
<td>20.0±10.1</td>
<td>16.1±8.8</td>
<td>18.0±9.7</td>
</tr>
<tr>
<td>Extension</td>
<td>Flexion(^2)</td>
<td>17.7±10.8</td>
<td>15.5±8.9</td>
</tr>
<tr>
<td>Radial(^1)</td>
<td>14.7±4.8</td>
<td>10.1±6.2</td>
<td>12.0±6.1</td>
</tr>
<tr>
<td>Ulnar(^1)</td>
<td>12.7±7.6</td>
<td>12.0±6.5</td>
<td>12.5±7.1</td>
</tr>
<tr>
<td>Radial</td>
<td>Ulnar Deviation(^2)</td>
<td>5.3±10.6</td>
<td>3.5±10.1</td>
</tr>
</tbody>
</table>

1. Mean values obtained for movement in one direction from the 0° position (e.g. extension only).
2. Mean values obtained for movement in one plane (e.g. extension and flexion). Extension is denoted by a positive value and flexion by a negative value.
3.3.2 Posture in Two Planes

Figure 3.6 indicates the wrist postures that are frequented the most during a computer task. This shows the majority of these postures are in a position of extension and ulnar deviation. This is indicated more clearly in Figure 3.7, where the most frequented position is seen to be Ext20°Ulnar20°. This accounted for over 10% of wrist position during the computer task. This is followed closely by an Ext20°Ulnar10° and an Ext30°Ulnar20°. Positions incorporating flexion or radial deviation did not enter the five most common wrist positions. However, this does not indicate that these positions do not play a part in the computer task.

![Figure 3.6](image)

**Figure 3.6** Representation of the most commonly frequented wrist postures during a computer task. Negative values on the x and y axis refer to radial deviation and flexion respectfully (n=20).

Although extension and ulnar deviation account for the majority of the postures recorded at 65.42%, extension and radial deviation accounts for 26.55%. This is a
significant proportion of the computer task. Flexion and ulnar deviation and flexion and radial deviation account for just over 4% of the entire task each, which indicates a minimal amount of computer activities involve these wrist positions.

![Graphs showing wrist postures](image)

**Figure 3.7** Percentage of time the wrist spent in a position of (a) FlexRad, (b) FlexUlnar, (c) ExtRad and (d) ExtUlnar. The summation of the percentages in figures (a), (b), (c) and (d) together is 100% (n=20).

Considering both wrists independently, large differences can be seen in certain positions (Figure 3.8). The most obvious of these is Ext20°Rad10°. In this instance the right wrist occupies this position over eight times as long as the left. Other noticeable variations can also be seen to occur across the results indicating a large degree of wrist variation when carrying out the task. However, statistical significance is not evident at any wrist posture when comparing left and right hands (p < 0.05). In general, it can be noted that the most common wrist positions for each hand matches those of the overall results.
Figure 3.8 Percentage of time the (a) right wrist and (b) left wrist spent in a position of FlexRad, FlexUlnar, ExtRad and ExtUlnar. The summation of the percentages in figure (a) and (b) individually is 100% (n=20). To refine the results, the wrist movements which accounted for less than 1.5% of the overall movements were removed. This encompassed all radial or ulnar deviations of 40° or greater and all flexion or extension movements of 50° or greater.

Although this study was not aimed at discovering the different techniques used by trained and untrained participants a comparison between the two can be made. The most prominent wrist position for trained and untrained participants was Ext20°Ulnar30° and Ext20°Ulnar20° respectively (Figure 3.9). Although the most prominent positions are similar, clear differences can be seen at Ext20°Ulnar20°, Ext20°Ulnar30° and Ext20°Rad10° with statistical significance only noted at a position of Ext20°Ulnar20° (p = 0.025, t = 2.352). This indicates the untrained subjects frequent a position of Ext20°Ulnar20° to a greater degree than the trained subjects.
Figure 3.9 Percentage of time trained (T) and untrained (U) participants spent in a position of (a) FlexRad, (a) ExtRad, (b) FlexUlnar and (b) ExtUlnar. The summation of the percentages in figure (a) and (b) individually is 100% (n=20). To refine the results, the wrist movements which accounted for less than 1.5% of the overall movements were removed. This encompassed all radial or ulnar deviations of 40° or greater and all flexion or extension movements of 50° or greater.

3.4 Discussion

Wrist position can vary greatly when carrying out computer tasks. This can be caused by participant’s preference, habit and level of comfort while performing the activity. This study looked at general computer users performing a computer task in their most natural way. This encompassed both trained and untrained participants completing the task with the work area adjusted to their own particular preference. This allowed for the test area to be adjusted to mimic the participants own work area and therefore obtain an accurate insight into the wrist postures involved in completing a computer task.

The breakdown of common wrist positions found here correlates well to those found by Tittiranonda et al. (1999) [54]. In Tittiranonda’s study, 35 subjects were required to perform a typing task on a conventional and a split design keyboard. The wrist positions visited throughout this task were calculated and the most common wrist position determined. It was noted that an extension angle of 21-30° and ulnar deviation of 11-20° were the most common ranges on the conventional keyboard. These are similar to the results of 20° extension and 15° ulnar deviation exhibited in this study. The mean wrist angles calculated for extension|flexion in this study also compare well
to the results of Serina et al. (1999) [59], Rempel et al. (2007) [58], Straker et al. (2008) [61], and Fagarasanu et al. (2005) [57] (Table 3.2). However, some variability can be noticed between the results. This can be explained by the slope of the keyboard used. A study by Simoneau et al. (2003) [60] determined that adjusting the slope of the keyboard affected the mean extension and mean ulnar deviation. Rempel’s study used a keyboard slope of 0° whereas the studies carried out by Serina, Fagarasanu and in this investigation were between 5° and 10°. Other factors such as keyboard position from the edge of the desk and the computer display height have also been shown to effect wrist posture [61, 122].

It can also be noticed that, in general, the mean values for radial|ulnar deviation found in the current study are noticeably lower than those found in previous studies (Table 3.2). This is due to the amount of radial deviation which occurs during the task. This study showed that radial deviation occurred for 33% of the time. It has a greater occurrence and range of postures than recorded in previous studies. A range of radial motion between 0-30° was also evident in this investigation whereas the study by Tittiranonda indicates that radial motion only occurred between 0-10°.

The mean radial/ulnar deviation value determined by Straker et al. (2008) [61], for the left wrist, did correspond to the results found in this study. However, the low standard deviation does not indicate that radial movements regularly took place. Removing the radial deviation data while calculating mean radial/ulnar deviation and considering only the mean ulnar movements demonstrates a greater correlation within results. This further emphasises the impact radial deviation has on the results found in this study.
Table 3.2  Summary of mean wrist angles (°) and standard deviations in flexion and extension (Flex|Ext) and radial and ulnar (Radial|Ulnar) deviation from previous studies involving a conventional computer keyboard.

| Study                  | No. of Subjects | R. Wrist Flex|Ext | L. Wrist Flex|Ext | R. Wrist Radial|Ulnar Deviation | L. Wrist Radial|Ulnar Deviation |
|------------------------|-----------------|---------------|-----------------|----------------|----------------|----------------|----------------|----------------|
| Serina et al. (1999) [59] | 25              | 19.9±8.6      | 23.4±10.9       | 18.6±5.8       | 14.7±10.1       |
| Rempel et al. (2007) [58] | 100             | 13.1±110      | 12.8±11.6       | 15.2±9.5       | 16.3±10.7       |
| Fagarasanu et al. (2005) [57] | 30              | 21.7±5.8      | 22.2±5.3        | 16.7±4.0       | 15.9±2.8        |
| Straker et al. (2008) [61]   | 36              | 13.9±0.5      | 16.5±2.4        | 14.4±2.9       | 7.5±2.4         |
| This Study              | 20              | 15.5±8.9      | 17.7±10.8       | 3.5±10.1       | 5.3±10.6        |

Note: R denotes right and L denotes left and negative values represent flexion or radial deviation.
Previous studies carried out detailed investigations on the variables that can impact wrist position during computer use. These studies looked at the effect of different computer keyboards, keyboard position, mice and wrist supports. However, these studies have not looked at the effect these variables have on wrist position in two planes. The most common positions of extension/flexion throughout a task have been determined, but these positions do not account for the simultaneous radial/ulnar deviation which takes place. This is also the case for the most common radial/ulnar positions ascertained. The results obtained in this study give a realistic representation of the wrist positions used throughout a computer task as both the extension/flexion and the coincident radial/ulnar deviation were examined.

The three most common wrist positions calculated in two planes account for over 30% of the overall wrist positions visited. This value is increased even further when each wrist is looked at individually, although variations can be seen when looking at the positions most often visited by each wrist. This could be due to the keyboard layout and the text which was typed. The text used in this instance may require the use of certain keys more often than others, accounting for increased movement to these areas. The position of the keyboard relative to the participant would also impact wrist movement. As participants were allowed to adjust the position of the keyboard, mouse, monitor and chair to their own specifications, it is possible that their workstation layout would encourage particular wrist positions to complete the task. However, these workstation modifications promote completion of the task in the participant’s most natural manner.

Comparing the wrist positions of trained and untrained subjects, also unveiled variations in common wrist positions used throughout the task. This indicates that typing courses or other types of computer training could alter the techniques of the general population. The results show that trained subjects were in a higher degree of ExtRad and ExtUlnar for a longer duration than untrained subjects. This could lead to a higher CTP being produced in trained subjects.

Positions of Ext20°Ulnar20°, Ext20°Ulnar10°, Ext30°Ulnar20° and Ext30°Ulnar10° are the most common wrist positions seen in two planes. Although previous studies did not categorise the most prevalent wrist positions in this manner, the work carried out by Tittiranonda et al. (1999) [54] is a good indication that these values are accurate.
Tittiranonda’s findings that the most prevalent wrist positions in one plane were from 21-30° for extension and 11-20° for ulnar deviation have been shown to correspond well to the results found in one plane for this study. These two positions also define one of the main wrist positions found in two planes (Ext30°Ulnar20°). This indicates that the most common wrist positions found in two planes are a suitable representation of wrist position for a computer task and relates to previous investigations carried out. From these results a clear representation of the wrist positions used in computer tasks have been identified. The effect these wrist positions have on nerve functionality can now be investigated.

In conclusion, this method demonstrates a representative method for categorising wrist positions while carrying out a computer task. The impact of these postures on the median nerve and the carpal tunnel can now be investigated.
Chapter IV

Compound Muscle Action Potential of the Median Nerve
4.0 Compound Muscle Action Potential of the Median Nerve

4.1 Introduction

As previously stated, one of the most commonly related activities to the development of carpal tunnel syndrome (CTS) is computer use. The risk of CTS developing has been shown to be associated with increased computer use [117, 118]. However, a direct link between computer use and CTS is still a matter of much debate. To determine if a connection exists, numerous areas such as finger tip forces, palm forces, wrist position and mouse usage have been examined [6, 22, 30, 40, 49]. Although these studies indicate that these activities lead to an increase in carpal tunnel pressure (CTP), they cannot be directly associated with the development of CTS. This is because the increase in pressure may not be great enough, or occur over a long enough period of time, to damage the median nerve.

The most commonly used method to determine if nerve damage has occurred is nerve conduction studies (NCS). This method is widely used to indicate the presence of neuropathy disorders and compression of the median nerve. This compression can be brought on by an increase of pressure within the carpal tunnel. Keir et al. (2007), Keir et al. (1997), Seradge et al. (1995) and Weiss et al. (1995) [8, 24, 33, 48] have shown that wrist posture can lead to this pressure increase, which may, in turn, damage the nerve. It is possible for pressures as low as 30 mmHg (4 kPa) to initiate axonal degeneration and demyelination [19], which reduces nerve functionality and alters the results of NCS. A significant change in nerve conduction data indicates that nerve functionality is reduced. This can be indicated by variations in the compound muscle action potentials (CMAPs) [37]. A reduction in CMAP amplitude and an extended distal motor latency (DML) or CMAP duration may indicate the extent of nerve dysfunction.

To establish if computer use reduces nerve functionality to a degree that indicates nerve damage, the effect of wrist posture during computer tasks needs to be investigated. The results seen in Chapter III, categorised the most common wrist postures frequented during a computer task. Unlike previous studies [56, 59, 60], these positions
encompassed both the extension/flexion and simultaneous radial/ulnar deviation of regular computer users. However, the effects of these wrist positions on the median nerve have not yet been investigated.

With that in mind, the focus of this section is to determine the effect of these wrist postures on CMAP data. This will indicate if a nerve dysfunction capable of damaging the median nerve is created. However, as nerve functionality decreases over a prolonged period of time applied pressures remain constant [37], it will also be necessary to maintain and monitor these wrist positions over an extended duration.

4.2 Materials and Methods

4.2.1 Participants

Fifteen healthy volunteers (12 male and 3 female), with no history or symptoms of CTS took part in this investigation. Participants’ ages ranged from 21-26 years with a mean age of 23.7 years. Of the 15 subjects, 12 had dominant right hands with the remainder being left handed. Prior to subjects taking part in this investigation they were required to fill out a subject information sheet and sign a consent form indicating that they understood what was entailed in the task. Any subject indicating that they were experiencing symptoms similar to CTS, such as numbness or wrist pain, were not considered for testing. This research method was reviewed and approved by the University of Limerick Research Ethics Committee.

4.2.2 Experimental Procedure

Participants were required to wear a specifically designed wrist support on their left hand to maintain a wrist posture associated with computer use. In this study five wrist postures were investigated. This resulted in three participants tested for each wrist posture. These included two base postures of 10° ulnar deviation (Ext0°Ulnar10°) and 20° ulnar deviation (Ext0°Ulnar20°). The three most common wrist postures employed during a typing process determined by means of motion analysis testing were also investigated. These were Ext20°Ulnar10°, Ext20°Ulnar20° and Ext30°Ulnar20°. These wrist postures were maintained for a duration of eight hours with nerve stimulation
being carried out at 30 minute intervals. Participants were allowed to move around during the testing period. However, excessive activity (jogging, exercising etc.) was prohibited. Subjects were also requested to maintain their hands in a pronated position as forearm supination and pronation have been shown to affect variables such as CTP [114]. This was only altered when the subject’s hand was placed in a supinated position for the purposes of carrying out NCS. Throughout the testing period sustenance was provided for all participants.

4.2.3 Wrist Support

All participants were required to wear a wrist support on the limb being tested for the duration of the testing period. This support was specifically designed to maintain the required wrist postures. It is composed of three distinct parts as shown in Figure 4.1 (a). Parts B and C slide over an aluminium bar of a predetermined angle (Parts A). Part B attaches to the forearm of the participant while part C secures the hand in the required position (Figure 4.1 (b)). This maintains the wrist posture being tested but allows for extension of the fingers. Alternative wrist postures can be obtained by interchanging the aluminium bar with alternative bars adjusted to the necessary angles.

![Wrist Support Diagram](image)

Figure 4.1 The images indicate (a) the parts and (b) application of wrist support used during testing.

4.2.4 Electrophysiological Testing

NCS was carried out in an isolated room with the participants seated in a relaxed position. Surface recording electrodes were placed on the abductor pollicis brevis muscle approximately 2-3 cm apart with a ground electrode placed on the dorsum of the wrist. The median nerve was stimulated at a location 7 cm proximal to the recording
site by a MLA265 Stimulator Rod (AD Instruments, Colorado Springs). The position of
the electrodes and stimulation point were marked on the subject. New electrodes were
placed on the subject on a regular basis to ensure results were not affected by a
reduction in electrode functionality. Nerve responses were recorded using a PowerLab
26T with Labchart software (AD Instruments, Colorado Springs). The skin temperature
over the palmar wrist was measured by means of a TN2 infrared thermometer (ETI,
West Sussex) prior to each motor nerve conduction test. Participants exhibiting a
temperature below 32° C had their limb warmed by means of a heat pack (Physiopack,
BSN Medical, Sweden) until the temperature at the palmar wrist was above this value
but not greater than 35° C.

Participants’ resting CMAP readings were taken with the wrist in a relaxed position.
This was followed by affixing the wrist support to the participant at the required angle
(Figure 4.1 (b)). Although use of the wrist splint minimized the pressure variances
placed on the median nerve due to wrist movement, current testing is still applicable.
Szabo and Sharkey (1993) [23] showed that “the average applied pressure, not the
cyclic loading, appeared to be the critical variable for nerve conduction”. This means
that during a cyclic compression of 30-60 mmHg, a constant pressure of 45 mmHg
would be representative of the cyclic loading. In a similar vein, maintaining CTP with a
fixed wrist posture would be equivalent to increasing and decreasing CTP by deviating
the wrist to the more extreme postures recorded during motion analysis. The postures
investigated would therefore replicate the wrist movements seen during the typing
activity. However, the effects of finger pressures and movements similar to those
applied during a computer activity were not assessed.

Initially, two readings were recorded at zero minutes with two further readings taken
every 30 minutes for an eight hour duration. The average of these two readings was
considered the recorded value at each 30 minute interval. If nerve conduction was
completely blocked before the completion of eight hours, testing was to be halted
immediately and the splint removed. However, this did not occur during testing.

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4.2.5 Data Analysis

The three values obtained from testing were the CMAP duration, CMAP amplitude and DML. The CMAP duration was from the onset of CMAP until its conclusion. The CMAP amplitude was considered to be the peak-to-peak value, while the DML was defined as the length of time from the stimulus to the onset of the CMAP. The percentage change in relation to time was calculated for all participants in each of these areas. For each participant, values greater than one standard deviation away from the previously recorded value were considered outliers and removed from analysis by passing the data through a filtering process. This was repeated until no change in data occurred or until a level of no greater than 30% of data was removed. This was a maximum amount of data that could be removed and was a level that was reached on only one occasion during testing. The mean value for each wrist position was determined and the best fit trendline to represent all data was fitted. The regression coefficients were also calculated for each posture.

The use of sensory nerve action potential (SNAP) data was also considered. SNAP amplitude has been shown to initially decrease at a similar pace to CMAP amplitude [123] and be beneficial at clinically grading the severity of CTS conditions [9]. It would also indicate if the sensory fascicles in the nerve are becoming damaged. However, a more recent study by Wilder-Smith et al. (2008) [10] found CMAP data to be a better linear indictor of median nerve damage in CTS. For this reason CMAP data was preferred as an indicator of nerve functionality in this study.

Computer based statistical analysis was carried out using SPSS software (v. 14.0, SPSS, Chicago Illinois). This entailed a means comparison being conducted by way of an independent samples t-test. Levene’s test was used to determine if equal variance was assumed. Statistical significance between the subjects’ genders and hand dominance was investigated.

Significance between values at the zero time step (zero minutes) and subsequent time steps for nerve conduction data was calculated by a paired sample t-test. A Pearson’s correlation coefficient was calculated to determine the relationship between time and percentage change. For all comparisons statistical significance was set at \( p < 0.05 \).
4.3 Results

A total of 15 left hands underwent NCS during this investigation. The mean values obtained for CMAP duration, CMAP amplitude and DML, while the wrist was in a relaxed supinated position, were 18.10±7.83 ms, 10.71±2.88 mV and 3.48±0.40 ms respectively. There was no statistical significance noted between the resting results for men and women (p = 0.655, 0.052 and 0.934 for CMAP duration, CMAP amplitude and DML respectively) or between subject’s hand dominance (p = 0.300, 0.858 and 0.732 for CMAP duration, CMAP amplitude and DML). The mean amplitude comparison between men and women was approaching significance, but this was not noticed in the other areas tested. A breakdown of this data can be seen in Table 4.1.
**Table 4.1** Mean results and standard deviations for CMAP duration, CMAP amplitude and DML with the corresponding p-values while the wrist is in a relaxed position.

<table>
<thead>
<tr>
<th>No. of Subjects</th>
<th>CMAP Duration (msec)</th>
<th>p-value</th>
<th>CMAP Amplitude (mV)</th>
<th>p-value</th>
<th>DML (msec)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Mean</td>
<td>15</td>
<td>18.10±7.83</td>
<td></td>
<td>10.71±2.88</td>
<td>3.48±0.40</td>
<td></td>
</tr>
<tr>
<td>Female Mean</td>
<td>3</td>
<td>16.20±12.95</td>
<td>0.655</td>
<td>12.60±1.05</td>
<td>3.50±0.25</td>
<td>0.934</td>
</tr>
<tr>
<td>Male Mean</td>
<td>12</td>
<td>18.61±6.69</td>
<td>0.052</td>
<td>10.19±3.04</td>
<td>3.48±0.44</td>
<td></td>
</tr>
<tr>
<td>Non Dominant Hand Mean Tested</td>
<td>12</td>
<td>19.27±6.68</td>
<td>0.300</td>
<td>10.79±3.03</td>
<td>3.50±0.39</td>
<td>0.732</td>
</tr>
<tr>
<td>Dominant Hand Mean Tested</td>
<td>3</td>
<td>13.78±11.83</td>
<td></td>
<td>10.43±2.83</td>
<td>3.42±0.52</td>
<td></td>
</tr>
</tbody>
</table>
The mean percentage change at each wrist posture for CMAP duration, CMAP amplitude and DML with respect to time can be seen in Figure 4.2 (a) & (b), Figure 4.3 (a) & (b) and Figure 4.4 (a) & (b). A second order polynomial trendline best fitted the recorded data. Following the eight hour period, CMAP duration (Figure 4.2 (a) & (b)) displayed a reduction in percentage change for all but one of the wrist postures investigated (Ext20°Ulnar20°). This indicates an increase in CMAP duration for a majority of the wrist postures during the testing period. However, the low $R^2$ values, indicated on the figures, calculated for the trendlines signify a poor correlation of the results.
Figure 4.2 The impact of positions involving (a) 10° ulnar deviation and (b) 20° ulnar deviation on CMAP duration over an eight hour period. Values showing statistical significance are denoted by an unfilled symbol. For each wrist posture investigated n=3.
A negative correlation can be noted in CMAP amplitude (Figure 4.3 (a) & (b)) through all wrist postures. This indicates a drop in amplitude, and therefore, a reduction in nerve functionality, in relation to time. This is most evident at Ext0°Ulnar10° and Ext30°Ulnar20°. However, a drop in amplitude of between 7% and 25% is noted in all wrist postures after eight hours.
Figure 4.3 The impact of positions involving (a) 10° ulnar deviation and (b) 20° ulnar deviation on CMAP amplitude over an eight hour time period. Values showing statistical significance are denoted by an unfilled symbol. For each wrist posture investigated n=3.
The results for DML (Figure 4.4 (a) & (b)) indicate a reduction in velocity (positive correlation) due to more extreme wrist postures. Although a reduction in percentage change is noted for the base postures and Ext20°Ulnar10° after eight hours, an increase is evident in the more extreme wrist postures. As would be expected, the greater the extension, the greater the velocity reduction.
Figure 4.4 The impact of positions involving (a) 10° ulnar deviation and (b) 20° ulnar deviation on DML over an eight hour time period. Values showing statistical significance are denoted by an unfilled symbol. For each wrist posture investigated n=3.
Although statistical significance is noted at certain time frames and wrist postures, as denoted in Figure 4.2, Figure 4.3 and Figure 4.4, the number of participants investigated at each wrist posture (n=3) makes it difficult to judge the weight of the statistical analysis. However, the trend of the results indicates a negative effect on the functionality of the nerve. This is clearly indicated by the Pearson’s correlation coefficient and p-value calculated for CMAP duration, CMAP amplitude and DML at each wrist posture investigated (Table 4.2). These data shows the majority of postures have a statistically significant change over the duration of the testing period (p < 0.05). The only exceptions to this were seen for CMAP duration and DML results.
Table 4.2 The Pearson’s correlation coefficient and p-value at each posture for CMAP duration, CMAP amplitude and DML.

<table>
<thead>
<tr>
<th>Wrist Posture</th>
<th>CMAP Duration</th>
<th>CMAP Amplitude</th>
<th>DML</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pearson's Correlation Coefficient</td>
<td>p-value</td>
<td>Pearson's Correlation Coefficient</td>
</tr>
<tr>
<td>U10</td>
<td>-0.439</td>
<td>0.078</td>
<td>-0.835</td>
</tr>
<tr>
<td>U20</td>
<td>-0.696</td>
<td>0.002*</td>
<td>-0.721</td>
</tr>
<tr>
<td>E20U10</td>
<td>0.007</td>
<td>0.979</td>
<td>-0.827</td>
</tr>
<tr>
<td>E20U20</td>
<td>0.256</td>
<td>0.322</td>
<td>-0.813</td>
</tr>
<tr>
<td>E30U20</td>
<td>-0.615</td>
<td>0.009*</td>
<td>-0.748</td>
</tr>
</tbody>
</table>

* Denotes highly significant data.
4.4 Discussion

Computer tasks often require wrist posture to deviate from the neutral position for prolonged periods. Knowing the effects of computer wrist postures on nerve functionality would aid in determining if computer use is capable of damaging the median nerve. If this happens, computer use could be associated to the development of CTS. A useful method for investigating nerve functionality or if nerve damage has occurred is CMAP data.

The results seen from the NCS indicate that the postures investigated increase the pressure placed on the median nerve to levels where functionality is reduced. Pressures of up to 20 mmHg have been shown not to impair nerve functionality [37]. This suggests that the pressure generated from these wrist postures is greater than this value. These postures have also been shown to account for approximately 30% of the wrist postures reached during a typing task. Occupations requiring numerous hours of computer activities would result in relatively large periods of time at these postures. If this was performed on a daily basis, it may be a contributing factor in the development of CTS. This is evident from previous studies that show computer use and cumulative computer use is associated with CTS and other upper limb disorders [117, 124, 125]. Gerr et al. (2002) [125] found that as little as 15 hours of computer use per week, resulted in 1% of healthy computer users with no symptoms of CTS to be electrodiagnostically and clinically confirmed with CTS within their first year at a new job. Of the employees investigated, 50% of them also reported symptoms of upper limb disorders. Although these studies depict a link between CTS and computer use, not all investigations concur. Andersen et al. (2003) [126] and Stevens et al. (2001) [127] found no association between CTS and computer use. However, it is due to the conflicting conclusions of these studies that further investigation is warranted.

For all wrist postures tested, a negative correlation can be seen for the CMAP amplitudes. This indicates an impairment of nerve functionality. This corresponds to the study of Hargens et al. (1979) [37] that determined CMAP amplitude reduced with time once constant constraint (in this case pressure) was maintained. It would also be expected that greater deviations from the neutral position would result in a greater
degree of nerve dysfunction. However, this was not the case in this study. The position Ext0°Ulnar10° shows the greatest reduction in CMAP amplitude even though it only slightly deviates from the resting position. Although Ext30°Ulnar20° is the second largest reduction in amplitude, the expected order is not resumed as Ext20°Ulnar20° showed the lowest percentage change of all postures tested. Although the furthest wrist postures form the neutral position did not exhibit the greatest reduction in nerve functionality as anticipated, an overall decrease in amplitude is evident. Reductions of up to 20% of amplitude are evident for all wrist deviations indicating nerve functionality reduces over time.

This is further iterated by the results seen for DML and CMAP duration. The DML can be seen to lengthen after eight hours in wrist postures that are further away from the neutral position. This is similar to results seen by Tankisi et al. (2007) [128] where lower CMAP amplitudes correspond to extended DMLs. Greater deviations from the resting wrist posture also indicate a longer DML. The visible reduction at the later stages of the testing is most evident in the base postures. This is in part explained by Rempel et al. (1997) [49]. This study measured the pressure within the carpal tunnel using a saline filled, blunt tipped, multiperforated 20 gauge catheter as wrist posture was varied using a test rig. It found that a position of 10° ulnar deviation exhibited a lower CTP when compared to a neutral posture. A reduction in CTP would not damage the nerve and therefore result in minimal changes to nerve functionality. Although this finding is not echoed in other studies [33, 50], it still indicates that variations can occur depending on the subject group.

In contrast to DML, CMAP duration indicated an increase in velocity after 8 hours for a majority of the postures. These findings agree with those of Stecker et al. (2008) [68]. Although a prolonged duration may be anticipated, Stecker’s study explained that CMAP only probes rapidly conducting myelinated axons of alpha motor neurons and not slow conducting C fibres which would result in an increased duration, as stated by Battista and Albans (1983) [129]. Even though CMAP duration decreases in Stecker’s study, the change was not as substantial as that in CMAP amplitude. The results recorded for DML were also not significant until a reduction of approximately 50% of CMAP amplitude occurred. Based on the results previously noted by Stecker et al. (2008) [68], and other studies [10, 37], CMAP amplitude appears to be the best
Chapter IV Compound Muscle Action Potential of the Median Nerve

indicator of nerve damage. This is further emphasised by the $R^2$ values produced for the results in this investigation. These values for the CMAP amplitude are clearly a better fit and show greater consistency than those for CMAP duration and DML. Although these values may improve for all results with greater numbers of participants, it highlights the capabilities of CMAP amplitude. However, complementary information may also be obtained from CMAP duration and DML.

Although statistical analysis was conducted on the results, a greater number of subjects would be advantageous. Statistical significance is noted at certain timeframes and wrist postures, as denoted in Figure 4.2, Figure 4.3 and Figure 4.4, but the number of participants investigated at each wrist posture devalues these results. For statistically relevant data to be obtained numerous more subjects would be necessary. However, the trend of the results is still important and indicates a negative effect on the functionality of the nerve due to wrist posture.

4.4.1 Limitations

Firstly, the number of participants used and the number of wrist postures investigated was limited. The small numbers involved in this study prevented beneficial statistical analysis from being conducted. However, the data presented were significant to demonstrate a relationship between wrist posture and a reduction in nerve functionality.

Secondly, the effect of wrist pronation and supination was also not monitored during the testing procedure. Ideally, no movement of the hand or arm would occur, but due to the duration of the investigation, restricting this movement would be both difficult and also reduce the comfort of the participants. However, the request of the investigators to limit this movement was adhered to and movement was minimal.

Thirdly, CTP was not recorded during testing. To determine if nerve functionality varied due to contact of hydrostatic pressures generated from wrist posture, pressure measurements would be advantages. This may give a better insight to the cause of the nerve dysfunction.
Finally, SNAP data were not recorded. Although CMAP data were the preferred choice for this study, SNAP data may have given greater information about nerve functionality. Acquiring both sets of results would have given insight into the effects of prolonged posture on the sensory nerve fibres.

### 4.5 Conclusions

In conclusion, it may be noted that nerve functionality is reduced when the wrist is placed in any of the postures investigated in this study. Amplitude shows the greatest variations with respect to time and is the clearest indicator of nerve dysfunction during testing. Although the most extreme wrist positions do not always correspond to the greatest reduction in nerve functionality, an overall decrease in nerve ability is evident.
Chapter V

Diagnostic Criterion for CTS: 3-D Reconstructions of the Median Nerve Created from Ultrasound Images
5.0 Diagnostic Criterion for CTS: 3-D Reconstructions of the Median Nerve Created from Ultrasound Images

5.1 Introduction

The sonographic criteria previously discussed in Chapter II have been shown to have a varying degree of success when diagnosing carpal tunnel syndrome (CTS). This has resulted in nerve conduction studies (NCS) remaining the predominant tool for CTS diagnosis. However, Chapter IV has shown that the NCS data of subjects without CTS indicate a reduction in nerve functionality due to prolonged wrist deviation. This would lead to the possibility of incorrect diagnosis occurring if patient’s wrist posture prior to and during NCS resulted in abnormal nerve responses. Cyclic motion has also been shown to maintain these elevated pressures [5]. This will in turn impact NCS data and may lead to false positives or the level of severity being overestimated.

Although NCS indicate the pressure increase within the carpal tunnel, it does not give an exact value or convey the cause of the increase. Cysts or other inclusions evident and affect the treatment options. The advantage of imaging techniques in these instances is undisputable. Sonography is a suitable imaging tool for determining inclusions but has limitations in terms of general diagnosis. However, continuing advancements in sonographic technology and image quality is resulting in a reassessment of the benefits and capabilities of ultrasound. The widespread availability of ultrasound in relation to NCS is also beneficial as it reduces the time until diagnosis can be made and increases the number of diagnosis locations. The development of 3-D ultrasound in particular creates an opportunity for new diagnostic criteria to be investigated. Using a unique method to create a 3-D reconstruction, this study examines the use of median nerve volume as an indicator of CTS and its severity. This is accomplished by using a number of B-scans to create a computational model from which the volume measurements can be calculated. The accuracy of this method is also compared to other recognized methods of CTS classification.
The advantages of computationally modelling the anatomical features of patients to determine the extent and severity of certain conditions have widely been investigated. These 3-D reconstructions are often created from MRI or CT scans [130-132]. However, the advancements in imaging technology have led to sonography becoming a valuable, convenient and cost effective alternative. Numerous sonographic methods exist to create 3-D representations of the anatomy. These include linear scans, fan scans and rotational scans. Although these methods are utilised, they do not match the freehand scan approach in terms of cost or flexibility [133], as specialised transducer assemblies or mechanical rigs are not required.

To obtain transducer location, a tracking system is used in conjunction with the imaging modality. This system calculates the transducer position in 3-D space and the resultant position of the obtained image. This would show a much greater accuracy than position estimation by eye. Freehand scans also have a clear advantage over current 3-D ultrasound as 2-D transducers have a higher resolution than 3-D transducers, leading to better image quality [134]. This is of high importance if precise models are to be created. The numerous advantages evident for this approach make it the most suitable method for 3-D modelling of the median nerve.

The most established methods of transducer positioning during freehand scans are electromagnetic positioning devices and optical tracking sensors. Although electromagnetic positioning devices are a prominent way of determining transducer position, errors can occur due to electromagnetic noise or metal objects within the operating environment. A complete operating system would also need to be purchased for this method. However, this is the case for most positioning systems and is also necessary for optical tracking sensors. Optical tracking sensors are often comprised of infrared cameras that register the light of reflective markers. This leads to positional data being calculated. However, it is necessary for all other reflective material to be removed from the test area to easily track the reflective markers. Since it may not be feasible to obtain the necessary equipment and restrict the sources of error in all clinical settings, an alternative positioning technique is presented in this study.
5.2 Materials and Methods

5.2.1 Participants

Thirty five volunteers (12 CTS patients and 23 asymptomatic subjects) took part in this investigation. This resulted in 17 CTS wrists and 23 asymptomatic wrists being investigated. A full break down of the number of subjects and the wrists tested can be seen in Table 5.1. The presence of CTS was clinically and electrodiagnostically confirmed in all 12 patients. All participants were given an information sheet regarding the study and the protocol involved within the ultrasound examination. Each participant was required to sign a consent form indicating they understood what was involved and that they were willing to take part in the study. However, participants retained the right to withdraw from the study at any time. Prior to the examination, CTS patients were requested to fill out a Boston Carpal Tunnel Questionnaire (BCTQ) (Appendix C) to obtain a patient orientated severity measurement [135]. This questionnaire assessed the patient’s symptom severity and functional status by asking a total of 19 multiple choice questions (11 and 8 questions in each area respectfully) that graded severity and functionality on a five point system. This research method was reviewed and approved by the University of Limerick Research Ethics Committee and the Health Service Executive (HSE) Ethics Research Committee in the Mid-Western Area.

Table 5.1 Break down of CTS patients and controls tested throughout this study.

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTS Patients</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. Of Subjects</td>
<td>4</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Symptomatic Left Wrist</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Symptomatic Right Wrist</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Bilateral Symptoms</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Number of Wrists Tested</td>
<td>7</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>Controls</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of Subjects</td>
<td>14</td>
<td>9</td>
<td>23</td>
</tr>
<tr>
<td>Left Wrist Imaged</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Right Wrist Imaged</td>
<td>14</td>
<td>9</td>
<td>23</td>
</tr>
<tr>
<td>Number of Wrists Tested</td>
<td>14</td>
<td>9</td>
<td>23</td>
</tr>
</tbody>
</table>
5.2.2 Patient Severity

CTS was confirmed in all patients by means of nerve conduction studies (NCS). This was carried out using a Nihon Kohden Neuropack SI unit (Nihon Kohden Corporation, Tokyo, Japan) with silver silver chloride disposable electrodes. NCS were performed in accordance with normal electrodiagnostic practices and adhered to the practice parameters of the American Association of Electrodiagnostic Medicine (AAEM). This included obtaining distal motor latency (DML), compound muscle action potential (CMAP) amplitude, motor conduction velocity (MCV), distal sensory latency (DSL), sensory nerve action potential (SNAP) amplitude and sensory conduction velocity (SCV). CTS confirmation and condition severity were determined by two experienced consultant neurologists taking all NCS results into account. Patients diagnosed with CTS were graded into one of three categories based on the NCS findings; mild, moderate or severe. All patients were subsequently recommended for carpal tunnel release surgery to treat the condition.

5.2.3 Ultrasound Imaging

Two ultrasound machines were used for this study. CTS patients were tested on a Siemens Acuson Sequoia 512 (Siemens AG, Erlangen, Germany) with a 15L8W linear transducer. Images obtained from this machine were automatically saved as Digital Imaging and Communications in Medicine (DICOM) images. These were subsequently opened in MATLAB Version 7.3.0.267 (Natick, Massachusetts, USA) and saved as JPEG images. Asymptomatic volunteers were tested using a GE LOGIQ e portable ultrasound machine with a GE 12L-RS linear array transducer (General Electric Healthcare Technologies, Waukesha, Wisconsin, USA). This system allowed for the export of images as JPEGs, resulting in no need for image conversion software to be applied.

5.2.4 Transducer Positioning

Photogrammetric techniques were used to calculate the transducer position during testing. This involved the use of photogrammetric software known as PhotoModeler (Eos Systems Inc., Vancouver, Canada) and two SLR cameras; a Sony DSLR-A220 with a ALC-SH0006 lens (Sony Corporation, Tokyo, Japan) and a Canon EOS 50D (Canon...
Inc., Tokyo, Japan) with a Tamron AF 28-75mm f/2.8 XR Di LD lens (Tamron Co., Ltd., Saitama, Japan). Prior to determining the transducer position, it was necessary for the respective cameras to be calibrated to account for the focal length and lens distortion. This was conducted for each camera by taking 12 photographs of a calibration grid (Figure 5.1). These photographs were taken from the four sides of the grid with the camera in a landscape and portrait orientation. These images were uploaded into the PhotoModeler software and the automatic camera calibration was conducted.

![Figure 5.1 Calibration grid used for camera calibration.](image)

To obtain accurate positional data for the transducer during the testing of each patient, a checkered grid was placed under the test area. An object of known dimensions was placed on the grid and numerous photographs centring on the object were taken from varying orientations. This object was modelled in PhotoModeler by defining points, such as corners, in each image and cross referencing them to other images visually displaying the same points. The known measurements and orientations were then applied to calculate scale. This dimensionalised the area in which the subject’s arm would be placed once the object was removed. Points on the chequered grid below the object were also cross referenced from the photographs taken and their positions determined. These points acted as fixed reference points throughout the testing. Once the test area had been fully photographed, the two cameras were strategically positioned on the left and right of the test area in an advanced position. The cameras were
mounted on stands at the necessary height and Young Nou Digital wireless receivers were attached (Hong Kong Yong Nuo Photographic Equipment Co. Ltd., Kowloon, Hong Kong). The wireless receivers on both cameras were set to the same frequency as an accompanying transmitter resulting in pictures being taken simultaneously with both cameras.

A reference marker was attached to the transducer at a fixed position (Figure 5.2). This was necessary as precise locations are obtained from points which can be easily cross referenced. However, the profile of the transducer has no clearly defined corners or edges making cross referencing difficult without such an aid.

![Figure 5.2 Ultrasound transducer and attached reference marker.](image)

During the patient examination the transducer progressed along the subject’s forearm and wrist, obtaining ultrasound images at various positions. To know the location of the transducer for each of these images, corresponding digital photographs were taken of the test area using the SLR cameras. These photographs were imported into the PhotoModeler software where the positions of three points on the reference marker were calculated in 3-D space (Figure 5.3). The accuracy of this software can be as high as 1:50000 with coordinate accuracy previously been shown to reach 1:8000 [136]. This was repeated for each corresponding ultrasound image. This information led to the position and orientation of the transducer head being calculated.
5.2.5 Experimental Procedure

Following a detailed explanation of the study objectives and testing protocol, subjects were seated facing the test area. They were instructed to place their forearm in a supinated position within the test area. An adjustable chair was used to obtain a comfortable height for each subject that allowed for minimal flexion of the elbow. This was necessary as the median nerve has been shown to migrate proximally by 12.3 mm due to 90° elbow flexion [137]. This would result in inconsistent nerve segments being reviewed if elbow flexion varied from subject to subject. A preliminary sweep scan of the median nerve was taken and recorded. This spanned from approximately the mid-forearm to the distal end of the carpal tunnel. This was to aid in nerve identification in the ultrasound images if necessary.

Following all preliminary procedures, subjects were requested to remain motionless for the remainder of the ultrasound exam. A sweep scan of the median nerve was once
again performed. In this instance, still ultrasound images were obtained at varying points along the course of the nerve similar to Figure 5.4. Photographs of the test area were taken simultaneously with the ultrasound images. A minimum of 14 images were obtained for each subject.

**Figure 5.4** Obtaining still ultrasound images along the course of the nerve.

### 5.2.6 Median Nerve Reconstruction

The positional data of the three points calculated from the reference marker attached to the ultrasound transducer at each photographic image location was imputed into the university edition of Pro/ENGINEER Wildfire 4.0 from PTC (PTC Corporate Headquarters, Massachusetts, USA). This consisted of three positions from the reference marker that were used to create a plane parallel to the plane of the ultrasound image. The ‘Trace Sketch’ function within the ‘Style’ tool was used to map an ultrasound image onto the individual plane. The positional data obtained from the reference marker acted as a guide for image placement. The offset of the image from the marker position had previously been determined during the transducer positioning phase. This procedure was repeated for all images. Once all images were placed and orientated in the correct location, they were scaled to actual size. Sketches were drawn on each plane using the ‘Spline’ tool. These sketches outlined the median nerve within the hyperechoic rim or epineurium. A boundary blend was formed between sketches to
create the nerve surface. Converting this to a solid structure required the extremities of the nerve to be enclosed. This was done by employing the ‘Fill’ tool at the initial and final sketches. These were merged to the boundary blend and the entire structure solidified using the ‘Solidify’ tool. This resulted in a complete 3-D representation of the median nerve (Figure 5.5).

Figure 5.5 Image of the median nerve (red) as (a) it passes through the ultrasound images that define its geometry and (b) with the ultrasound images removed.

5.2.7 Data Analysis

An area immediately proximal to the carpal tunnel and distal end of the carpal tunnel were defined using the anatomical landmarks of the radioulnar joint and hook of hamate respectfully. These were identified from the ultrasound images (Figure 5.6). The volume of the median nerve within these landmarks was calculated in the reconstructed model. A nerve segment of equal length originating from the radioulnar articulation in a proximal direction was defined and the volume of this segment once again recorded. This procedure was repeated two further times with the originating position classified as the conclusion of the previous segment. This led to a total of four volumes being recorded for each subject; the initial nerve volume between the radioulnar joint and hook of hamate encompassing the nerve volume within the carpal tunnel (NVCT), nerve
volume of the segment of identical length to NVCT immediately proximal to it (NVP1), nerve volume of the segment of identical length to NVCT immediately proximal to NVP1 (NVP2) and nerve volume of the segment of identical length to NVCT immediately proximal to NVP2 (NVP3) (Figure 5.7). A value for volume ratio was calculated by dividing NVP1, NVP2 and NVP3 by NVCT.

![Figure 5.6](image)

**Figure 5.6** Sonographic images of the anatomical landmarks used to define (a) the radioulnar articulation and (b) the hook of hamate.

Statistical analysis was computationally conducted using SPSS software (v. 16.0, SPSS, Chicago, Illinois). This compared the means of the controls and all patients for each volume ratio by means of an independent samples t-test. Equality of variances was assessed using Levene’s test leading to statistical significance between subjects and controls being determined. Statistical significance within the severity groups was evaluated by comparing the mean values using the One-Way ANOVA option. This method was also used in determining if significance was noted for the volume ratio within patients and controls. If the assumption for homogeneity of variances was not met, the Brown-Forsythe and Welch methods were employed to determine if the statistical data was relevant. A post hoc analysis was conducted to determine which aspects were responsible for the difference. This utilized Bonferroni’s algorithms if equal variance was assumed and Games-Howell algorithms if equal variance was not assumed. For all statistical analysis statistical significance was set at $p < 0.5$. 
**Figure 5.7** An illustration of the nerve segments used to calculate volume ratio from the distal (NVCT) to the proximal (NVP3) portion of the median nerve.

### 5.3 Test Method Validation

#### 5.3.1 Reconstruction Validation

Validation of the 3-D reconstruction method used in this study was carried out in two ways. First, both an ultrasound and MRI reconstruction of one subject’s median nerve was created and compared. This is beneficial as MRI has been described as superior than ultrasound in providing information regarding bony and soft tissue damage and is capable of providing high resolution images of the carpal tunnel and its contents [138, 139]. It has also been used for creating 3-D models of the carpal tunnel and in the calculation of volume measurements of carpal tunnel contents [140, 141]. The second validation method involved using a specifically designed ultrasound phantom. This would compare a model of known dimension and shape to the reconstructed ultrasound model.
The 3-D reconstruction from MRI was created using similar techniques to the ultrasound models. The parameters for the MRI process are indicated in Table 5.2. In this instance, 42 parallel images equally spaced at 1.3 mm were used for the creation of the model. This created a length of nerve that encompassed NVCT and NVP1. The images were imported into Pro/ENGINEER Wildfire 4.0 (, Massachusetts, USA) and scaled to actual size. The outline of the median nerve was defined and a 3-D representation of the nerve created as previously described. For a comparison to be made between both reconstruction models, the outline of the median nerve in the ultrasound model was redefined as the area outside the hyperechoic rim. This was necessary as ultrasound diagnosis generally defines the border of the nerve within the hyperechoic rim as it can be clearly identified. However, the nerve defined from MRI likely encompasses the hyperechoic rim resulting in a greater area measurement if not accounted for [142]. Once this was taken into consideration, the segment of the nerve was trimmed to be identical in length to the NVCT and NVP1. The volume of the nerve was calculated for these two segments and compared to that of the ultrasound model. The area at the proximal and distal end of these segments was also computed for the MRI and ultrasound models. This led to four area measurements being recorded for each reconstruction method (Area 1-4) (Figure 5.8). These data were once again compared.

<table>
<thead>
<tr>
<th>MRI Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slice Thickness</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>230 x 284 pixels</td>
</tr>
<tr>
<td>Field of View</td>
<td>150 x 200 mm²</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>0.598 x 0.652 mm²</td>
</tr>
</tbody>
</table>

The specifically designed phantom was constructed from a gelatine based tissue-mimicking material (TMM). Gelatine has commonly been used in the construction of phantoms with various additives, such as flour, graphite and Metamucil (a dietary fiber supplement (Proctor & Gamble, Cincinnati, Ohio)), being included to obtain more realistic models [143-147]. In this instance, 0.3μm Al₂O₃ powder was added. This would affect the attenuation of the phantom and modify the backscatter to mimic tissue. This material has previously been added to agar based TMMs to obtain a similar affect.
However, obtaining the precise acoustic properties of tissue was not a necessity in this instance with the main objective placed on acquiring an echogenic medium.

![Diagram showing the location of area measurements in relation to the nerve volume within the carpal tunnel (NVCT) and nerve volume of the segment of identical length to NVCT immediately proximal to it (NVP1).](image)

Figure 5.8 Location of the area measurements in relation to the nerve volume within the carpal tunnel (NVCT) and nerve volume of the segment of identical length to NVCT immediately proximal to it (NVP1).

A silicone model of an idealised abdominal aortic aneurysm (AAA) was the object utilised in this reconstruction Figure 5.9. This was chosen as it would retain water and displayed suitable geometric and dimensional changes for validation. The silicone model was created as per Corbett et al. (2009) [149]. The model was sealed at all bar one orifice and filled with water, ensuring minimal trapped air remained. The final opening was occluded and the model checked for leaks. The model was placed in the test container with restrictions placed above the extremities of its branches. This was necessary as the water filled model had a lower density than that of the gelatine mixture. This resulted in it floating to the top, preventing it from being entirely surrounded by the
gelatine. The restrictions allowed the model to float to a central height within the test container without deforming the model.

![Figure 5.9](image)

**Figure 5.9** Front and side view of the silicone model of idealised AAA.

The phantom mixture was created by gradually adding 20 g of unflavoured gelatine (Dr. Oetker powdered gelatine, Leeds, United Kingdom) to every 250 ml of boiling water while continuously stirring. Once the gelatine has been completely dissolved, 7.5 g of 0.3µm Al₂O₃ powder was also added for every 250 ml of water and uniformly dispersed throughout the mixture. The mixture was then poured into the test container, engulfing the silicone model. The mixture was finally allowed to cool and solidify.

Once the phantom was ready for testing, ultrasound images were obtained and the idealised AAA was computationally reconstructed as previously described in section 5.2.6. This was conducted on two distinct occasions to determine if a large variance was evident. The idealised AAA, on which the ultrasound model was recreated, was trimmed to the equivocal length of the reconstructed model. This allowed for accurate
comparisons to be made between the ultrasound model and a precise geometry model (idealised model trimmed to have the same length as the ultrasound model). These comparisons related to object volume, geometry and centroidal position.

5.3.2 Comparative Results

The comparison between the 3-D nerve reconstruction created from MRI and ultrasound images indicate a high similarity for the volume and area measurements obtained (Table 5.3). A percentage difference of less than 6% is evident for the volumes of both segments measured. This indicates a high level of precision in both methods for modelling the median nerve. The similarities are further emphasised with the area measurements. Areas 1-3 have a percentage difference ranging from 1.24-5.26%. Although this value increases to 15.36% for area 4, it does not adversely affect the accuracy of the volume measurement.

<table>
<thead>
<tr>
<th>Table 5.3 Volume and area measurements for segments NVCT and NVP1.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurement</strong></td>
</tr>
<tr>
<td>NVCT</td>
</tr>
<tr>
<td>NVP1</td>
</tr>
<tr>
<td><strong>Area</strong></td>
</tr>
<tr>
<td>Area 1</td>
</tr>
<tr>
<td>Area 2</td>
</tr>
<tr>
<td>Area 3</td>
</tr>
<tr>
<td>Area 4</td>
</tr>
</tbody>
</table>

The reconstructed models of the idealised AAA using ultrasound can been seen in Figure 5.10. These models were compared to an equivalent sized AAA of precise geometry. The volume of each model was calculated for each validation scan (VS1 and VS2) and the percentage difference calculated. The results of these findings can be seen in Table 5.4.
Table 5.4  Volume measurement and percentage difference between the equivocally sized AAA of known geometry and the corresponding ultrasound reconstructions (VS1 and VS2).

<table>
<thead>
<tr>
<th>Validation Attempt</th>
<th>Precise Geometry ($10^5 \text{mm}^3$)</th>
<th>Ultrasound Model ($10^5 \text{mm}^3$)</th>
<th>Percentage Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VS1</td>
<td>0.919</td>
<td>0.905</td>
<td>1.52</td>
</tr>
<tr>
<td>VS2</td>
<td>0.904</td>
<td>0.887</td>
<td>1.91</td>
</tr>
</tbody>
</table>

To determine the geometric accuracy, the ultrasound AAA model was superimposed over the precise geometry model in a similar orientation. This gave a visual indication of the accuracy and geometrical alignment of the ultrasound reconstruction (Figure 5.11). This was numerically analysed in two ways: by determining the amount of volume coincidence between the precise geometry and ultrasound model and by centroidal comparison. The first method would calculate a 100% coincidence between the ultrasound model and the precise geometry model, if they matched exactly. This geometric coincidence was calculated using the analysis options in Pro Engineer. For the models VS1 and VS2 created in this instance, values of 82.01% and 83.77% were obtained respectfully.

Centroidal comparison was conducted to confirm both geometric accuracy and dimensional insignificance for model reconstruction. Ideally centroidal position would remain minimal regardless of model size or dimensions. Mean centroidal errors of 1.91 mm and 0.54 mm were noted for the models VS1 and VS2 respectfully. These were the mean distances calculated from the centroid of the precise geometry model to a
centroidal line of the ultrasound models across an intersecting plane. These planes were at increments of 5 mm spanning from the onset of model coincidence until its conclusion. The distance between centroids on the planes was calculated using a specifically written MATLAB program (Appendix D) and the mean errors calculated.

Figure 5.11 A visual representation of the coincidence between the precise geometry (gray) and ultrasound model (red) for (a) VS1 and (b) VS2. The percentage coincidence was determined by the amount of overlap between the two models.
5.4 Results

5.4.1 Median Nerve Volume

The median nerve volumes within the carpal tunnel and at three equivalent locations immediately proximal to the carpal tunnel were measured and recorded (Figure 5.12). This resulted in ratios of NVP1:NVCT, NVP2:NVCT and NVP3:NVCT being calculated (Figure 5.13). The mean volumes and volume ratios for patients and controls can be seen in Table 5.5. The p-values calculated following the comparison of controls to patients are also indicated. The nerve volume of patients can be seen to be substantially higher with regard to sections NVCT and NVP1. The statistical significance of these data indicates a substantial difference in median nerve volume within the carpal tunnel and NVP1. The increase in volume ratio NVP1:NVCT noted for patients when compared to controls also indicates swelling of the nerve directly proximal to the carpal tunnel at NVP1. This supports the data recorded for nerve volume. The volume ratio can also be seen to decrease for patients, as volumes are calculated using more proximal nerve sections (p < 0.001). This is not evident for control ratios with these values remaining relatively constant, or increasing, as volumes are taken more proximally (p=0.309).
Figure 5.12 Volume measurements of controls and patients for different nerve segments along the median nerve.

Figure 5.13 Volume ratios for patients and controls with corresponding trendlines.
Table 5.5 Mean volumes and volume ratios with standard deviations for participants with corresponding p-value for each computed ratio. p-values were determined using the independent samples t-test.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Controls</th>
<th>Patients</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 23</td>
<td>n = 17</td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NVCT (mm³)</td>
<td>153.6±72.7</td>
<td>220.5±110.2</td>
<td>0.024</td>
</tr>
<tr>
<td>NVP1 (mm³)</td>
<td>189.4±84.3</td>
<td>268.6±114.5</td>
<td>0.015</td>
</tr>
<tr>
<td>NVP2 (mm³)</td>
<td>184.8±82.9</td>
<td>175.7±51.3</td>
<td>0.668</td>
</tr>
<tr>
<td>NVP3 (mm³)</td>
<td>203.9±103.9</td>
<td>151.2±54.1</td>
<td>0.070</td>
</tr>
<tr>
<td>Volume Ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NVP1:NVCT</td>
<td>1.27±0.33</td>
<td>1.32±0.41</td>
<td>0.626</td>
</tr>
<tr>
<td>NVP2:NVCT</td>
<td>1.25±0.34</td>
<td>0.92±0.35</td>
<td>0.004</td>
</tr>
<tr>
<td>NVP3:NVCT</td>
<td>1.40±0.48</td>
<td>0.82±0.32</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

A breakdown of patient severity compared to controls can be seen in Figure 5.14. Similar to the overall results, clear differences in the volume ratios are observed at each severity level with controls remaining relatively unchanged. Volume increases in NVCT and NVP1 are once again indicated across the severities with similar trends noted across the volume ratios at each of these instances. A negative trend is evident for the severities of all the volume ratios calculated. This resulted in a linear trendline being fitted to the three volume ratios calculated (Figure 5.15). NVP2:NVCT showed a clear linear trend ($R^2=0.989$) with NVP3:NVCT also showing similar findings. However, determining the presence or severity of CTS due to NVP1:NVCT does not seem feasible from the results obtained. Although a decrease in volume ratio is noted for all severity levels of NVP2:NVCT and NCP3:NVCT when compared to control subjects, this is not the case for NVP1:NVCT. This shows an increase in volume ratio for mild and moderate patients.
Figure 5.14 Mean volume ratios and standard deviations for participants as defined by severity.

Figure 5.15 Linear trendlines fitted to the mean volume ratios as defined by severity.
The results of the BCTQ, NCS and volume ratio data for patients are indicated in Table 5.6 in terms of severity. The BCTQ data are in contrast to those seen for the NCS and volume ratio. Symptom severity and functional status are highest for subject’s electrodiagnostically confirmed to have mild CTS. This indicates that subjects with mild CTS have greater difficulties in performing everyday tasks and believe the pain they are experiencing to be quite intense.

Table 5.6  The mean and standard deviations obtained for the BCTQ, NCS and volume ratio overall and at each severity level.  p-values were determined using one-way ANOVA between mild, moderate and severe cases only.

<table>
<thead>
<tr>
<th>Nerve Conduction Determined Severity</th>
<th>All Cases n = 17</th>
<th>Mild n = 9</th>
<th>Moderate n = 3</th>
<th>Severe n = 5</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCTQ Symptom Severity</td>
<td>2.82±0.86</td>
<td>3.35±0.66</td>
<td>2.27±0.47</td>
<td>2.71±0.96</td>
<td>0.210</td>
</tr>
<tr>
<td>BCTQ Functional Status</td>
<td>2.23±0.92</td>
<td>3.20±0.71</td>
<td>1.96±0.75</td>
<td>1.78±0.67</td>
<td>0.008</td>
</tr>
<tr>
<td>NCS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DML (ms)</td>
<td>5.44±2.19</td>
<td>3.82±0.05</td>
<td>4.47±0.19</td>
<td>6.67±2.44</td>
<td>0.034</td>
</tr>
<tr>
<td>CMAP (mV)</td>
<td>6.38±5.35</td>
<td>10.90±4.97</td>
<td>10.19±5.84</td>
<td>2.61±1.48</td>
<td>0.002</td>
</tr>
<tr>
<td>MCV (m/s)</td>
<td>52.30±3.87</td>
<td>52.52±1.57</td>
<td>53.47±1.03</td>
<td>51.38±6.30</td>
<td>0.783</td>
</tr>
<tr>
<td>DSL (ms)</td>
<td>2.85±0.51</td>
<td>3.02±0.52</td>
<td>2.73±0.20</td>
<td>2.44±0.31</td>
<td>0.152</td>
</tr>
<tr>
<td>SNAP (μV)</td>
<td>7.02±4.15</td>
<td>8.90±2.36</td>
<td>9.30±4.83</td>
<td>5.26±4.74</td>
<td>0.326</td>
</tr>
<tr>
<td>SCV (m/s)</td>
<td>42.83±4.65</td>
<td>43.18±2.55</td>
<td>39.13±5.81</td>
<td>46.06±4.19</td>
<td>0.194</td>
</tr>
<tr>
<td>Volume Ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NVP1:NVCT</td>
<td>1.32±0.41</td>
<td>1.46±0.57</td>
<td>1.31±0.41</td>
<td>1.25±0.34</td>
<td>0.679</td>
</tr>
<tr>
<td>NVP2:NVCT</td>
<td>0.92±0.35</td>
<td>1.09±0.34</td>
<td>0.97±0.37</td>
<td>0.80±0.34</td>
<td>0.324</td>
</tr>
<tr>
<td>NVP3:NVCT</td>
<td>0.82±0.32</td>
<td>0.98±0.21</td>
<td>0.92±0.54</td>
<td>0.68±0.25</td>
<td>0.213</td>
</tr>
</tbody>
</table>

1. For sensory conduction testing, the severity of some cases resulted in no values being recorded.

As would be expected, the results of the NCS generally signify a lower state of functionality due to an increase in severity. This is clearly indicated by the distal motor latency (DML) and compound muscle action potential (CMAP) amplitude. Distal sensory latency (DSL) shows a reduction in response time as severity worsens while little change is seen for motor conduction velocity (MCV) with sensory nerve action.
potential (SNAP) amplitude and sensory conduction velocity (SCV) showing contrasting results due to an increase in severity.

The results of the volume ratio compare favourably with the defined severity. A progressive decrease in volume ratio can be seen as severity increases. This is most beneficial for NVP2:NVCT and NVP3:NVCT as these values are also lower than values obtained for control subjects as indicated in Figure 5.14. The breakdown of the statistical data can be seen in the post hoc analysis in Appendix E. This indicates which comparisons between the severities of mild, moderate and severe were statistically significant for each CTS indicator.

To determine the capabilities of volume ratio as an indicator of severity, linear trendlines were fitted to the recorded data and $R^2$ values calculated. This was carried out for all diagnostic methods availed of in this study, to establish if any method showed linearity for increased severity (Figure 5.16). Volume ratio shows the greatest linear trend with $R^2$ values ranging between 0.882 and 0.973. NCS of motor nerves also illustrate a strong linear trend for DML ($R^2 = 0.910$) and CMAP amplitude ($R^2 = 0.813$), but are not as promising as volume ratio. A good linear fit is also noted for DSL ($R^2 = 1.000$) and the BCTQ functional status scale ($R^2 = 0.843$). However, these data display an increase in functionality as severity worsens, contradicting the diagnosis and other results.
5.5 Discussion

The diagnostic advantages of sonography for CTS are evident from previous studies [87, 88]. However, the accuracy and consistency of certain diagnostic criteria has been brought into question. This study’s objective was to investigate an alternative diagnostic criterion which could surpass alternative methods of diagnoses and be capable of assessing CTS severity. The proposed method in this study was volume ratio. Prior to assessing this approach of CTS diagnosis, the acquisition of the nerve volume had to be assessed. The method used to reconstruct a 3-D model from ultrasound and in turn obtain a volume measurement, is similar to alternative method
that utilized optical tracking sensors. In this instance transducer position and orientation were calculated with the use of digital cameras and a reference marker.

The modelling process results in volume measurements being ascertained. To determine if accurate volume measurements were attained a reconstruction from the MRI and ultrasound images of one participant was created. The results of this showed a minimal difference in the volume values with the majority of area values also aligning between the two methods. However, a large variation is noticed at Area 4. This could be as a result of wrist posture during the examination. The MRI and ultrasound examination cannot be conducted simultaneously. This allows for variations in wrist posture to occur. This would affect the location along the nerve where area measurements are taken resulting in the nerve area at two distinct locations being compared. Although this discrepancy occurs, the percentage difference between volumes remains relatively small. The volume measurements were further investigated using an idealised AAA within a phantom material. This led to the precise geometry AAA being compared to the ultrasound reconstruction from the phantom. As can be seen from the validation results, the ultrasound reconstructions have volumes within 2% of the precise geometry volumes of the AAA model. This indicates high precision for the ultrasound reconstruction method as equivalent volume measurements are obtainable.

The reconstruction method is also evaluated in terms of geometric accuracy. As can be seen from Figure 5.11, a high correlation is evident between the precise geometry and ultrasound models. A coincidence of greater than 80% is evident in both reconstructions with the geometric trends highly aligned. Although variations in geometric alignment between the precise geometry model and the ultrasound model are apparent, they do not significantly influence the volume measurements obtained. These inaccuracies would be attributable to errors associated with determining transducer position. Positional data off by 1 mm or approximately 0.5% the length of the precise geometry model would produce misalignments similar to those seen in Figure 5.11. However, the defined model area would not vary, resulting in similar volume measurements being calculated.
Geometric accuracy was also reviewed by calculating the distance between the centroid of the precise geometry model and the ultrasound models. This led to a mean difference of less than 2 mm in both cases. The error associated with VS2 is significantly less than that of VS1. This could be attributed to errors in calculating transducer location or excessive transducer pressure being applied during freehand scanning. Sufficient pressure placed on the scanning area would deform the resultant image. This would occur with both the phantom and during testing with subjects. However, the amount of pressure applied and extent of deformation was not recorded in this investigation. Nevertheless, the volumes calculated for the validation models were not adversely affected by these variables. Although volume may not be impacted, other criteria, such as flattening ratio, used for diagnostic purposes could be influenced. The effect of pressure on sonographic diagnosis is further reviewed in Chapter VI. The errors of 1.91 mm and 0.54 mm also indicate the capabilities of this method for producing accurate 3-D models of all dimensions. Since this is the case, the ultrasound reconstruction method proposed here is suitable for obtaining nerve volumes.

The accuracy of nerve volumes recorded in this study is further proven by previous studies. Investigations by Cobb et al. (2002) [150] and Bower et al. (2006) [141] recorded the volume of the carpal tunnel and the carpal tunnel contents. In these instances the carpal tunnel contents were considered as the median nerve and the nine flexor tendons. However, median nerve volume was not independently calculated. To estimate the volume of the nerve in these instances, it was assumed that the median nerve volume occupied 8.2% of the tunnel contents volume. This value was calculated from an image presented by Bower et al. (2006) [141] that outlined the area of the median nerve and carpal contents of which 8.2% of the entire area was dominated by the nerve. This results in estimated nerve volumes of 132 mm$^3$ and 164 mm$^3$ for the studies of Bower and Cobb respectively. These values are extremely similar to those noted for the controls in this investigation.

The results noted for nerve volume show a significant increase at NVCT and NVP1 for patients when compared to controls. However, neither subject’s wrist nor carpal tunnel size was recorded during testing. It is possible that nerve volume measurements would be subject dependent (i.e. the larger the wrist the larger the nerve volume). To obtain data which would account for or nullify subject anthropometric data, volume ratio was
Chapter V Diagnostic Criterion for CTS

calculated. Statistically significant differences can be noted when comparing patients and controls for NVP2:NVCT (p=0.004) and NVP3:NVCT (p<0.001). Large differences are noticed here as enlargement of the median nerve occurs within the carpal tunnel as stated in previous studies calculating median nerve area in this location [104, 138, 151, 152]. However, NVP1:NVCT remained relatively consistent. This is attributable to swelling of the median nerve proximal to the carpal tunnel. Since the median nerve may migrate due to flexion and extension of the elbow or wrist joints [137], the nerve will undergo friction at areas normally proximal to the carpal tunnel during repetitive tasks. The enlargement of the nerve in this location would also result in greater hydrostatic pressures placed on it, if a posture other than a relaxed posture was maintained for a prolonged period (e.g. while sleeping).

The breakdown of volume ratio in terms of severity shown in Figure 5.15 identifies the usefulness of this method at grading CTS severity. A poor linear trend is indicated for NVP1:NVCT (R²=0.071) with volume ratios for the mild and severe cases similar to those of the controls. This is as a result of enlargement at both NVCT and NVP1 which would maintain a comparable ratio. However, the subsidence of swelling at more proximal sections results in an increasingly lower volume ratio being obtained. This led to highly correlated linear regression lines fitted to NVP2:NVCT and NVP3:NVCT. This indicates the possible benefits of this method for severity determination. It is likely that severe cases would have the least errors in diagnosis, due to the clear distinctions in volume ratios for controls and patients with NVP3:NVCT showing the largest variation in results. However, large scale sensitivity and specificity tests would need to be conducted to show the most accurate approach.

Interesting results are seen when comparing those of the BCTQ, NCS and volume ratio (Table 5.6). In contradiction to previous studies [17, 153], the BCTQ indicates that patients with mild cases of the condition have the greatest pain and functional limitations with moderate and severe cases having substantially lower mean values. However, this data is solely based on patient’s perception of pain and discomfort. Gender, age, higher individual pain thresholds or longer symptom duration may vary these results. These findings are similar to the results of Mondelli et al. (2008) [79] where no correlation between the BCTQ and NCS or ultrasound was found. Although these results do not correspond to the NCS defined severity data or that of the volume
ratio, the questionnaires may still be beneficial in determining symptom relief following treatment [98, 135].

The NCS data is, generally, as expected. The clearest indicators of severity are DML and CMAP amplitude with statistically significant changes in results evident for both these values. In these instances, a good linear trend is also evident as severity increases. MCV remains relatively consistent for all patients with unexpected variations seen for the sensory nerve data. It would be expected that sensory nerve data would be similar to motor nerve data and display a decrease in functionality. However, this is not the case for any of the SNAP data. These anomalies are as a result of sensory nerve data being unrecordable for the more severe cases of CTS. An amplitude or onset of sensory response was not visible in these instances, resulting in no information being obtained for these patients. This would skew the results as it would be envisaged that the higher severity cases would have prolonged DSL and SCV and lower SNAP amplitude. Although SNAP data may still be capable of diagnosing CTS, it would exhibit some limitations in determining severity.

The results for volume ratio show no statistical significance between patient severities. However, a significant difference is still noted between the mean ratios of CTS patients and controls for NVP2:NVCT and NVP3:NVCT (Table 5.6). A linear trend is also evident for NVP1:NVCT, NVP2:NVCT and NVP3:NVCT. This is similar to the results of DML and CMAP amplitude. In these instances a reduction in volume ratio is represented by an increase in DML and a reduction in CMAP amplitude due to severity.

The results of this study show the benefits of volume ratio as a determinate of CTS. The ratio calculated between NVP2:NVCT and NVP3:NVCT are the most suitable for CTS classification due to the significant differences between patients and controls and the high R² value seen across the severity grades. Although NVP1:NVCT showed similar results to healthy subjects due to swelling in the carpal tunnel and the level directly proximal to it, these results may still be beneficial. A progressive decrease in volume ratio is evident between NVP1:NVCT, NVP2:NVCT and NVP3:NVCT for patients. This is in contrast to the controls that indicate a relatively unchanged or slight rise in ratio across the same variables (Figure 5.14). This variation in trend may also be
beneficial in diagnosis. In conclusion, the volume ratio criterion may be considered a valuable aid in the diagnosis of CTS and CTS severity.
Chapter VI

Ultrasound Transducer Force: The Impact on Anatomical Shape in the Diagnosis of Carpal Tunnel Syndrome
6.0 Ultrasound Transducer Force: The Impact on Anatomical Shape in the Diagnosis of Carpal Tunnel Syndrome

6.1 Introduction

One mechanism for the development of CTS is the sustained elevation of the fluid pressure within the carpal tunnel [154]. This rise in pressure can be induced by an increase in the volume of the contents within the tunnel, or a decrease in the size of the tunnel. This pressure increase has also been shown to result in anatomical changes such as bowing of the flexor retinaculum, increased median nerve area and increased flattening ratio [138, 152, 155, 156]. Radiologic imaging techniques have the capacity to observe these changes, but have not succeeded in overtaking electrodiagnostic testing for diagnosis of this condition. As discussed earlier and shown in Chapter V, sonography is one method that has shown promise in this area.

Sonography can display a clear image of the anatomical features of the carpal tunnel, allowing for variations to the median nerve and its surroundings to be detected [85, 86]. It has image quality comparable to magnetic resonance imaging (MRI) and computed tomography [14] and is considered a beneficial diagnostic tool for CTS [87, 88]. Numerous criteria have been investigated to determine the presence of CTS by means of ultrasound. These include median nerve area, swelling ratio, median nerve width, bowing of the flexor retinaculum and flattening ratio [13, 90, 92, 95, 100, 101, 103]. The level of success achieved from employing these criteria varies greatly from study to study. This could be due to the methodology in performing the studies or the sample groups investigated. However, an alternative source of variance in ultrasound results is operator ability or technique.

Ultrasound operators or sonographers have a significant impact on the outcome of the results. This is due to the way each examination is performed. The angle of the transducer when obtaining images of the carpal tunnel would have a large bearing on
the results obtained. Images at angles that do not axially slice the wrist would result in imprecise dimensions being recorded for the carpal tunnel and the median nerve at that location [140]. The force applied by the transducer will also generate inaccuracies in readings. Although only a relatively small amount of contact force is necessary to obtain an image, it is substantial enough for deformation of the skin and underlying tissue [19, 110] (in this case the carpal tunnel and its contents) to take place. Burcher et al. (2001) [19] found that the application of force as small as 1 N led to surface displacement of 11 mm on breast tissue. This deformation will inevitably increase with greater applications of force. However, the degree of displacement is dependent on the examining location. The close proximity of the median nerve to the outer aspects of the carpal tunnel will result in the nerve being more susceptible to shape change due to these forces. This would have a considerable influence on the diagnosis of CTS by means of ultrasound.

The force applied by the operator could alter the nerve area, flattening ratio, bowing of the flexor retinaculum and nerve volume. To the authors knowledge, force measurements during an ultrasound examination have not been investigated to date. The most closely related study is one carried out by Burcher et al. (2001) [19]. This investigation recorded the surface displacement of a phantom up to transducer forces that allowed smooth probe movement over the surface to be maintained. This resulted in forces of over 7 N being applied. Forces of this level are possibly to be the greatest of those placed on a subject during an ultrasound examination. It is likely that force would have an impact on the nerve reconstructions created in chapter V and may be a source of error for misalignments or measurements. However, the impact of this force has not previously been investigated.

The lack of information regarding external forces placed on the carpal tunnel and the impact of these pressures on ultrasound diagnosis is surprising. The influence of external force may alter the criteria chosen during an ultrasound examination for confirming CTS as the interpretation of the results may change. This may bring into question the results of previous studies investigating ultrasound diagnosis. With this in mind, the objective of this study was to determine the effect of transducer force on the flattening ratio and area of the median nerve at various anatomical sites. The results of
this investigation will indicate if operator force has a bearing on the accuracy of diagnostic techniques previously investigated.

6.2 Materials and Methods

6.2.1 Participants

Twenty healthy subjects (13 male and 7 female) volunteered to partake in this study. Subjects had no history of CTS or exhibited any clinical signs of CTS at the time of testing. Following a detailed introduction to the study and its requirements, subjects were requested to sign a consent form. This was completed prior to commencement of the study but did not infringe on a subject’s right to withdraw from the study at any time. Subject’s ages ranged from 20 to 35 years with a mean age of 25.3 years. All participants were instructed to inform the investigator of any discomfort noticed during testing, at which stage the test would be immediately halted. This research method was reviewed and approved by the University of Limerick Research Ethics Committee.

6.2.2 Sonographic Imaging

The sonographic examination was conducted using a GE LOGIQ e portable ultrasound machine (General Electric Healthcare Technologies, Waukesha, WI, USA) with a linear array transducer ranging from 4-12 MHz. Imaging was performed at four distinct locations; the distal third of the forearm, the radioulnar articulation, the intermediate carpal tunnel and the distal carpal tunnel (Figure 6.1). The first location was determined by calculating one third the distance from the distal wrist crease to the elbow crease. The final three aforementioned locations were defined sonographically using the anatomical landmarks of the radioulnar articulation, the pisiform and the hook of hamate respectively. Axial video footage of the median nerve was obtained at each of these locations during the application of force. This footage was exported as a video file from which still images at specified time points were obtained. These images were imported into the open source GNU Image Manipulation Program (GIMP) where the large and small cross sectional diameters of the median nerve were recorded. This allowed for the flattening ratio and median nerve area to be calculated at each force measurement. The flattening ratio was calculated using the ratio between the maximal
nerve dimension in a radial-ulnar and palmer-dorsal direction. The median nerve area was assumed to be an ellipse [101] and calculated using Equation 2.1 presented in Chapter II. All measurements were taken from the inner hyperechoic rim of the median nerve. This was carried out for all required forces at each measuring location.

![Figure 6.1 Locations along the arm where sonographic imaging took place.](image)

**6.2.3 Experimental Procedure**

Throughout the procedure participants were required to maintain a relaxed wrist posture with their hand in a supinated position and their fingers semi extended. Participants were requested to refrain from movement for the duration of each test. An experimental test system was specifically designed that was capable of applying pressure and obtaining ultrasound images (Figure 6.2). It comprised of a Mecmesin basic force gauge (Mecmesin Limited, West Sussex, United Kingdom), an adapted Mecmesin MDD manual test stand, a specifically developed transducer holder and an ultrasound machine with a linear transducer. The Mecmesin MDD manual test stand was adapted by attaching a motor that allowed for automatic movement of the force gauge to take place.

The transducer was placed into the specifically developed holder which was tightened to ensure firm contact to the transducer. This removed the risk of transducer movement. The holder was firmly affixed to a Mecmesin basic force gauge by screwing the extension rod onto the internal stud. The force gauge was in turn mounted to an adapted Mecmesin MDD test stand using a dovetailed bracket. The force gauge recorded and
plotted the compression force using Mecmesin DataPlot-X software, Version 1.05a (Mecmesin Limited, West Sussex, United Kingdom). To account for the error associated with the transducer not being held directly below the force gauge, the recorded results were calibrated against a RDP Electronics Ltd. tension/compression load cell (Wolverhampton, United Kingdom). This was done on three separate occasions by applying an increasing force directly onto the load cell from the force gauge and recording the corresponding forces from both mechanisms. The mean value of the forces from the Mecmesin force gauge at certain forces from the load cell was calculated and the data plotted. A linear relationship is evident between the recorded values from the basic force gauge and those using the load cell as indicated in Figure 6.3. The equation of the resultant trend line, as determined by Microsoft Excel 2007 (Microsoft®, Washington, USA), was used to convert the recorded force to the actual force.
Chapter VI Ultrasound Transducer Force

Figure 6.2 Attachment of the transducer to the Mecmesin basic force gauge.

The participant’s arm was positioned beneath the force gauge at the measuring site and supported by the base of the experimental rig. The force gauge was lowered on to the site at a constant displacement rate of 30 mm/min with time and force data being recorded. Displacement continued to increase until the subject noticed discomfort or a 50 N load was achieved. At this stage the test was stopped and the applied force removed. The participant’s arm was repositioned at an alternative measuring site and
the test repeated. Still images were obtained from the exported video file at time points corresponding to applied forces of 2, 4, 6, 8, 10, 12, 16, 20 and 30 N, where applicable.

Figure 6.3 The relationship between the recorded values from the force gauge and the corresponding true force determined from the load cell. Error bars indicating one standard deviation are also included.

6.2.4 Data Analysis

The area of the median nerve at each force increment and the percentage change of flattening ratio with respect to force were calculated for all participants. A logarithmic regression line was fitted to the percentage change of flattening ratio with respect to force data and $R^2$ values calculated. Statistical significance was investigated between the mean area measurement recorded with minimal application of force and areas at subsequent forces by way of paired samples T-Test. The correlation coefficients between these sets of data were also calculated to determine if median nerve area varied greatly for any subject. For the purposes of statistical evaluation, any subject that did not reach a force of 30 N had their final area measurement entered for any absent data.

A range of error for area was also determined to remove the possibility of sonographer error skewing the results. This value was calculated as 12.95%. This was established
from a previous study that showed ultrasound exhibited standard deviations of ±0.21-0.27 for diameter measurements of tubes with similar dimension to the median nerve [157]. These standard deviations indicate that the majority of diameter measurements are within a range of ±6.37% of the mean value. Applying this percentage to the median nerve diameters recorded for healthy subjects in a study by [97], led to an area variation of 12.95%.

Percentage change of flattening ratio with respect to force was also investigated using the paired samples t-test. This compared the initial mean flattening ratio to flattening ratios at subsequent force increments. Images obtained at the intermediate carpal tunnel, the radioulnar articulation and the distal third of the forearm had an initial mean flattening ratio at a force of 2 N. However, the natural curvature of the palm at the distal carpal tunnel required greater force to be applied before a clear image could be obtained. This resulted in an initial mean flattening ratio at a force of 4 N for this location. Statistical analysis was performed computationally using SPSS software (v. 16.0, SPSS, Chicago, Illinois). Statistical significance was set at p < 0.05 for all comparisons.

6.3 Results

At the location of the distal carpal tunnel, five participants were excluded from the final analysis of flattening ratio percentage change with respect to force. Two participants were excluded at the level of the intermediate carpal tunnel and one participant at the level of the radioulnar articulation. Four participants were also excluded from the area measurements at the distal carpal tunnel. All excluded participants were as a result of poor visibility of nerve extremities during imaging at the initial forces. This was as a result of artefacts or incomplete contact between the test area and the transducer.

The mean cross sectional area of the median nerve at the forearm, radioulnar articulation, intermediate carpal tunnel and distal carpal tunnel with minimal application of force is 8.41±3.42, 8.73±2.64, 9.21±2.29 and 6.49±1.92 mm² respectively. No statistical significance was noted on comparing the mean initial nerve area to subsequent values (p>0.5). The mean areas for all forces can be seen to fall within the calculated values for range of error (Table 6.1). The lack of variation in the area is also
noted by a strong correlation between area values with minimal application of force to those at greater force (ranging from 0.933-0.993, 0.654-0.888, 0.825-0.947 and 0.812-0.989 for the forearm, proximal, intermediate and distal carpal tunnel respectffully).
Table 6.1  Mean area calculated using minimal application of force at each measuring site. The mean range of subsequent forces and range of error are also displayed.

<table>
<thead>
<tr>
<th></th>
<th>Mean Area at Initial Force (mm²)</th>
<th>Mean Range at Subsequent Forces (mm²)</th>
<th>Range of Error² (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm</td>
<td>8.41±3.42</td>
<td>8.24-8.64</td>
<td>7.32-9.50</td>
</tr>
<tr>
<td>Proximal CT¹</td>
<td>9.21±2.29</td>
<td>8.90-9.62</td>
<td>8.02-10.41</td>
</tr>
<tr>
<td>Intermediate CT¹</td>
<td>8.73±2.64</td>
<td>8.76-9.17</td>
<td>7.60-9.86</td>
</tr>
<tr>
<td>Distal CT¹</td>
<td>6.49±1.92</td>
<td>6.42-6.96</td>
<td>5.65-7.33</td>
</tr>
</tbody>
</table>

¹. CT refers to the carpal tunnel.

2. Range of error was set at 12.95% of the mean median nerve area at each location.
The mean flattening ratio observed with minimal application of force was 1.78±0.37 at the forearm, 2.32±0.64 at the radioulnar articulation, 2.29±0.53 at the intermediate carpal tunnel and 2.39±0.50 at the distal carpal tunnel. This noticeably increases to values as high as 2.30±0.40, 3.10±0.78, 3.05±0.88 and 3.06±0.67 respectively, due to elevated force. The deviation in flattening ratio results in statistically significant percentage changes at all measuring sites (p < 0.05). Significant results are first noted at 6 N (p = 0.012), 4 N (p = 0.017), 4 N (p = 0.008) and 8 N (p < 0.001) for the forearm, proximal, intermediate and distal carpal tunnel respectfully. The most noticeable increases in percentage change are visible during the initial application of force (2-20 N) with values continuing to increase as greater forces are applied. This leads to a logarithmic trend being displayed for the results at all measuring locations (Figure 6.4).

![Figure 6.4](image)

**Figure 6.4** Indicates the rate of percentage change of flattening ratio due to the application of force at the measuring site. Statistically significant data is denoted by an unfilled symbol.
An example of the effect of force on the measuring site can be seen in Figure 6.5. The large and small cross sectional diameters of the ellipse defining the median nerve can be seen to alter due to increases in force. The extent of these changes can be seen more clearly in Figure 6.6 (a) where the centre of each ellipse is aligned to clearly indicate true shape change. Migration of the nerve is also evident in Figure 6.5. Since the transducer’s position only moved in one plane and the subject remained still, migration was calculated from the centre of nerve to the edges of the obtained ultrasound image. The extent of migration of the nerve in this instance is seen in Figure 6.6 (b).

Figure 6.5 Axial slices of the median nerve at the distal third of the forearm during the application of (a) 4, (b) 8, (c) 16, and (d) 30 N of force on one subject. The nerve is outlined in each image by the best fit ellipse which was used to determine the flattening ratio. The red ellipse depicts the nerve shape at 4 N and is indicated in all images. The green, purple and blue ellipses depict the nerve shape at 8, 16, and 30 N respectively.
Figure 6.6 The extent of (a) shape change and (b) nerve migration due to the application of forces ranging from 4 - 30 N for one participant. Migration is calculated in relation to the initial positional measurement at 4 N.

The impact of force on flattening ratio in comparison to area is clearly emphasised in Figure 6.7. The large percentage change in flattening ratio and relatively small percentage change in area is clearly noted at all measuring locations. The values for flattening ratio can be seen to exceed 35% as greater force is applied with noticeable differences evident at all applied forces. In contrast, area change remains minimal with
9.86% being the highest percentage change at any measuring location or force and the majority of values remaining within 5% of the initial area measurement.

![Figure 6.7](image)

**Figure 6.7** The percentage change for flattening ratio and area at the (a) forearm, (b) radioulnar articulation, (c) intermediate carpal tunnel and (d) distal carpal tunnel.

### 6.4 Discussion

The use of sonography as a diagnostic tool for CTS has been investigated on numerous occasions with an increase in median nerve area, bowing of the flexor retinaculum and nerve flattening being the main areas of investigation [13, 18, 92, 95, 97, 100]. However, the results of these investigations have varied greatly. This can be, in part, explained by the methods incorporated to carry out the studies. A uniform method of testing was not employed across the studies. This can lead to large variations in the results obtained. These variations could possibly be attributed to transducer angle, subject’s wrist posture [140], transducer force and severity of CTS in the population investigated. The results in this study emphasise the impact transducer force has on flattening ratio which has previously been used and in some cases shown to be an aid in diagnosing CTS [13, 93].
The effect of force on the flattening ratio of the median nerve is evident from Figure 6.4. A statistically significant percentage change for the flattening ratio is noted at all force increments apart from 4 N for the forearm and 6 N for the distal carpal tunnel. The exception of these two points can be attributed to the anatomy of these areas. At a distal one third of the forearm, the nerve is not in as superficial a location in comparison to its course through the carpal tunnel. The impact of surrounding bones is also not as influential. In contrast, the bones at the distal carpal tunnel have a much larger relevance. In this instance, the bones surrounding the nerve dissipate much of the applied force. In both cases a greater force is required before a significant difference is noted in the flattening ratio.

The flattening ratio values seen for the initial measurements (2 N and 4 N) fall well within the range of values exhibited for controls from previous studies [89, 92, 95, 100] and are similar to the mean value exhibited in Table 2.5. Values observed once the applied force is increased, also achieve and surpass those seen for patients in Table 2.5. This highlights the possibility of patients being falsely diagnosed using flattening ratio or nerve width as the indicator due to the operator applying too great a force on the measuring site. A force of 8 N shows statistically significant changes in flattening ratio at all locations with a number of locations showing significant differences at lower forces. Bucher et al. (2001) [19] indicates that these values may be within the levels of force applied by the sonographer. It was also noted that an increase in force led to migration of the median nerve in the axial plane (Figure 6.6 (b)). This could result in a shape change or compression of the median nerve due to surrounding anatomy, once again leading to inaccurate measurements. Migration may also be evident in the sagittal plane. This would lead to inaccuracies being recorded as nerve shape and area vary along the course of the nerve. However, measuring the degree of migration in this plane was not incorporated into the current study.

The mean median nerve area did not vary significantly, due to force, at any of the four measuring sites. All mean area values are seen to fall well within the range of error with mean maximum deviations not exceeding 2.73%, 4.45%, 5.04% and 7.24% for the forearm, proximal, intermediate and distal carpal tunnel respectfully (Table 6.1). The strong correlations noted between recorded areas at the minimal force and increased forces, also indicates nerve area remained relatively constant. This would be expected
if the nerve could only deform in the axial plane since compressed 2-D structures would maintain a constant area due to the addition of force, if deformation was the only change to take place. However, the nerve must be considered as a 3-D object as it can move in more than one plane during ultrasound imaging. The slight variations noted in area could be attributed to nerve migration in the sagittal plane due to the applied force. Since the ultrasound images obtained in this study were only captured in the axial plane, tissue forced in a sagittal direction cannot be accounted for. However, the correlation values indicate that median nerve area did not vary substantially. This is further emphasised in Figure 6.7 where the percentage change of area in comparison to flattening ratio is displayed. It can be noted that only minor changes in area occur due to the application of force. However, flattening ratio can be seen to alter significantly under the same conditions. This is not just relevant for the results of area and flattening ratio indicated here, but also to the volume measurements calculated in Chapter V. If area measurements remain equivocal due to the application of force, volume measurements will subsequently remain equivocal.

The effect of force during an ultrasound examination has a large bearing on the result obtained. Using flattening ratio as one of the main criteria would lead to false conformation of CTS if the transducer force applied during the examination was excessive. Maintaining a constant force during an examination would also be difficult as Burcher et al. (2001) [19] observed that force varied by almost 1 N despite efforts to keep it constant. For diagnosis of CTS by ultrasound to be considered beneficial and accurate, the influence of force must be accounted for in the diagnostic criteria used.
Chapter VII

Discussion and Conclusions
7.0 Discussion and Conclusions

7.1 Discussion

Carpal tunnel syndrome (CTS) is an upper limb neuropathy of the median nerve. It occurs due to stretching, pinching, contact pressure or hydrostatic pressure placed on the nerve as it travels through the carpal tunnel and can be debilitating for its sufferers. It is one of the leading causes of days away from work in private industry [29] and is, therefore, commonly considered work related. However, a definitive cause for its development cannot be attributed to one individual aspect. Repetitive tasks, working environment and certain medical conditions are all associated with a higher risk of CTS. This has led to the relationship between numerous occupations and CTS being investigated [158-160]. However, no specific task has been established as the main contributing factor for the development of this condition. Therefore, determining which activities contribute to a reduction in nerve functionality would lead to advancements in preventing, diagnosing and treating CTS. One activity that has commonly been linked to CTS is computer use.

Computer use has often been linked with CTS due to the movements that are undertaken while performing a computer task. The individual aspects of computer use such as fingertip forces, wrist posture, palm forces and repetitive movements have all been shown to increase carpal tunnel pressure (CTP). This pressure may damage the median nerve if a high enough level is reached and maintained for an extended duration. However, determining a relationship between computer use and CTS development has proven inconclusive. To conclude if a link exists, postures found during computer use were focused on. Although previous studies have shown that deviations of the wrist from a neutral position result in increased CTP, certain limitations were evident in these studies and needed to be addressed. One of these was the categorisation of wrist posture.

Numerous studies have investigated the wrist postures involved in computer use. These studies have calculated the frequency of extension, flexion, radial deviation and ulnar
deviation taking place. However, the majority of studies only categorised wrist posture in one direction at a time. The positions of extension/flexion and a coincident radial/ulnar deviation have not been extensively investigated. This results in a more representative wrist posture frequented during computer use not being categorised. In a similar vein, the impact of extension/flexion with a coincident radial/ulnar deviation on nerve functionality has remained unexamined. Previous studies, have exhibited obvious pressure changes within the carpal tunnel as the wrist deviates away from a neutral position in one plane of motion. This pressure increase becomes greater as more extreme wrist postures are reached. Although recording the CTP of these wrist positions is beneficial, it does not represent the variance in nerve functionality exhibited during these postures or postures that involve movement of both an extension/flexion and a simultaneous radial/ulnar deviation. To address these shortcomings, it was first necessary to create a new categorisation of computer wrist posture as demonstrated in Chapter III.

The wrist postures recorded in this study are similar to those found in previous research. This is indicated by the results in (Table 3.2) that compare results of wrist motion in one direction. However, a more realistic representation of wrist posture during a computer task is also presented. This accounts for motion in two coincident directions and determined positions of Ext20°Ulnar20°, Ext20°Ulnar10° and Ext30°Ulnar20° to be the most common. The inclusion of wrist deviation in a second direction would increase the pressure within the carpal tunnel. However, an assessment of computer wrist posture on median nerve function was lacking. This was addressed by determining the effect of these wrist postures, and two base postures of Ext0°Ulnar10° and Ext0°Ulnar20°, on compound muscle action potential (CMAP) data. The nerve conduction data recorded were distal motor latency (DML), CMAP amplitude and CMAP duration. These were recorded over an eight hour period while the wrist was maintained in a specified wrist posture. Although maintaining a constant posture does not replicate the movement demonstrated during computer use, it gave an insight into the impact of a maintained wrist posture on median nerve functionality.

The results from the nerve conduction studies (NCS) indicate a negative effect on nerve functionality. This is most evident for the results of CMAP amplitude, where the amplitude after the eight hour period was substantially decreased. The negative effect
of these wrist postures on nerve functionality is displayed further in the CMAP duration and DML results. However, this study corresponds to previous studies in concluding that CMAP amplitude is the most suitable indicator of nerve dysfunction.

The NCS data presented in Chapter IV, was only recorded from healthy subjects. Considering the NCS was shown to alter due to wrist posture alone, the possibility of false diagnosis using these techniques is highlighted. Healthy subjects may exhibit reduced nerve functionality as a result of activities they have undertaken prior to testing. This raises questions over the suitability of NCS for diagnosing CTS. Error associated with this method can be overcome by visually diagnosing CTS. This can be conducted with any imaging technique. One method that has been investigated and developed in this regard is sonography. Measurements such as median nerve area, bowing of the flexor retinaculum and flattening ratio have all been reviewed as diagnostic criteria. Although median nerve area has shown considerable promise at diagnosing and grading the severity of CTS, a large variability is seen across results. This has hampered the use of ultrasound for this purpose. For ultrasound to be recognised as a suitable diagnostic tool of CTS, a new diagnostic criterion that surpassed previous criteria was required. The criterion proposed in this study was volume ratio.

One physiological change that may occur in CTS patients is an inflammation of the median nerve. This results in an increase in the size of the nerve as it passes though the carpal tunnel. Calculating the volume of the nerve would act as an indicator of the presence of this condition. However, the nerve volume would vary greatly depending on the subject examined. To negate the variation associated with a subject’s anthropometrical data, volume ratio was calculated. This compared the volume of the nerve as it passed through the carpal tunnel to equivalent sized segments in locations proximal to this. To calculate volume, a novel nerve reconstruction method was employed. This used sonographic images to define the outline of the nerve. The alignment of these sonographic images was calculated using photogrammetric techniques. To ensure the volume measurements obtained from this reconstruction were accurate, validation of this method was conducted. This was done by comparing the results of a phantom model to its known dimensions and also by creating a reconstruction of one subject’s nerve from both B-scans and MRI. The results of this
showed that volume measurements obtained from sonography were within 2% for the phantom model and 6% of the MRI model.

Once the reconstruction technique was considered suitable, nerve models were created for all participants and the volume ratios calculated. The results revealed a significant difference between the volume ratio of controls and patients for NVP2:NVCT ($p = 0.004$) and NCP3:NVCT ($p < 0.001$). A negative trend was also evident across the severities of these volume ratios. These results also compared favourably against alternative diagnostic criteria, which are often used for CTS confirmation. This method exhibited the most suitable linear trends for diagnosing CTS severity with CMAP data showing similar findings. However, severity as determined by sensory nerve action potential (SNAP) data and patient questionnaires was unsuitable for such grading. The advantages of this diagnostic criterion are evident with further advancements possible in this area. However, for these improvements to be implemented the possible reasons for inaccuracies in models need to be investigated. One aspect that can lead to inaccuracies is operator technique.

The results of an ultrasound examination can vary greatly depending upon the examiner. Criteria like median nerve area or flattening ratio are dependent upon the angle of the transducer and the force applied by it. Adjusting transducer angle will vary the visible cross sectional area (CSA), leading to an altered CSA being recorded. This will result in incorrect diagnosis. This would also affect the reconstruction of 3-D models from B-scans if angle was not accounted for, as done so in Chapter V. The application of transducer force on the measuring site would also cause tissue displacement as shown by Burcher et al. (2001) [19]. However, the extent of this on the area of the carpal tunnel or on the median nerve was unknown. To determine if this impacted alternative diagnostic criteria or modelling of the median nerve, the effect of force was investigated.

The application of force, at locations, along the carpal tunnel or forearm was investigated in terms of flattening ratio and median nerve area. It was found that a significant difference was noted in flattening ratio at all locations. This is most likely due to the relatively superficial location of the median nerve and emphasises the possibility of misdiagnosis using this criterion. Although clear differences are noticed
in flattening ratio, area measurements remain equivalent throughout the application of force. This verifies the benefits of median nerve area as a diagnostic measurement, if transducer angle is accounted for. The influence of force on volume measurements can also be considered minimal if area is not largely altered. However, it may still be accountable for slight inaccuracies in the model.

This thesis demonstrates the effect of three static wrist postures, determined during computer activity, on median nerve functionality by means of NCS. The results of this indicate that nerve function decreased on account of maintaining these wrist postures for an extended period of time. This highlights the link between these postures and nerve conduction data. Owing to this, an alternative diagnostic criterion was investigated. In this instance, volume ratio of the median nerve was considered. Sonographic techniques were used to calculate these values. The results of this showed clear differences between patients and controls and a strong trend in defining CTS severity. This signified the effectiveness of median nerve volume in diagnosing CTS. The benefits of this criterion are emphasised following an investigation into the possible variations associated with alternative criteria as a result of operator technique.

### 7.2 Conclusions

- The alternative categorisation method demonstrated in this study accounted for wrist posture of extension/flexion and simultaneous radial/ulnar deviation.
- The most common wrist postures show a decrease in nerve functionality when maintained for an extended period of time.
- Median nerve volume ratio calculated from sonographic images shows significant differences between patients and controls.
- Median nerve volume ratio has shown greater linear trends than nerve conduction data or patient questionnaires across severities.
- Transducer force has been shown to alter median nerve shape, altering values for flattening ratio.
- Median nerve area did not vary greatly due to increasing transducer force.
Chapter VIII

Future Work
8.0 Future Work

8.1 Introduction

The results of this study support two distinct beliefs; that wrist postures found from computer use effect NCS and that a new diagnostic criterion by means of ultrasound is viable. The findings presented here open the door for further testing in these areas to be conducted. This varies from conducting larger studies in similar areas to those previously investigated or advancing these areas based on the results observed. This will inevitably lead to a greater understanding of CTS development and diagnosis. The most practical areas that could be further explored, based on this body of work, are presented in this chapter.

8.2 Computer Use and CTS

Determining the most prominent wrist postures during computer use is the first step in establishing its impact on the median nerve. Although the effect of extended computer wrist posture on NCS was noted, the corresponding CTP was not directly attained. This information would bring the results in line with similar studies by Rempel et al. (2008), Sanz et al. (2005) and Keir et al. (1999) [6, 39, 40], where wrist posture was associated with a corresponding CTP. However, the range of wrist postures investigated in previous studies was not based on computer postures or maintained for a substantial length of time. The wrist postures investigated were often in one plane of motion (either extension/flexion or radial/ulnar deviation) [8, 23]. This is not fully representative of postures frequented during computer use. Therefore, a direct pressure measurement would greatly complement the current findings and allow for a correlation between wrist posture, nerve conduction data and CTP to be created.

The effects of these parameters in relation to time should also be investigated. The influence of wrist posture on NCS over an eight hour period was examined but can once again be enhanced with direct pressure measurements over this duration. This will indicate which wrist postures increase CTP to such an extent that nerve functionality is
impaired over time. A further study investigating the length of time until total nerve recovery or normal function returned would also have its benefits. This would lead to a set of limits or controls for computer use being produced. The safe extent of wrist posture during computer use could be clearly defined, resulting in more ergonomically friendly devices being produced. The configuration or layout of computer keyboards could be adjusted to reduce the necessity of postures that have been shown to reduce nerve functionality. The duration of computer use and subsequent recovery period necessary for normal CTP to resume could also be defined. This would improve both time management in a working environment and reduce the risk of work related musculoskeletal disorders developing.

The dynamic nature of performing a computer activity should also be looked at. Although Szabo and Sharkey (1993) [38] showed that the mean applied pressure was the significant value when increasing CTP and not the cyclic loading of the nerve, knowing the effects of these movements on the pressure changes over an extended time period would still be necessary. The pressure reached during some computer tasks may be dominated by minor wrist movements which would not reach the CTP threshold. Even if this value was exceeded during this task, recovery may occur if the following wrist postures visited were not at a damaging level. However, to determine if this is the case a range of dynamic tests would need to be performed.

8.3 Ultrasound Diagnosis

Expanding the areas of research in terms of diagnosing CTS by ultrasound can be conducted on many levels. Improving the methods of calculating transducer position is one such area. Although the method depicted in this study was sufficient for the necessary volume calculations, it could be developed to obtain 3-D reconstructions of even greater accuracy. This can be achieved by increasing the number of cameras positioned around the test area. The location of any point is calculated by the intersection of lines of sight from the respective cameras through that point. Since this is the case, increasing the lines of sight for any particular point in the test area or on the transducer would reduce the positional error. Using alternative techniques for determining positional data may also be implemented to determine their suitability.
This can be easily conducted, as the integration of these techniques would not alter the current reconstruction method.

The use of ultrasound at the post surgical stage would verify the success or failure of this invasive treatment for each individual case. Apart from confirming successful bisection of the flexor retinaculum took place, it would be capable of determining if anatomical changes occurred. A reduction in pressure placed on the median nerve would result in relatively swift relief of discomfort. This would in turn lead to a decline in swelling of the median nerve. This is most evident from studies recording the cross sectional area at the proximal carpal tunnel [98, 99, 102] with the mid carpal tunnel also displaying a reduction in nerve area [99]. However, this decrease in size has not always resulted [161, 162]. To verify if nerve dimensions are altered following carpal tunnel release, the impact on the volume segments measured in this study needs to be investigated both pre and post operatively. This will conclude if the volume ratios calculated for CTS patients return to normal values following surgery. This follow up study should also be conducted in conjunction with electrodiagnostic studies and patient questionnaires.

Although reconstruction of the median nerve has shown to have beneficial diagnostic capabilities, expanding the amount of features reconstructed using ultrasound could have further advantages. Calculating the ratio between the median nerve and carpal tunnel or the carpal tunnel contents and the carpal tunnel, similar to Bower et al. (2006) [141], may also be diagnostically useful. Although Bower et al. indicates changes in volume measurements and volume ratios due to wrist postures, CTS patients were not included in this study. Incorporating these subjects would determine any variations that may be evident between the two groups. These measurements could also be taken both pre and post operatively to investigate if improvements in these values are evident following surgery.

Further investigation into median nerve volume ratio as a diagnostic indicator or sign of recovery would lead to these measurements being used to determine suitable treatments. The impact of non invasive treatments on the anatomy of the nerve could be easily monitored. These may show a clear reduction in nerve dimensions prior to significant
improvements in nerve function being obtained. This would lead to the correct action being taken in terms of treatment and remove the necessity of surgery in some cases.
References
References


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66. Dahlin LB, Thambert C: *Acute nerve compression at low pressures has a conditioning lesion effect on rat sciatic nerves*. 1993.


with carpal tunnel syndrome before and after endoscopic release of the transverse carpal ligament. Clinical Radiology, 2007; 62:891-894.


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Appendices
Appendix A – Studies Used in Creating the Funnel Plot

Studies used in creating funnel plot

<table>
<thead>
<tr>
<th>Author</th>
<th>Number of Criteria Investigated in the Study</th>
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<td>Duncan et al. (1999) [97]</td>
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<td>Hobson-Webb et al. (2008) [90]</td>
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<tr>
<td>Klauser et al. (2009) [103]</td>
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<td>Kotevoglu and Gulbache-Saglam (2005) [91]</td>
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<td>Mondelli et al. (2008) [98]</td>
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<tr>
<td>Moran et al. (2007) [15, 18]</td>
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<td>Nakamichi et al. (2002) [15]</td>
<td>3</td>
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<tr>
<td>Sarria et al. (2000) [95]</td>
<td>8</td>
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<tr>
<td>Sernik et al. (2008) [101]</td>
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<tr>
<td>Visser et al. (2007) [16]</td>
<td>1</td>
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<tr>
<td>Yesiladg et al. (2004) [100]</td>
<td>1</td>
</tr>
<tr>
<td>Ziswiler et al. (2005) [106]</td>
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Appendix B – Extract of Short Story Used During Motion Analysis

Extract from short story which was typed during the motion analysis testing.

I don't want to bore you, don't you know, and all that sort of rot, but I must tell you about dear old Freddie Meadowes. I'm not a flier at literary style, and all that, but I'll get some writer chappie to give the thing a wash and brush up when I've finished, so that'll be all right.

Dear old Freddie, don't you know, has been a dear old pal of mine for years and years; so when I went into the club one morning and found him sitting alone in a dark corner, staring glassily at nothing, and generally looking like the last rose of summer, you can understand I was quite disturbed about it. As a rule, the old rotter is the life and soul of our set. Quite the little lump of fun, and all that sort of thing.

Jimmy Pinkerton was with me at the time. Jimmy's a fellow who writes plays--a deuced brainy sort of fellow--and between us we set to work to question the poor pop-eyed chappie, until finally we got at what the matter was.

As we might have guessed, it was a girl. He had had a quarrel with Angela West, the girl he was engaged to, and she had broken off the engagement. What the row had been about he didn't say, but apparently she was pretty well fed up. She wouldn't let him come near her, refused to talk on the phone, and sent back his letters unopened.

I was sorry for poor old Freddie. I knew what it felt like. I was once in love myself with a girl called Elizabeth Shoolbred, and the fact that she couldn't stand me at any price will be recorded in my autobiography. I knew the thing for Freddie.

"Change of scene is what you want, old scout," I said. "Come with me to Marvis Bay. I've taken a cottage there. Jimmy's coming down on the twenty-fourth. We'll be a cosy party."

"He's absolutely right," said Jimmy. "Change of scene's the thing. I knew a man. Girl refused him. Man went abroad. Two months later girl wired him, 'Come back. Muriel.' Man started to write out a reply; suddenly found that he couldn't remember girl's surname; so never answered at all."

But Freddie wouldn't be comforted. He just went on looking as if he had swallowed his last sixpence. However, I got him to promise to come to Marvis Bay with me. He said he might as well be there as anywhere.

Do you know Marvis Bay? It's in Dorsetshire. It isn't what you'd call a fiercely exciting spot, but it has its good points. You spend the day there bathing and sitting on the sands, and in the evening you stroll out on the shore with the gnats. At nine o'clock you rub ointment on the wounds and go to bed.

It seemed to suit poor old Freddie. Once the moon was up and the breeze sighing in the trees, you couldn't drag him from that beach with a rope. He became quite a popular pet.
with the gnats. They'd hang round waiting for him to come out, and would give perfectly good strollers the miss-in-baulk just so as to be in good condition for him.
Appendix C - MATLAB Programs for Determining Wrist Posture

Program to measure, categorise and summate the flexion or extension undertaken during a computer task.

clc
clear all

data1 = input('State excelfile and worksheet1 ');
data2 = input('State excelfile and worksheet2 ');
data3 = input('State excelfile and worksheet3 ');
data4 = input('State excelfile and worksheet4 ');
data5 = input('State excelfile and worksheet5 ');
data6 = input('State excelfile and worksheet6 ');

s = size(data1, 1);
Angles_Ext = [];
Angles_Flex = [];

for i = 1:s
    x1 = data1(i, 1);
y1 = data1(i, 2);
z1 = data1(i, 3);

    x2 = data2(i, 1);
y2 = data2(i, 2);
z2 = data2(i, 3);

    x3 = data3(i, 1);
y3 = data3(i, 2);
z3 = data3(i, 3);

    x4 = data4(i, 1);
y4 = data4(i, 2);
z4 = data4(i,3);
x5 = data5(i,1);
y5 = data5(i,2);
z5 = data5(i,3);
x6 = data6(i,1);
y6 = data6(i,2);
z6 = data6(i,3);

a1 = y1*(z2-z3)+y2*(z3-z1)+y3*(z1-z2);
b1 = z1*(x2-x3)+z2*(x3-x1)+z3*(x1-x2);
c1 = x1*(y2-y3)+x2*(y3-y1)+x3*(y1-y2);
a2 = y4*(z5-z6)+y5*(z6-z4)+y6*(z4-z5);
b2 = z4*(x5-x6)+z5*(x6-x4)+z6*(x4-x5);
c2 = x4*(y5-y6)+x5*(y6-y4)+x6*(y4-y5);

v = (a1*a2+b1*b2+c1*c2)/(((a1^2+b1^2+c1^2)^0.5)*((a2^2+b2^2+c2^2)^0.5));
q = acos(v);

Angle = q*180/pi;
dataa=(data2 + data3)/2;

if dataa(i,2)>data6(i,2);
    Flex=180-Angle;
    Angles_Flex = [Angles_Flex; Flex];
else
    Ext=180-Angle;
    Angles_Ext = [Angles_Ext; Ext];
end

end

flexcount5=0;
flexcount10=0;
flexcount15=0;
flexcount20=0;
flexcount25=0;
flexcount30=0;
flexcount35=0;
flexcount40=0;
flexcount45=0;
flexcount50=0;
flexcountover50 = 0;
flexcountNaN = 0;

S = size(Angles_Flex,1);

for i = 1:S

    NewAngles_Flex = Angles_Flex(i,1);

    if NewAngles_Flex >= 0 && NewAngles_Flex <= 5
        flexcount5 = flexcount5 + 1;
    elseif NewAngles_Flex > 5 && NewAngles_Flex <= 10
        flexcount10 = flexcount10 + 1;
    elseif NewAngles_Flex > 10 && NewAngles_Flex <= 15
        flexcount15 = flexcount15 + 1;
    elseif NewAngles_Flex > 15 && NewAngles_Flex <= 20
        flexcount20 = flexcount20 + 1;
    elseif NewAngles_Flex > 20 && NewAngles_Flex <= 25
        flexcount25 = flexcount25 + 1;
    elseif NewAngles_Flex > 25 && NewAngles_Flex <= 30
        flexcount30 = flexcount30 + 1;
    elseif NewAngles_Flex > 30 && NewAngles_Flex <= 35
        flexcount35 = flexcount35 + 1;
    elseif NewAngles_Flex > 35 && NewAngles_Flex <= 40
        flexcount40 = flexcount40 + 1;
    elseif NewAngles_Flex > 40 && NewAngles_Flex <= 45
        flexcount45 = flexcount45 + 1;
    elseif NewAngles_Flex > 45 && NewAngles_Flex <= 50
        flexcount50 = flexcount50 + 1;
    elseif NewAngles_Flex > 50
        flexcountover50 = flexcountover50 + 1;
    else
        NewAngles_Flex = NaN;
        flexcountNaN = flexcountNaN + 1;
    end

end

extcount5 = 0;
extcount10 = 0;
extcount15 = 0;
extcount20 = 0;
extcount25 = 0;
extcount30 = 0;
extcount35 = 0;
extcount40 = 0;
extcount45=0;
extcount50=0;
extcountover50=0;
extcountNaN=0;

O = size(Angles_Ext,1);

for i = 1:O

    NewAngles_Ext=Angles_Ext(i,1);

    if NewAngles_Ext>=0&NewAngles_Ext<=5
        extcount5=extcount5+1;
    elseif NewAngles_Ext>5&NewAngles_Ext<=10
        extcount10=extcount10+1;
    elseif NewAngles_Ext>10&NewAngles_Ext<=15
        extcount15=extcount15+1;
    elseif NewAngles_Ext>15&NewAngles_Ext<=20
        extcount20=extcount20+1;
    elseif NewAngles_Ext>20&NewAngles_Ext<=25
        extcount25=extcount25+1;
    elseif NewAngles_Ext>25&NewAngles_Ext<=30
        extcount30=extcount30+1;
    elseif NewAngles_Ext>30&NewAngles_Ext<=35
        extcount35=extcount35+1;
    elseif NewAngles_Ext>35&NewAngles_Ext<=40
        extcount40=extcount40+1;
    elseif NewAngles_Ext>40&NewAngles_Ext<=45
        extcount45=extcount45+1;
    elseif NewAngles_Ext>45&NewAngles_Ext<=50
        extcount50=extcount50+1;
    elseif NewAngles_Ext>50
        extcountover50=extcountover50+1;
    else NewAngles_Ext = NaN;
        extcountNaN=extcountNaN+1;
    end
end

disp('flexcount5'),disp(flexcount5)
disp('flexcount10'),disp(flexcount10)
disp('flexcount15'),disp(flexcount15)
disp('flexcount20'),disp(flexcount20)
disp('flexcount25'),disp(flexcount25)
disp('flexcount30'),disp(flexcount30)
Program to measure, categorise and summate the radial or ulnar deviation undertaken during a computer task.

clc
clear all

data1 = input('State excelfile and worksheet1 ');
data2 = input('State excelfile and worksheet2 ');
data3 = input('State excelfile and worksheet3 ');
data4 = input('State excelfile and worksheet4 ');
data5 = input('State excelfile and worksheet5 ');
data6 = input('State excelfile and worksheet6 ');
s = size(data1,1);
for i = 1:s;
x1 = data1(i,1); 
y1 = data1(i,2); 
z1 = data1(i,3); 

x2 = data2(i,1); 
y2 = data2(i,2); 
z2 = data2(i,3); 

x3 = data3(i,1); 
y3 = data3(i,2); 
z3 = data3(i,3); 

x4 = data4(i,1); 
y4 = data4(i,2); 
z4 = data4(i,3); 

x5 = data5(i,1); 
y5 = data5(i,2); 
z5 = data5(i,3); 

x6 = data6(i,1); 
y6 = data6(i,2); 
z6 = data6(i,3); 

a1(i) = y1*(z2-z3)+y2*(z3-z1)+y3*(z1-z2); 
b1(i) = z1*(x2-x3)+z2*(x3-x1)+z3*(x1-x2); 
c1(i) = x1*(y2-y3)+x2*(y3-y1)+x3*(y1-y2); 
a2(i) = y4*(z5-z6)+y5*(z6-z4)+y6*(z4-z5); 
b2(i) = z4*(x5-x6)+z5*(x6-x4)+z6*(x4-x5); 
c2(i) = x4*(y5-y6)+x5*(y6-y4)+x6*(y4-y5); 

dataa=(data2 + data3)/2; 

t=2; 
end 

a1 = a1'; 
b1 = b1'; 
c1 = c1'; 
a2 = a2'; 
b2 = b2'; 
c2 = c2'; 

m = data1(:,1)+a1*t;
n = data1(:,2)+b1*t;
o = data1(:,3)+c1*t;
p = data6(:,1)+a2*t;
q = data6(:,2)+b2*t;
r = data6(:,3)+c2*t;
datab=[m,n,o];
datac=[p,q,r];

% second run

s = size(data1,1);
Angles_Radial = [];
Angles_Ulnar = [];

for i = 1:s

x7 = data1(i,1);
y7 = data1(i,2);
z7 = data1(i,3);

x8 = dataa(i,1);
y8 = dataa(i,2);
z8 = dataa(i,3);

x9 = datab(i,1);
y9 = datab(i,2);
z9 = datab(i,3);

x10 = dataa(i,1);
y10 = dataa(i,2);
z10 = dataa(i,3);

x11 = datac(i,1);
y11 = datac(i,2);
z11 = datac(i,3);

x12 = data6(i,1);
y12 = data6(i,2);
z12 = data6(i,3);

a1 = y7*(z8-z9)+y8*(z9-z7)+y9*(z7-z8);
b1 = z7*(x8-x9)+z8*(x9-x7)+z9*(x7-x8);
c1 = x7*(y8-y9)+x8*(y9-y7)+x9*(y7-y8);
a2 = y10*(z11-z12)+y11*(z12-z10)+y12*(z10-z11);
b2 = z10*(x11-x12)+z11*(x12-x10)+z12*(x10-x11);
c2 = x10*(y11-y12)+x11*(y12-y10)+x12*(y10-y11);

v = (a1*a2+b1*b2+c1*c2)/((a1^2+b1^2+c1^2)^0.5)*((a2^2+b2^2+c2^2)^0.5));

q = acos(v);

Angle = q*180/pi;

if dataa(i,3)>data6(i,3);
    Radial=Angle;
    Angles_Radial=[Angles_Radial; Radial];
else Ulnar=Angle;
    Angles_Ulnar=[Angles_Ulnar; Ulnar];
end

end

radialcount5=0;
radialcount10=0;
radialcount15=0;
radialcount20=0;
radialcount25=0;
radialcount30=0;
radialcount35=0;
radialcount40=0;
radialcount45=0;
radialcount50=0;
radialcountover50=0;
radialcountNaN=0;

S = size(Angles_Radial,1);

for i = 1:S

    NewAngles_Radial=Angles_Radial(i,1);

    if NewAngles_Radial>=0 & NewAngles_Radial<=5
        radialcount5=radialcount5+1;
    elseif NewAngles_Radial>5 & NewAngles_Radial<10
        radialcount10=radialcount10+1;
    elseif NewAngles_Radial>10 & NewAngles_Radial<=15
        radialcount15=radialcount15+1;
    elseif NewAngles_Radial>15 & NewAngles_Radial<=20

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radialcount20 = radialcount20 + 1;
elseif NewAngles_Radial > 20 && NewAngles_Radial <= 25
    radialcount25 = radialcount25 + 1;
elseif NewAngles_Radial > 25 && NewAngles_Radial <= 30
    radialcount30 = radialcount30 + 1;
elseif NewAngles_Radial > 30 && NewAngles_Radial <= 35
    radialcount35 = radialcount35 + 1;
elseif NewAngles_Radial > 35 && NewAngles_Radial <= 40
    radialcount40 = radialcount40 + 1;
elseif NewAngles_Radial > 40 && NewAngles_Radial <= 45
    radialcount45 = radialcount45 + 1;
elseif NewAngles_Radial > 45 && NewAngles_Radial <= 50
    radialcount50 = radialcount50 + 1;
elseif NewAngles_Radial > 50
    radialcountover50 = radialcountover50 + 1;
else NewAngles_Radial = NaN;
    radialcountNaN = radialcountNaN + 1;
end

end

ulnarcnt5 = 0;
ulnarcnt10 = 0;
ulnarcnt15 = 0;
ulnarcnt20 = 0;
ulnarcnt25 = 0;
ulnarcnt30 = 0;
ulnarcnt35 = 0;
ulnarcnt40 = 0;
ulnarcnt45 = 0;
ulnarcnt50 = 0;
ulnarcntover50 = 0;
ulnarcntNaN = 0;

O = size(Angles_Ulnar, 1);

for i = 1:O
    NewAngles_Ulnar = Angles_Ulnar(i, 1);

    if NewAngles_Ulnar >= 0 && NewAngles_Ulnar <= 5
        ulnarcnt5 = ulnarcnt5 + 1;
    elseif NewAngles_Ulnar > 5 && NewAngles_Ulnar <= 10
        ulnarcnt10 = ulnarcnt10 + 1;
    elseif NewAngles_Ulnar > 10 && NewAngles_Ulnar <= 15
        ulnarcnt15 = ulnarcnt15 + 1;
    elseif NewAngles_Ulnar > 15 && NewAngles_Ulnar <= 20
        ulnarcnt20 = ulnarcnt20 + 1;
    elseif NewAngles_Ulnar > 20 && NewAngles_Ulnar <= 25
        ulnarcnt25 = ulnarcnt25 + 1;
    elseif NewAngles_Ulnar > 25 && NewAngles_Ulnar <= 30
        ulnarcnt30 = ulnarcnt30 + 1;
    elseif NewAngles_Ulnar > 30 && NewAngles_Ulnar <= 35
        ulnarcnt35 = ulnarcnt35 + 1;
    elseif NewAngles_Ulnar > 35 && NewAngles_Ulnar <= 40
        ulnarcnt40 = ulnarcnt40 + 1;
    elseif NewAngles_Ulnar > 40 && NewAngles_Ulnar <= 45
        ulnarcnt45 = ulnarcnt45 + 1;
    elseif NewAngles_Ulnar > 45 && NewAngles_Ulnar <= 50
        ulnarcnt50 = ulnarcnt50 + 1;
    elseif NewAngles_Ulnar > 50
        ulnarcntover50 = ulnarcntover50 + 1;
    else NewAngles_Ulnar = NaN;
        ulnarcntNaN = ulnarcntNaN + 1;
    end
end
ulnarcoun15=ulnarcoun15+1;
elseif NewAngles_Ulnar>15&NewAngles_Ulnar<=20
ulnarcoun20=ulnarcoun20+1;
elseif NewAngles_Ulnar>20&NewAngles_Ulnar<=25
ulnarcoun25=ulnarcoun25+1;
elseif NewAngles_Ulnar>25&NewAngles_Ulnar<=30
ulnarcoun30=ulnarcoun30+1;
elseif NewAngles_Ulnar>30&NewAngles_Ulnar<=35
ulnarcoun35=ulnarcoun35+1;
elseif NewAngles_Ulnar>35&NewAngles_Ulnar<=40
ulnarcoun40=ulnarcoun40+1;
elseif NewAngles_Ulnar>40&NewAngles_Ulnar<=45
ulnarcoun45=ulnarcoun45+1;
elseif NewAngles_Ulnar>45&NewAngles_Ulnar<=50
ulnarcoun50=ulnarcoun50+1;
else NewAngles_Ulnar=NaN;
ulnarcounNaN=ulnarcounNaN+1;
end
end
disp('radialcount5'),disp(radialcount5)
disp('radialcount10'),disp(radialcount10)
disp('radialcount15'),disp(radialcount15)
disp('radialcount20'),disp(radialcount20)
disp('radialcount25'),disp(radialcount25)
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disp('radialcount35'),disp(radialcount35)
disp('radialcount40'),disp(radialcount40)
disp('radialcount45'),disp(radialcount45)
disp('radialcount50'),disp(radialcount50)
disp('radialcountover50'),disp(radialcountover50)
disp('radialcountNaN'),disp(radialcountNaN)
disp('ulnarcoun5'),disp(ulnarcoun5)
disp('ulnarcoun10'),disp(ulnarcoun10)
disp('ulnarcoun15'),disp(ulnarcoun15)
disp('ulnarcoun20'),disp(ulnarcoun20)
disp('ulnarcoun25'),disp(ulnarcoun25)
disp('ulnarcoun30'),disp(ulnarcoun30)
disp('ulnarcoun35'),disp(ulnarcoun35)
disp('ulnarcoun40'),disp(ulnarcoun40)
disp('ulnarcoun45'),disp(ulnarcoun45)
Program to measure, categorise and summate the FlexUlnar, FlexRad, ExtUlnar or ExtRad undertaken during a computer task.

clc
clear all

data1 = input('State excelfile and worksheet1 ');
data2 = input('State excelfile and worksheet2 ');
data3 = input('State excelfile and worksheet3 ');
data4 = input('State excelfile and worksheet4 ');
data5 = input('State excelfile and worksheet5 ');
data6 = input('State excelfile and worksheet6 ');
s = size(data1,1);
Angles_Flex = [];
for i = 1:s
    x1 = data1(i,1);
y1 = data1(i,2);
z1 = data1(i,3);
    
x2 = data2(i,1);
y2 = data2(i,2);
z2 = data2(i,3);
    
x3 = data3(i,1);
y3 = data3(i,2);
z3 = data3(i,3);
    
x4 = data4(i,1);
y4 = data4(i,2);
\begin{verbatim}
z4 = data4(i,3);

x5 = data5(i,1);
y5 = data5(i,2);
z5 = data5(i,3);

x6 = data6(i,1);
y6 = data6(i,2);
z6 = data6(i,3);

a1 = y1*(z2-z3)+y2*(z3-z1)+y3*(z1-z2);
b1 = z1*(x2-x3)+z2*(x3-x1)+z3*(x1-x2);
c1 = x1*(y2-y3)+x2*(y3-y1)+x3*(y1-y2);

a2 = y4*(z5-z6)+y5*(z6-z4)+y6*(z4-z5);
b2 = z4*(x5-x6)+z5*(x6-x4)+z6*(x4-x5);
c2 = x4*(y5-y6)+x5*(y6-y4)+x6*(y4-y5);

v = (a1*a2+b1*b2+c1*c2)/(((a1^2+b1^2+c1^2)^0.5)*((a2^2+b2^2+c2^2)^0.5));

q = acos(v);

Angle = q*180/pi;

dataa=(data2 + data3)/2;

if dataa(i,2)>data6(i,2);
    Flex=180-Angle;
else
    Flex=-(180-Angle);
end

Angles_Flex = [Angles_Flex; Flex];

t=2;

end

a1 = a1';
b1 = b1';
c1 = c1';
a2 = a2';
b2 = b2';
c2 = c2';

m = data1(:,1)+a1*t;
\end{verbatim}
n = data1(:,2)+b1*t;
o = data1(:,3)+c1*t;
p = data6(:,1)+a2*t;
q = data6(:,2)+b2*t;
r = data6(:,3)+c2*t;
datab=[m,n,o];
datac=[p,q,r];

%second run%
s = size(data1,1);
Angles_Radial = [];
for i = 1:s
    x7 = data1(i,1);
y7 = data1(i,2);
z7 = data1(i,3);

    x8 = dataa(i,1);
y8 = dataa(i,2);
z8 = dataa(i,3);

    x9 = datab(i,1);
y9 = datab(i,2);
z9 = datab(i,3);

    x10 = dataa(i,1);
y10 = dataa(i,2);
z10 = dataa(i,3);

    x11 = datac(i,1);
y11 = datac(i,2);
z11 = datac(i,3);

    x12 = data6(i,1);
y12 = data6(i,2);
z12 = data6(i,3);

    a3 = y7*(z8-z9)+y8*(z9-z7)+y9*(z7-z8);
b3 = z7*(x8-x9)+z8*(x9-x7)+z9*(x7-x8);
c3 = x7*(y8-y9)+x8*(y9-y7)+x9*(y7-y8);
a4 = y10*(z11-z12)+y11*(z12-z10)+y12*(z10-z11);
\[ b_4 = z_{10} \times (x_{11} - x_{12}) + z_{11} \times (x_{12} - x_{10}) + z_{12} \times (x_{10} - x_{11}) \];

\[ c_4 = x_{10} \times (y_{11} - y_{12}) + x_{11} \times (y_{12} - y_{10}) + x_{12} \times (y_{10} - y_{11}) \];

\[ w = (a_3 \times a_4 + b_3 \times b_4 + c_3 \times c_4) / ((a_3^2 + b_3^2 + c_3^2)^{0.5} \times (a_4^2 + b_4^2 + c_4^2)^{0.5}) \];

\[ j = \cos^{-1}(w) \];

\[ \text{Angle1} = j \times 180 / \pi; \]

\[
\text{if dataa(i,3)} > \text{data6(i,3)}; \\
\quad \text{Radial} = \text{Angle1}; \\
\text{else} \\
\quad \text{Radial} = -(\text{Angle1}); \\
\text{end}
\]

\[ \text{Angles_Radial} = [\text{Angles_Radial}; \text{Radial}]; \]

end

\[
\text{flex5rad5} = 0; \\
\text{flex10rad5} = 0; \\
\text{flex15rad5} = 0; \\
\text{flex20rad5} = 0; \\
\].
\[
\text{flex45radover50} = 0; \\
\text{flex50radover50} = 0; \\
\text{flexover50radover50} = 0; \\
\text{flexradNaN} = 0; \\
\]

\[
\text{flex5ulnar5} = 0; \\
\text{flex10ulnar5} = 0; \\
\text{flex15ulnar5} = 0; \\
\text{flex20ulnar5} = 0; \\
\].
\[
\text{flex45ulnarover50} = 0; \\
\text{flex50ulnarover50} = 0; \\
\]

% All code from flex20rad5=0 to flex45radover50=0 in increments of 5 for both flex and rad were stated.

% All code from flex20ulnar5=0 to flex45ulnarover50=0 in increments of 5 for both flex and ulnar were stated.
flexover50ulnarover50=0;
flexulnarNaN=0;

ext5rad5=0;
ext10rad5=0;
ext15rad5=0;
ext20rad5=0;
.                        % All code from ext20rad5=0 to ext45radover50=0
.                        in increments of 5 for both ext and rad were
.                        stated.
.                        % All code from ext20ulnar5=0 to
.                        ext45ulnarover50=0 in increments of 5 for both
.                        ext and ulnar were stated.
.                        % All code from ext20ulnar5=0 to
.                        ext45ulnarover50=0 in increments of 5 for both
.
S = size(Angles_Flex,1);

for i = 1:S

        NewAngles_Flex=Angles_Flex(i,1);
        NewAngles_Radial=Angles_Radial(i,1);

        if
        NewAngles_Flex>=0&NewAngles_Flex<=5&NewAngles_Radial>=0&NewAngles_Radial<=5
        flex5rad5=flex5rad5+1;
        elseif
        NewAngles_Flex>5&NewAngles_Flex<=10&NewAngles_Radial>=0&NewAngles_Radial<=5
        flex10rad5=flex10rad5+1;
        elseif
        flex15rad5=flex15rad5+1;
        elseif
        flex20rad5=flex20rad5+1;
        elseif
        flex25rad5=flex25rad5+1;
        elseif
        flex30rad5=flex30rad5+1;
        elseif
        flex35rad5=flex35rad5+1;
        elseif
        NewAngles_Flex>35&NewAngles_Flex<=40&NewAngles_Radial>=0&NewAngles_Radial<=5
        flex40rad5=flex40rad5+1;
        elseif
        NewAngles_Flex>40&NewAngles_Flex<=45&NewAngles_Radial>=0&NewAngles_Radial<=5
        flex45rad5=flex45rad5+1;
        else
        extradNaN=extradNaN+1;
        end
        end
        end
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        en
flex10rad5 = flex10rad5 + 1;

elseif

flex15rad5 = flex15rad5 + 1;
else

flex20rad5 = flex20rad5 + 1;
else

flex25rad5 = flex25rad5 + 1;
else

flex30rad5 = flex30rad5 + 1;
else

flex35rad5 = flex35rad5 + 1;
else

NewAngles_Flex > 35 & NewAngles_Flex <= 40 & NewAngles_Radial >= 0 & NewAngles_Radial <= 5
flex40rad5 = flex40rad5 + 1;
else

NewAngles_Flex > 40 & NewAngles_Flex <= 45 & NewAngles_Radial >= 0 & NewAngles_Radial <= 5
flex45rad5 = flex45rad5 + 1;
else

NewAngles_Flex > 45 & NewAngles_Flex <= 50 & NewAngles_Radial >= 0 & NewAngles_Radial <= 5
flex50rad5 = flex50rad5 + 1;
else

NewAngles_Flex > 50 & NewAngles_Radial >= 0 & NewAngles_Radial <= 5
flexover50rad5 = flexover50rad5 + 1;
else

NewAngles_Flex >= 0 & NewAngles_Flex <= 5 & NewAngles_Radial > 5 & NewAngles_Radial <= 10
flex5rad10 = flex5rad10 + 1;
else

NewAngles_Flex > 5 & NewAngles_Flex <= 10 & NewAngles_Radial >= 0 & NewAngles_Radial <= 10
flex10rad10 = flex10rad10 + 1;
else
All code categorising the determined wrist postures increasing in increments of 5 for Flex and Radial were stated.

NewAngles_Flex>40&NewAngles_Flex<=45&NewAngles_Radial>45&NewAngles_Radial<=50
flex45rad50=flex45rad50+1;
elseif
NewAngles_Flex>45&NewAngles_Flex<=50&NewAngles_Radial>45&NewAngles_Radial<=50
flex50rad50=flex50rad50+1;
elseif
NewAngles_Flex>50&NewAngles_Radial>45&NewAngles_Radial<=50
flexover50rad50=flexover50rad50+1;
elseif
NewAngles_Flex>=0&NewAngles_Flex<=5&NewAngles_Radial>50
flex5radover50=flex5radover50+1;
elseif
NewAngles_Flex>5&NewAngles_Flex<=10&NewAngles_Radial>50
flex10radover50=flex10radover50+1;
elseif
NewAngles_Flex>10&NewAngles_Flex<=15&NewAngles_Radial>50
flex15radover50=flex15radover50+1;
elseif
NewAngles_Flex>15&NewAngles_Flex<=20&NewAngles_Radial>50
flex20radover50=flex20radover50+1;
elseif
NewAngles_Flex>20&NewAngles_Flex<=25&NewAngles_Radial>50
flex25radover50=flex25radover50+1;
elseif
NewAngles_Flex>25&NewAngles_Flex<=30&NewAngles_Radial>50
flex30radover50=flex30radover50+1;
elseif
NewAngles_Flex>30&NewAngles_Flex<=35&NewAngles_Radial>50
flex35radover50=flex35radover50+1;
elseif
NewAngles_Flex>35&NewAngles_Flex<=40&NewAngles_Radial>50
flex40radover50=flex40radover50+1;
elseif
NewAngles_Flex>40&NewAngles_Flex<=45&NewAngles_Radial>50
flex45radover50=flex45radover50+1;
elseif
NewAngles_Flex>45&NewAngles_Flex<=50&NewAngles_Radial>50
flex50radover50=flex50radover50+1;
elseif
NewAngles_Flex>50&NewAngles_Radial>50
flexover50radover50=flexover50radover50+1;
elseif
flex5ulnar5=flex5ulnar5+1;
elseif
flex10ulnar5=flex10ulnar5+1;
elseif
flex15ulnar5=flex15ulnar5+1;
elseif
flex20ulnar5=flex20ulnar5+1;
elseif
flex25ulnar5=flex25ulnar5+1;
elseif
flex30ulnar5=flex30ulnar5+1;
elseif
flex35ulnar5=flex35ulnar5+1;
elseif
flex40ulnar5=flex40ulnar5+1;
elseif
flex45ulnar5=flex45ulnar5+1;
elseif
flex50ulnar5=flex50ulnar5+1;
elseif
    NewAngles_Flex>50&NewAngles_Radial<=0&NewAngles_Radial>=-5
    flexover50ulnar5=flexover50ulnar5+1;
elseif
    NewAngles_Flex>=0&NewAngles_Flex<=5&NewAngles_Radial<-10
    flex5ulnar10=flex5ulnar10+1;
elseif
    NewAngles_Flex>5&NewAngles_Flex<=10&NewAngles_Radial<-10
    flex10ulnar10=flex10ulnar10+1;
elseif
        % All code categorising the determined wrist postures
decreasing in increments of 5 for Flex and Radial
        were stated.
.
.
.
.
.
.
    flex45ulnar50=flex45ulnar50+1;
elseif
    NewAngles_Flex>45&NewAngles_Flex<=50&NewAngles_Radial<-50
    flex50ulnar50=flex50ulnar50+1;
elseif
    NewAngles_Flex>50&NewAngles_Radial<-50
    flexover50ulnar50=flexover50ulnar50+1;
elseif
    NewAngles_Flex>=0&NewAngles_Flex<=5&NewAngles_Radial<-50
    flex5ulnarover50=flex5ulnarover50+1;
elseif
    NewAngles_Flex>5&NewAngles_Flex<=10&NewAngles_Radial<-50
    flex10ulnarover50=flex10ulnarover50+1;
elseif
    NewAngles_Flex>10&NewAngles_Flex<=15&NewAngles_Radial<-50
    flex15ulnarover50=flex15ulnarover50+1;
elseif
    NewAngles_Flex>15&NewAngles_Flex<=20&NewAngles_Radial<-50
    flex20ulnarover50=flex20ulnarover50+1;
elseif
    flex25ulnarover50=flex25ulnarover50+1;
elseif

NewAngles_Flex>25&NewAngles_Flex<=30&NewAngles_Radial<-50
flex30ulnarover50=flex30ulnarover50+1;
elseif
NewAngles_Flex>30&NewAngles_Flex<=35&NewAngles_Radial<-50
flex35ulnarover50=flex35ulnarover50+1;
elseif
NewAngles_Flex>35&NewAngles_Flex<=40&NewAngles_Radial<-50
flex40ulnarover50=flex40ulnarover50+1;
elseif
NewAngles_Flex>40&NewAngles_Flex<=45&NewAngles_Radial<-50
flex45ulnarover50=flex45ulnarover50+1;
elseif
NewAngles_Flex>45&NewAngles_Flex<=50&NewAngles_Radial<-50
flex50ulnarover50=flex50ulnarover50+1;
elseif
NewAngles_Flex>50&NewAngles_Radial<-50
flexover50ulnarover50=flexover50ulnarover50+1;
elseif
NewAngles_Flex<=0&NewAngles_Flex>=-5&NewAngles_Radial>=0&NewAngles_Radial<=5
ext5rad5=ext5rad5+1;
elseif
ext10rad5=ext10rad5+1;
elseif
ext15rad5=ext15rad5+1;
elseif
ext20rad5=ext20rad5+1;
elseif
ext25rad5=ext25rad5+1;
elseif
ext30rad5=ext30rad5+1;
elseif
ext35rad5=ext35rad5+1;
elseif
    ext40rad5=ext40rad5+1;
elseif
    ext45rad5=ext45rad5+1;
elseif
    ext50rad5=ext50rad5+1;
elseif
    NewAngles_Flex<-50&NewAngles_Radial>=0&NewAngles_Radial<=5
    extover50rad5=extover50rad5+1;
elseif
    NewAngles_Flex<=0&NewAngles_Flex>=-5&NewAngles_Radial>5&NewAngles_Radial<=10
    ext5rad10=ext5rad10+1;
elseif
    NewAngles_Flex<-5&NewAngles_Flex>=-10&NewAngles_Radial>5&NewAngles_Radial<=10
    ext10rad10=ext10rad10+1;
elseif
    NewAngles_Flex<=0&NewAngles_Flex>=-5&NewAngles_Radial>5&NewAngles_Radial<=10
    extover5rad10=extover5rad10+1;
elseif
    ext45rad50=ext45rad50+1;
elseif
    ext50rad50=ext50rad50+1;
elseif
    NewAngles_Flex<-50&NewAngles_Radial>45&NewAngles_Radial<=50
    extover50rad50=extover50rad50+1;
elseif
    NewAngles_Flex<=0&NewAngles_Flex>=-5&NewAngles_Radial>50
    ext5radover50=ext5radover50+1;
elseif
    NewAngles_Flex<-5&NewAngles_Flex>=-10&NewAngles_Radial>50
    ext10radover50=ext10radover50+1;
elseif
    .
    % All code categorising the determined wrist postures
    .
    increasing in increments of 5 for Flex and Radial
    .
    .
    .
    .
    ext45rad50=ext45rad50+1;
elseif
    ext50rad50=ext50rad50+1;
elseif
    NewAngles_Flex<-50&NewAngles_Radial>45&NewAngles_Radial<=50
    extover50rad50=extover50rad50+1;
elseif
    NewAngles_Flex<=0&NewAngles_Flex>=-5&NewAngles_Radial>50
    ext5radover50=ext5radover50+1;
elseif
    NewAngles_Flex<-5&NewAngles_Flex>=-10&NewAngles_Radial>50
    ext10radover50=ext10radover50+1;
elseif
    .
NewAngles_Flex<-5&NewAngles_Flex>=-10&NewAngles_Radial>50
ext10radover50=ext10radover50+1;
elseif
NewAngles_Flex<-10&NewAngles_Flex>=-15&NewAngles_Radial>50
ext15radover50=ext15radover50+1;
elseif
NewAngles_Flex<-15&NewAngles_Flex>=-20&NewAngles_Radial>50
ext20radover50=ext20radover50+1;
elseif
NewAngles_Flex<-20&NewAngles_Flex>=-25&NewAngles_Radial>50
ext25radover50=ext25radover50+1;
elseif
NewAngles_Flex<-25&NewAngles_Flex>=-30&NewAngles_Radial>50
ext30radover50=ext30radover50+1;
elseif
NewAngles_Flex<-30&NewAngles_Flex>=-35&NewAngles_Radial>50
ext35radover50=ext35radover50+1;
elseif
NewAngles_Flex<-35&NewAngles_Flex>=-40&NewAngles_Radial>50
ext40radover50=ext40radover50+1;
elseif
NewAngles_Flex<-40&NewAngles_Flex>=-45&NewAngles_Radial>50
ext45radover50=ext45radover50+1;
elseif
NewAngles_Flex<-45&NewAngles_Flex>=-50&NewAngles_Radial>50
ext50radover50=ext50radover50+1;
elseif
NewAngles_Flex<-50&NewAngles_Radial>50
extover50radover50=extover50radover50+1;
elseif
ext5ulnar5=ext5ulnar5+1;
elseif
ext10ulnar5=ext10ulnar5+1;
elseif
ext15ulnar5=ext15ulnar5+1;
elseif
ext20ulnar5=ext20ulnar5+1;
elseif
    ext25ulnar5=ext25ulnar5+1;
elseif
    ext30ulnar5=ext30ulnar5+1;
elseif
    ext35ulnar5=ext35ulnar5+1;
elseif
    ext40ulnar5=ext40ulnar5+1;
elseif
    ext45ulnar5=ext45ulnar5+1;
elseif
    ext50ulnar5=ext50ulnar5+1;
elseif
    extover50ulnar5=extover50ulnar5+1;
elseif
     NewAngles_Flex<0&NewAngles_Flex>=-5&NewAngles_Radial<-5&NewAngles_Radial>=-10
    ext5ulnar10=ext5ulnar10+1;
elseif
    ext10ulnar10=ext10ulnar10+1;
elseif
    % All code categorising the determined wrist postures
decreasing in increments of 5 for Flex and Radial were stated.
    %
    %
    %
    %
    %
ext45ulnar50=ext45ulnar50+1;
ext50ulnar50=ext50ulnar50+1;
extover50ulnar50=extover50ulnar50+1;
elseif NewAngles_Flex<-50&NewAngles_Flex>=-5&NewAngles_Radial<-50
ext5ulnarover50=ext5ulnarover50+1;
elseif NewAngles_Flex<-5&NewAngles_Flex>=-10&NewAngles_Radial<-50
ext10ulnarover50=ext10ulnarover50+1;
ext15ulnarover50=ext15ulnarover50+1;
ext20ulnarover50=ext20ulnarover50+1;
ext25ulnarover50=ext25ulnarover50+1;
ext30ulnarover50=ext30ulnarover50+1;
ext35ulnarover50=ext35ulnarover50+1;
ext40ulnarover50=ext40ulnarover50+1;
elseif NewAngles_Flex<-40&NewAngles_Flex>=-45&NewAngles_Radial<-50
ext45ulnarover50=ext45ulnarover50+1;
ext50ulnarover50=ext50ulnarover50+1;
elseif NewAngles_Flex<-50&NewAngles_Radial<-50
extover50ulnarover50=extover50ulnarover50+1;
else
NewAngles_Flex = NaN;
flexradNaN=flexradNaN+1;
end
end

disp(flex5rad5)
disp(flex10rad5)
disp(flex15rad5)
disp(flex20rad5)
.
% All code used to disp(flex20rad5) to disp(flex45radover50) in increments of 5 for both flex and rad were stated.
.
.
disp(flex40radover50)
disp(flex45radover50)
disp(flex50radover50)
disp(flexover50radover50)
.
disp(flex5ulnar5)
disp(flex10ulnar5)
disp(flex15ulnar5)
disp(flex20ulnar5)
.
% All code used to disp(flex20ulnar5) to disp(flex45ulnarover50) in increments of 5 for both flex and ulnar were stated.
.
.
disp(flex40ulnarover50)
disp(flex45ulnarover50)
disp(flex50ulnarover50)
disp(flexover50ulnarover50)
.
disp(ext5rad5)
disp(ext10rad5)
disp(ext15rad5)
disp(ext20rad5)
.
% All code used to disp(ext20ulrad5) to disp(ext45radover50) in increments of 5 for both ext and rad were stated.
.
.
disp(ext40radover50)
disp(ext45radover50)
disp(ext50radover50)
disp(extover50radover50)
disp(ext5ulnar5)
disp(ext10ulnar5)
disp(ext15ulnar5)
disp(ext20ulnar5)
.
% All code used to disp(ext20ulnar5) to
disp(ext45ulnarover50) in increments of 5 for both
ext and ulnar were stated.
.
disp(ext45ulnarover50)
disp(ext50ulnarover50)
disp(extover50ulnarover50)
disp(flexradNaN)
Appendix D - Boston Carpal Tunnel Questionnaire

Symptom Severity Scale

The following questions refer to your symptoms for a typical twenty-four-hour period during the past two weeks (Tick the appropriate box).

How severe is the hand or wrist pain that you have at night?
1) I do not have hand or wrist pain at night
2) Mild pain
3) Moderate pain
4) Severe pain
5) Very severe pain

How often did hand or wrist pain wake you up during a typical night in the past two weeks?
1) Never
2) Once
3) Two or three times
4) Four or five times
5) More than five times

Do you typically have pain in your hand or wrist during the daytime?
1) I never have pain during the day
2) I have mild pain during the day
3) I have moderate pain during the day
4) I have severe pain during the day
5) I have very severe pain during the day

How often do you have hand or wrist pain during the daytime?
1) Never
2) Once or twice a day
3) Three to five times a day
4) More than five times a day
5) The pain is constant

How long, on average, does an episode of pain last during the daytime?
1) I never get pain during the day
2) Less than 10 minutes
3) 10 to 60 minutes
4) Greater than 60 minutes
5) The pain is constant throughout the day

Do you have numbness (loss of sensation) in your hand?
1) No
2) I have mild numbness
3) I have moderate numbness
4) I have severe numbness
5) I have very severe numbness

Do you have weakness in your hand or wrist?
1) No weakness
2) Mild weakness
3) Moderate weakness
4) Severe weakness
5) Very severe weakness

Do you have tingling sensations in your hand?
1) No tingling
2) Mild tingling
3) Moderate tingling
4) Severe tingling
5) Very severe tingling

How severe is numbness (loss of sensation) or tingling at night?
1) I have no numbness or tingling at night
2) Mild
3) Moderate
4) Severe
5) Very severe

How often did hand numbness or tingling wake you up during a typical night during the past two weeks?
1) Never
2) Once
3) Two or three times
4) Four or five times
5) More than five times

Do you have difficulty with the grasping and use of small objects such as keys or pens?
1) No difficulty
2) Mild difficulty
3) Moderate difficulty
4) Severe difficulty
5) Very severe difficulty
### Functional Status Scale

On a typical day during the past two weeks have hand and wrist symptoms caused you to have any difficulty doing the activities listed below? Please circle one number that best describes your ability to do the activity.

<table>
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<tr>
<th>Activity</th>
<th>No Difficulty</th>
<th>Mild Difficulty</th>
<th>Moderate Difficulty</th>
<th>Severe Difficulty</th>
<th>Cannot Do at All Due to Hand or Wrist Symptoms</th>
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<td>Bathing and dressing</td>
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<td>3</td>
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Appendix E - MATLAB Program for Determining the Distance from the Centroid of the Precise Geometry Model to a Centroidal Line of the Ultrasound Models

clc
clear all

X = input('State excelfile and worksheet1 '); 
[coeff, score, roots] = princomp(X);
plot3(X(:,1),X(:,2),X(:,3),'bo');

grid on;

[n,p] = size(X);
meanX = mean(X,1);
dirVect = coeff(:,1);

Xfit1 = repmat(meanX,n,1) + score(:,1)*coeff(:,1)';
t = [min(score(:,1))-.2, max(score(:,1))+.2];
endpts = [meanX + t(1)*dirVect'; meanX + t(2)*dirVect'];
plot3(endpts(:,1),endpts(:,2),endpts(:,3),'k-');

X1 = [X(:,1) Xfit1(:,1) nan*ones(n,1)];
X2 = [X(:,2) Xfit1(:,2) nan*ones(n,1)];
X3 = [X(:,3) Xfit1(:,3) nan*ones(n,1)];

hold on
plot3(X1',X2',X3','b-', X(:,1),X(:,2),X(:,3),'bo');
hold off

grid on

endpt1 = [meanX + t(2)*dirVect']
endpt2 = [meanX + t(1)*dirVect']

for i=0:5:180;
P1=[1000,1000,i];
P2=[-1000,1000,i];
P3=[-2000,0,i];
Q=[0, 0, i];

normal = cross(P1-P2, P1-P3);
syms x y z

P = [x,y,z];
planefunction = dot(normal, P-P1);
P4 = [66 90 -72];
P5 = [52 80 2];
syms t

line = endpt1 + t*(endpt2-endpt1);
newfunction = subs(planefunction, P, line);
t0 = solve(newfunction);
point = subs(line, t, t0);
G=Q(i/5+1,:)-point;

xd = G(1,1);
yd = G(1,2);
zd = G(1,3);

ans = subs(planefunction, P, point);
Distance = sqrt(xd*xd + yd*yd + zd*zd);

disp(Distance)

end
Appendix F - Post Hoc Analysis for the One Way ANOVA Statistical Data Seen in Table 5.6.

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<th>(J) VAR001</th>
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