Wrist partial arthrodesis or other motion preserving surgery for degenerative wrist disease: Prospective comparative assessment of grip strength, range of motion, function and disability.

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by

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Abstract

Traumatic osteoarthritis of the wrist is a disabling disease that affects middle-aged active adults in the prime of their working life. I set out to assess wrist function and disability in patients with traumatic wrist osteoarthritis before and after surgery. I measured wrist range of motion with flexible electrogoniometer, grip strength with force-time curves using dynamometer, hand function with timed Sollerman hand function test and patient-reported outcome. I first developed these techniques in normal volunteers and then extended them to patients with wrist osteoarthritis before surgery and after four-corner fusion, three-corner fusion, total wrist fusion, and proximal row carpectomy.

I used flexible electrogoniometry to generate circumduction curves to measure range, rate and rhythm of circumduction of the wrist. It showed that there was no difference in range of motion parameters in patients with wrist osteoarthritis before surgery and after four-corner fusion and three-corner fusion. Proximal row carpectomy provides better flexion-extension and poorer radio-ulnar deviation than four-corner fusion. Three-corner fusion allows better rate and rhythm of movements in flexion and ulnar deviation compared to four-corner fusion.

Grip strength was measured with dynamometer to generate force time curves to measure sustainability of grip. There was no difference between our groups with wrist osteoarthritis before surgery and after wrist fusion, four-corner fusion or three-corner fusion.

I developed the Timed Sollerman hand function test by measuring the time taken to complete each of the tasks without summarisation into a 5-point scale. It showed that volunteers completed the tasks quicker with the dominant hand than with the nondominant hand. Women took less time to complete the tasks in the 30-40 years age group than women in the 20-30 years age group and beyond 40 years. The patients with PRC completed the different activities of daily living quicker than the 4CF patients, except for activities requiring wrist torque strength.
Acknowledgements

I would like to express my gratitude to my supervisor Prof Joseph J Dias for introducing me to this project, the useful comments, remarks and engagement through the learning process of this dissertation. Furthermore, I would like to thank Mr. Rob Ashford and Mr. Grahame Taylor for their support and comments.

I would like to thank my wife Dr. Jaspreet Kaur, who has supported me throughout entire process, both by keeping me harmonious and helping me put pieces together. To my Daughter, Jasvin and my parents, I will be grateful forever for their love.

Above all, I thank the patients and volunteers who agreed to participate in this study, without whom there would have been no learning.
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<td>CT</td>
<td>Computed Tomography</td>
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<tr>
<td>DASH</td>
<td>Disabilities of the Arm, Shoulder and Hand</td>
</tr>
<tr>
<td>DISI</td>
<td>Dorsal Intercalated Segmental Instability</td>
</tr>
<tr>
<td>DRUJ</td>
<td>Distal Radio Ulnar Joint</td>
</tr>
<tr>
<td>4CF</td>
<td>Four-corner fusion</td>
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<tr>
<td>FCU</td>
<td>Flexor Carpi Ulnaris</td>
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<td>MHQ</td>
<td>Michigan hand Questionnaire</td>
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<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
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<tr>
<td>PEM</td>
<td>Patient Evaluation Measure</td>
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<td>PRC</td>
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<tr>
<td>3CF</td>
<td>Three-corner fusion</td>
</tr>
<tr>
<td>TFCC</td>
<td>Triangular Fibrocartilagenous Complex</td>
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<tr>
<td>VAS</td>
<td>Visual Analogue Scale</td>
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1 Introduction

Traumatic osteoarthritis of the wrist is a disabling disease that affects middle-aged active adults in the prime of their working life. It can occur after scaphoid a fracture nonunion or ligament injuries to the wrist. When pain is not controlled by non-operative methods of treatment, consideration has to be given to surgery. Surgery aims to reduce pain and disability, improve grip strength and preserve some range of motion.

There are a number of surgical options available, including total wrist fusion, partial wrist fusion (four-corner fusion, three-corner fusion or lunocapitate fusion), proximal row carpectomy (complete excision of proximal row of bones of the wrist), and wrist arthroplasty (replacement). The results of wrist arthroplasty are very unpredictable, so this method has not been widely accepted and is still largely experimental. Therefore, the main choices of surgical management of wrist osteoarthritis currently are total wrist fusion, proximal row carpectomy, or partial wrist fusion.

Arthrodesis (fusion) of the wrist reduces pain and improves grip strength, however, it completely restricts motion so is therefore considered very disabling. Proximal row carpectomy (PRC), scaphoid excision with four-corner fusion (4CF) and three-corner fusion (3CF) are common motion-preserving procedures advocated by surgeons for symptomatic osteoarthritis. 4CF involves fusion of four bones (capitate, lunate, triquetrum and hamate) in the wrist with excision of the scaphoid. 3CF involves excision of triquetrum and scaphoid and fusion of three bones (capitate, lunate and hamate). Advocates of PRC claim that the procedure gives a greater range of motion and involves a simpler surgical technique without the risk of nonunion or complications secondary to hardware associated with fusion. Advocates of 4CF claim the results will be greater grip strength with less chance of progression of radiocarpal arthritis. 3CF improves the range of motion of the wrist compared to 4CF. However, there is no clear
evidence to suggest which of these procedures will have a better outcome for the patients.

There are currently no good prospective comparative studies for these techniques, as wrist osteoarthritis is a relatively rare condition and the numbers of surgeries performed for this disorder are low. There are various retrospective case series relating to these procedures, but again the numbers are quite small. There are also differences between countries and surgeons in their preference in managing this condition; for example, British surgeons prefer 4CF, while surgeons from continental Europe generally choose PRC.

Previous authors have used the following outcome methods to study these patients:

1. Range of movements (maximum movement in two planes: flexion/ extension and ulnar/ radial deviation).
2. Grip strength (peak/ maximum grip strength).

There are no studies where disabilities experienced by these patients after surgery have been discussed. Previous studies have not used functional assessments such as the Sollerman hand function test, to compare the surgical groups. The grip strength has only been studied as the peak force achieved and not the sustainability of the grip. The range of movement of the wrist has not been studied as a composite of movement (circumduction), but only compared as the maximum achievable in two planes (flexion/ extension and radial/ ulnar deviation).

This thesis describes these innovative methods of wrist assessment that have never been used on patients with wrist osteoarthritis, either before or
after surgery. I wished to understand the disability experienced by these patients in greater detail and used the following assessments to try to achieve this:

1. Range of motion assessment with electrogoniometer.
2. Grip strength assessment with force-time curves.
3. Timed Sollerman hand function test.
4. Patient-reported outcome questionnaires, 4a) Michigan Hand Questionnaire (MHQ) and 4b) Patient evaluation measure (PEM).

This thesis describes the wrist assessments using the above techniques firstly in 100 normal volunteers. It then describes the effects of disease on patients with 16 patients with wrist osteoarthritis before surgery, 24 patients after four-corner fusion, 22 patients after proximal row carpectomy, 12 patients after three-corner fusion and 12 patients after total wrist fusion.
This chapter describes the key parts of this thesis:

1.1 *The anatomy of the wrist* describes how the bones and ligaments are arranged in the wrist joint; it includes relevant osteology (bony anatomy), anatomy of ligaments, kinematics of carpal bones and radiological anatomy of the wrist.

1.2 *Wrist osteoarthritis* describes why and how wrist osteoarthritis develops and the ways in which the disease compromises the wrist.

1.3 *Functional wrist motion* describes the biomechanics of the wrist with the coupled motion in two planes.

1.4 *Wrist assessment* discusses how an osteoarthritic wrist is assessed, including clinical examination with assessment of grip strength, range of motion, function and patient-reported outcome questionnaires. This is the key concept in the thesis and is discussed in the context of previous literature.

1.5 *Management* discusses the various non-surgical and surgical treatments that can be used to treat symptomatic osteoarthritis of the wrist.

1.6 *The aims and objectives* of this thesis are discussed in this section.
1.1 Wrist Anatomy

I initially discuss the anatomy of the wrist, focusing on the most relevant areas for the diagnosis and management of wrist osteoarthritis. This review will cover the osteology, ligamentous structure, wrist kinematics, important tendons and soft tissue structures around the wrist joint.

The wrist joint is a bridge between the forearm and the hand and allows the hand to be placed in a three-dimensional space to allow function. Eight carpal bones, the end of the radius and ulna form this complex joint. These bones allow the hand to move relative to the forearm in flexion, extension, radial deviation and ulnar deviation. Supination and pronation occurs principally at the forearm. The ligaments maintain the stability of this joint.
1.1.1 Osteology

The bones in the wrist are arranged in two rows. The proximal row consists of the scaphoid, lunate, triquetrum and pisiform (radial to medial). The pisiform is a sesamoid bone located in the tendon of the flexor carpi ulnaris and is an important stabiliser of the wrist joint. The distal row of carpal bones consists of the trapezium, trapezoid, capitate and hamate from the radial to medial side. All the tendons are attached to the distal row (Figure 1.1).

Figure 1.1 Radiograph of left wrist showing bones in the wrist with radioscaphoid osteoarthritis.
R Radius, U Ulna, S Scaphoid, L Lunate, T Triquetrum, P Pisiform, Trm Trapezium, Trd Trapezoid, C Capitate, H Hamate.
The articular surface of the distal end of the radius is covered with hyaline cartilage and consists of two facets divided by the antero-posterior ridge. The radial facet for the scaphoid is triangular (Figure 1.2) and is separate from the quadrilateral facet for the lunate.
Figure 1.2 Drawing of the radius and radiocarpal capsule and ligaments from a distal and slightly radial perspective, with the carpus removed. Reprinted with permission from Wolters Kluwer Health (Richard A Berger, 2003) S Scaphoid fossa, L Lunate fossa.

The ulnar head articulates with the concave facet on the ulnar aspect of the distal radius, although it does not articulate directly with the carpal bones. A specialist cartilaginous structure arises from the ulnar border of the lunate fossa and inserts into the fovea at the base of the ulnar styloid. This triangular fibrocartilagenous complex (TFCC) also extends into the ulnar collateral, the lunotriquetral and ulno-hamate ligaments and extends to the base of the fifth metacarpal. This acts to stabilise the distal radioulnar joint and forms a sling for the ulnar aspect of the carpal bones (Figure 1.2). This is also associated on the dorsal aspect with the tendon sheath of the extensor carpi ulnaris, which acts as the dorsal stabiliser for the ulnar aspect of the wrist.
1.1.2 Ligaments

There are two sets of robust ligament that stabilise the wrist. The extrinsic ligaments extend from the radius or metacarpals to the carpal bones, while the intrinsic ligaments originate and insert on the carpal bones. The palmar extrinsic ligaments are very robust and stabilise the wrist joint, but also have a role in wrist kinematics. The palmar carpal ligaments are arranged in the form of two inverted V-shaped structures, with the lunate at the apex of the first V and capitate at the apex of the second. In the first configuration, the radiolunate ligament forms the strong attachment of the lunate to the radius and on the ulnar aspect; the lunate becomes attached to the radius, ulnar styloid and triquetrum. In the second V configuration, the capitate is located at the apex, the radioscapohamate ligament is on the radial and the ulnocapitate ligaments are on the ulnar side. (Figure 1.3)

Figure 1.3 Extrinsic palmar ligaments of the wrist.
LRL, long radiolunate ligament; RSL, radioscapohamate ligament; SRL, short radiolunate ligament; UL, ulnolunate ligament; UT, ulnotriquetral ligament; LT, lunotriquetral ligament; RLA, radial arm of the arcuate ligament; ULA, ulnar arm of the arcuate ligament. Reprinted with permission Elsevier (Lichtman and Wroten, 2006)
The radioscaphocapitate ligament is palmar to the waist of the scaphoid, which allows the rotation of the scaphoid in radial and ulnar deviation. The strong radiolunate ligament is tense at the extremes of wrist motion, particularly in scaphoid flexion and extension (Taleisnick, 1985). The space of Poirier is an inherent gap between the extrinsic palmar carpal ligaments, from which the synovial out-pouching can occur overlying the capitolunate ligament, and where also the capitate and lunate can sublux in a perilunate dislocation. On the ulnar side, the triquetrum acts as the convergence point of the TFCC, palmar radiolunotriquetral ligaments, capitotriquetral ligaments and the dorsal intercarpal ligaments.

Figure 1.4 Dorsal wrist ligaments.
RS, radioscaphoid ligament; RT, radiotriquetral ligament; DIC, dorsal intercarpal ligament. Reprinted with permission Elsevier (Lichtman and Wroten, 2006) Bold lines show the Berger’s ligament splitting approach to the wrist.

The Dorsal extrinsic ligaments (Figure 1.4) are arranged in the form of the transverse intercarpal ligament distally and the proximal oblique ligament. It is arranged in a V configuration, with the apex ulnarwards on the triquetrum.
and the base towards the radial aspect. The proximal radiolunate and radiotriquetral ligaments insert together on the triquetrum. The Berger’s ligament splitting approach utilises this anatomy to split the ligament fibers longitudinally to base the flap on the radial aspect.

The intrinsic ligaments gain the attachment from the scaphoid to lunate and the lunate to triquetrum. The scapholunate ligament is a key ligament of the wrist joint that is commonly injured and can lead to instability. It comprises a C-shaped structure with a stronger dorsal portion for controlling flexion and extension and a weaker palmar part to control rotation (Figure 1.5). The posterior part can resist more than 300 N tensile stresses, while the anterior part fails with 150 N (Sokolow and Saffar, 2001).

Figure 1.5 Gross anatomy of the scapholunate interosseous ligament. (a) An intact ligament in the right wrist showing its volar (V), proximal (P) and dorsal (D) regions; (b) ligament from the left wrist with a partial rupture (arrow). L, lunate; S, scaphoid. The volar side of the carpal bones face upwards in both specimens. Reproduced with permission John Wiley and Sons (Milz et al., 2006)

The lunotriquetral (LT) ligament has the opposite configuration, with a thicker palmar region and a weaker dorsal fibrocartilaginous structure. In normal wrists, the lunate appears to be balanced between the torque from
the scaphoid exerting a flexion moment through the scapholunate ligament and an extension moment through the LT ligament.

1.1.3 **Kinematics of carpal bones:**

The main flexors of the wrist are the flexor carpi ulnaris (FCU) inserted on the hamate and little finger metacarpal through the pisiform bone, and the flexor carpi radialis (FCR), which is inserted into the base of the second metacarpal with slips into the third metacarpal and trapezoidal tuberosity. The extensor tendons comprise the extensor carpi ulnaris (ECU), which inserts into the base of the fifth metacarpal, extensor carpi radialis brevis (ECRB) and extensor carpi radialis longus (ECRL), which insert into the dorsal surface of the base of the second metacarpal bone.

The proximal carpal row acts as an intercalated segment, as there are no tendons inserted on the proximal row of carpal bones. Its movement is driven by the distal row and limited by the interosseus ligaments. In radial deviation, the proximal carpus flexes with flexion of both scaphoid and lunate, while the triquetrum moves proximally in relation to the hamate. In ulnar deviation, however, the proximal carpal row dorsiflexes with the scaphoid and lunate, while the triquetrum moves distally in a helical fashion.
In radial deviation, the scaphoid (S) rotates toward the palm and appears foreshortened. The distal scaphoid is projected end-on and appears as a circular density (asterisk). In ulnar deviation, the scaphoid rotates (its distal pole moving dorsally and toward the ulna) and appears to elongate (arrows). Reproduced with permission Elsevier (Loredo et al., 2005).

Two theories have been proposed for carpal kinematics, as follows (Craigen and Stanley, 1995):

1. Row theory: Here the proximal row moves over the distal row and flexion extension of wrist is believed to occur mainly at the mid-carpal joint; and any radioulnar deviation of the wrist is believed to occur at the radiocarpal joint with translation of the scaphoid along the radial slope (Navarro, 1921).

2. Column theory: True columns of carpal bones are believed to exist with the central column consisting of the lunate, capitate and hamate. Flexion-extension movement occurs mainly at this column. Lateral column bones consist of the scaphoid, trapezoid and trapezium, while the medial column
comprises of the triquetrum and pisiform. Taleisnik (Taleisnik, 1976) represented the distal row and lunate as the central column, with the scaphoid as the lateral column and the triquetrum as the medial column. He believed that the flexion extension occurs mainly at the central column while, in radial deviation, the scaphoid flexes and in ulnar deviation the triquetrum extends (Figure 1.6).

Other authors believe that there exists a spectrum of models based on the row theory or the column theory, when the wrist is moved in a radio-ulnar deviation. However, some patients show greater flexion and extension of the scaphoid with radioulnar deviation, especially in women (Craigen and Stanley, 1995), while others exhibit more translation of the scaphoid on radioulnar deviation. This spectrum of movement patterns has been confirmed by the use of three-dimensional CT imaging (Moojen et al., 2003) and in vivo MRI scanning techniques (Moritomo et al., 2006). Some authors believe that, during radial deviation of the wrist, the joints that are more lax show movement of the scaphoid along the sagittal plane of flexion and extension with little lateral derivation (Garcia-Elias et al., 1995)

1.1.4 Radiological Anatomy of the Wrist

Postero-anterior view: This is taken with the arm at 90° abduction to the trunk, the elbow flexed 90° and forearm pronated. In pronation, the ulnar styloid is seen in profile and in supination; the styloid appears in the middle of the ulna. Gilula's lines (Figure 1.7) are intact when a normal relationship between bones is maintained (Mann 1997). Arc 1 is the proximal surface of the scaphoid, lunate and triquetrum. Arc 2 is the distal surfaces of the same bones. Arc 3 is the proximal surfaces of the capitate and hamate. (Figure 1.7) When these arcs are disrupted, or there is overlapping between bones, then one should suspect subluxation or dislocation of the carpal bones, if associated with trauma. There are two situations that are normal variants, but have the appearance of a break in the three arcs. Firstly, when the
proximal to distal length of the triquetrum is shorter compared to the lunate, giving the appearance of a break in the first arc. Secondly, in type II lunate, which has separate facets for the capitate and hamate, the second and the third arcs may appear disrupted.

![Figure 1.7 Radiograph of left wrist with scapholunate dissociation showing Gilula’s lines. Line 1 traces the proximal aspect of the proximal row of carpal bones, Line 2 traces the distal aspect of the proximal row and Line 3 traces the proximal aspect of distal row of carpal bones. Normally the lines traced are smooth without any breaks or steps.](image)

Scapholunate Interval: The normal gap between the scaphoid and lunate bones remains constant in radial or ulnar deviation of the wrist and measures 2 mm. A gap greater than 5 mm on any view is abnormal, suggesting disruption of the scapholunate ligament. (Figure 1.8)
Ulnar variance: The difference in length between the distal ends of the radius and ulna, as projected on the radiographs, varies with pronation and supination of the forearm and also on loading of the hand and power grip (Jung et al., 2001). The standardised position to measure ulnar variance is from an antero-posterior (AP) view of the wrist, with the shoulder abducted 90 degrees, elbow at 90 degrees, and the forearm in neutral rotation. The hand is kept flat on the cassette, while the X-Ray beam is directed to the center of the carpus. For a lateral view, the patient is standing with the ulnar border of the forearm kept flat on the cassette. (Figure 1.9)
Ulnar variance tends to increase with pronation and grip. In neutral variance, 80% of the load is borne by the radius and 20% by the ulna (mean normal ulnar variance is 0.9mm) (Jung et al., 2001, Palmer et al., 1982). When the ulna is shorter (negative ulnar variance), the increased force between the radius and lunate could explain the increased association with Kienböck’s disease (Bonzar et al., 1998). (Figure 1.9) Positive ulnar variance may be associated with limited forearm rotations, while ulna abutment syndrome is associated with TFCC thinning or perforations.
Figure 1.10 Radiograph of right wrist showing negative ulnar variance associated with Kienbock’s disease.

Carpal height: The length of the carpus as measured from the base of the third metacarpal to the distal articular surface of the wrist. The carpal height ratio is the carpal height divided by the length of the third metacarpal. The carpal height index is the ratio of the carpal height ratio on the diseased side and the normal side (Mann 1997).

Lateral view of the wrist: In a lateral projection, the long axis of the radius is parallel to the long axis of the third metacarpal, while the pisiform overlies the distal pole of the scaphoid. (Figure 1.10) The long axis of the capitate is at the center of the head to the center of the distal articular surface. The long axis of the lunate is along a line joining the center of the proximal and distal articular surfaces, and the long axis of the scaphoid is a line joining the proximal and distal convex margins:
1) Long axis of radius, lunate, capitate and third metacarpal (Figure 1.10) are parallel in a neutral position, or within 10° of the capitate and lunate axis.

![Figure 1.11 Lateral radiograph of the Wrist. Long axis of radius is parallel to long axis of third metacarpal. Normal Scapholunate angle measures 30-60 degrees.]

2) Scapholunate axis is normally 30° to 60°. Dorsal Intercalated segment Instability (DISI) deformity (Figure 1.11) is when the scapholunate angle is more than 60°. Volar intercalated segment instability (VISI) is when the scapholunate angle is less than 30°. Gilula and Weeks (Gilula and Weeks, 1978) suggested that, on lateral projection, a line connecting the proximal and distal convexities of the scaphoid is the long axis of scaphoid.
Figure 1.12 Lateral radiograph of radius. Left: LU indicates line along axis of lunate drawn as a perpendicular (PA) to line connecting the palmar and dorsal tip of distal end of lunate. RA is the long axis of radius. CA is long axis of capitate and TM is the axis of the 3rd metacarpal. Figure shows a DISI deformity with dorsiflexion of lunate and an increase in the scapholunate angle (SL) of more than 60°. Right: Ring sign: Overlap of proximal and distal poles of the scaphoid due to foreshortening of Scaphoid with flexion.

Distal Radius Measurements

1) Radial length: Distance between the perpendicular line at radial styloid and ulnar articular surface (Normal 11-22mm). (Figure 1.9) 
2) Radial inclination (RI): Angle between perpendicular (P) to long axis of the radius and the tangential line (T) to most distal points of the articular surface of radius (Norm ally 11°- 22°). (Figure 1.12 A) 
3) Volar tilt (VT): Angle between the intersection of the line perpendicular to the long axis of the radius (R), and the line joining the most distal points on the articular surface of the radius on lateral projection (Normal 11°). (Figure 1.12 B)
Figure 1.13 Normal lateral views illustrating measurements.
A: Radial inclination (RI) is the angle between perpendicular (P) to long axis of the radius and the tangential line (T) to most distal points of the articular surface of radius. B: Volar tilt (VT) is the angle between the intersection of the long axis of the radius (R), and the line perpendicular to line joining the most distal points on the articular surface of the radius on lateral projection.

Radial and Ulnar Deviation views: Radial deviation causes the scaphoid to flex, while the overlying distal and distal poles give the appearance of a ring. Ulnar deviation makes it appear elongated; however, the distance between the scaphoid and lunate remains within 2 to 4 mm. Overlap of proximal and distal poles of the scaphoid due to foreshortening of Scaphoid with flexion gives the appearance of “Ring Sign” (Figure 1.11). Scapholunate Instability: This indicates incompetence of the volar radiocarpal ligaments and the scapholunate ligaments. It leads to rotatory subluxation of the Scaphoid:
1) Terry Thomas sign: scapholunate interval > 5mm (Figure 1.8).
2) DISI deformity: Dorsal tilting of lunate with an associated increase in the scapholunate angle of more than 60°. (Figure 1.11 A).
3) Ring sign: Overlap of proximal and distal poles of the scaphoid due to foreshortening of Scaphoid with flexion. (Figure 1.11 B)
Medical Resonance (MR) Imaging: The use of MR arthrography helps identify any early tears before the gap appears between the lunate and scaphoid. (Figure 1.13) It appears as an increased signal between the bones, a hyper-intense fluid-filled signal, or has the appearance of dye communicating between the radiocarpal and the mid-carpal joints. It can also visualise the volar radiocarpal ligaments and the disruption of the dorsal end of the scapho lunate ligament. CT arthrography can also be used to identify the Scapholunate ligament tears.

Figure 1.14 Figure showing MR arthrogram of the Wrist.
1.2 Functional wrist motion

In order to enable hands to perform specific tasks of daily living, high mobility of the wrist is desirable. At the same time, the wrist allows large force production at the fingers to be transferred more proximally without damaging the involved structures. Three types of movements of the wrist can be differentiated: flexion-extension, radial-ulnar deviation, and supination-pronation. Flexion and extension occurs at the radiocarpal joint and the midcarpal joint. During radial deviation, the proximal row of the carpal bones flexes and, during ulnar deviation, it extends. For the wrist to pronate and supinate, the radius needs to rotate around the ulna. There is no direct tendinous attachment to the proximal carpal row, except for the pisiform bone. The proximal carpal row moves in a rotational motion as a result of muscle contractions that move the distal carpal row. The distal carpal row can be considered as one functional unit because it is quite rigid. The bones of the proximal carpal row move in coordination in different directions.

During an assessment of the range of motion of the wrist, the measurements are taken in the sagittal and coronal planes. The range of flexion extension, radial and ulnar deviation allows a comparison between individuals. However, most of the activities of daily living are rarely performed in these isolated planes of motion. The wrist uses a unique oblique motion plane for most activities of daily living, from a radio-dorsal to ulno-palmar direction that is often referred to as the Dart-throwing plane (Moritomo et al., 2004, Wolfe et al., 2006) (Figure 1.14). This unique plane of motion depends on the mid-carpal joint (joint between proximal and distal row of carpal bones, intercarpal joint) and, specifically the scapho-trapezio-trapezoidal (STT) joint. An obliquely oriented ridge present on the distal articular surface of the scaphoid allows movement of the STT joint in a semi-constrained fashion.
Figure 1.15 Radioscaphocapitate articulation displayed in cadaver wrist. The distal scaphoid surface contains an obliquely oriented ridge (arrows), the orientation of which guides scaphotrapeziotrapezoidal motion in a semiconstrained fashion. The dart-throwing motion (DTM) plane (Black dashed line) can be defined as a plane in which wrist functional oblique motion occurs, specifically from radial extension (radial deviation-extension) to ulnar flexion (ulnar deviation-flexion); C, Capitate; S, Scaphoid; Td, Trapezoid; Tm, Trapezium. Green dashed line is in the plane of radial-ulnar deviation and it is at 45° to the DTM plane) Reprinted with permission Elsevier (Moritomo, 2010)

The two major ligaments that act as collateral ligaments for this mono-articulation are:

1) Scapho-capitate ligament, which inserts on the medial side of the scaphoid tuberosity,

2) STT ligament, which inserts on the antero-lateral side of the tuberosity.

If a line connected the two insertion sites, it would lie perpendicular to the ridge on the distal end of the scaphoid (Figure 1.14). The Dart throwing motion (DTM) occurs at STT, mid-carpal and the triquetro-hamate joint and occurs in a radio-dorsal and ulno-palmar direction. The axis of this joint runs from the radio-palmar aspect of the scaphoid tuberosity to the ulno-dorsal aspect of the hamate. During the DTM, there is relatively little movement of the scaphoid and lunate (Werner et al., 2010, Crisco et al., 2005, Upal, 2003). In addition, it was quantified in a study on cadavers that the scapholunate interosseous ligaments (SLIL) have minimal elongation
duration DTM. The dorsal insertion of the SLIL is elongated minimally, when DTM occurs in a plane with minimal lunate motion. The palmar insertion of SLIL is elongated minimally, when DTM occurs in a plane with minimum scaphoid motion. During DTM at 45° to the sagittal plane of the wrist, the motion of the scaphoid approaches zero. During DTM at 30° to the sagittal plane of the wrist, the motion of lunate approaches zero (Crisco et al., 2005). The DTM was quantified first by (Palmer et al., 1985) by using a triaxial electrogoniometer. They felt that most of the activities of daily living, such as hammering, combing hair, or opening cans, were performed in a dart-throwing plane from a radio-dorsal to ulno-palmar direction. The three main muscles that drive the DTM are flexor carpi ulnaris, extensor carpi radialis longus and extensor carpi radialis brevis.

DTM is the plane of motion from the radio-dorsal to ulno-palmar plane when there is minimal scaphoid and lunate motion (Werner et al., 2010) when compared to flexion-extension and radio-ulnar deviation (Moritomo et al., 2007). Peak and mean forces through the flexor carpi ulnaris (FCU) is greater during the DTM than during flexion extension and radio-ulnar deviation, which is suggestive that FCU could be firing during the DTM.

Carpal Instability

Carpal stability (dynamic and static) is achieved by multiple factors, such as normal bone geometry, or adequate tensioning of ligaments under load and proper contraction of specific stabilising muscles. The proximal row has a tendency to undergo mechanical collapse when there is an interruption within the ligamentous or bony segments. There is much debate about the definition of instability. It was initially considered as a malalignment, where the carpal bones move out of normal alignment on AP and lateral views. There are four different types of carpal instability:

1) Dorsal intercalated segment instability (DISI).
2) Volar intercalated segment instability (VISI).
3) Ulnar translocation: the proximal row is translocated ulnarwards relative to the radius.

4) Dorsal translocation: the carpus is subluxed dorsally due to a malunited distal radial fracture.

Malalignment can be seen in patients with hyperlaxity without any symptoms or requiring any treatment. Hence, instability was redefined as an inability to bear physiological loads with associated malalignment (García-Elias, 1997). This definition does not cover dynamic instability when malalignment is seen in only certain situations, or during certain tasks. Static instability is when carpal bones remain malaligned, despite absence of load applied on the wrist. When referring to kinetic and kinematic dysfunction, carpal dysfunction is now defined as a loss of normal kinetics (ability to transfer physiological loads) and normal kinematics (capacity to move through a normal range of wrist motion) without any alteration in intercarpal alignment (Larsen et al., 1995).

The various patterns of carpal instability (Larsen et al., 1995) are:

1. Carpal instability dissociative (CID) occurs when there is disruption of the ligaments between the two carpal bones in the same row (proximal or distal). CID Proximal occurs between the scapholunate and lunotriquetral. CID Distal occurs between the capitate and hamate.

2. Carpal instability non-dissociative (CIND) occurs between the two rows, radiocarpal or midcarpal, and is usually due to damage to the extrinsic ligaments. These are usually associated with ulnar translocation of the proximal row or midcarpal instability.

3. Carpal instability complex (CIC) is a combination of CID and CIND and is usually due to perilunate dislocation. (Figure 1.15)

4. Carpal instability adaptive (CIA) is carpal malalignment and is usually due to causes outside of the carpus, e.g. malunited distal radius fracture.
### Table 1. Analysis of Carpal Instability

<table>
<thead>
<tr>
<th>Category I Chronicity</th>
<th>Category II Constancy*</th>
<th>Category III Etiology</th>
<th>Category IV Location</th>
<th>Category V Direction</th>
<th>Category VI Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute &lt;1 week (ie, maximum primary healing potential)</td>
<td>Static†</td>
<td>Congenital</td>
<td>Radiocarpal</td>
<td>VISI</td>
<td>Carpal instability dissociative (CID)</td>
</tr>
<tr>
<td>Subacute 1–6 weeks (ie, some primary healing potential)</td>
<td>Dynamic‡</td>
<td>Traumatic</td>
<td>Intercarpal</td>
<td>DISI</td>
<td>Carpal instability nondissociative (CIND)</td>
</tr>
<tr>
<td>Chronic &gt;6 weeks (ie, little primary healing potential; surgical repair or reconstruction needed)</td>
<td>Inflammatory</td>
<td>Midcarpal</td>
<td>Ulnar</td>
<td>Combinations (CIC)§</td>
<td></td>
</tr>
<tr>
<td>Arthritis</td>
<td>Carpometacarpal</td>
<td>Radial</td>
<td>Carpal instability adaptive (CIA)ǁ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neoplastic</td>
<td>Specific bone(s)</td>
<td>Ventral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iatrogenic</td>
<td>Specific ligament(s)</td>
<td>Dorsal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscellaneous</td>
<td></td>
<td>Proximal</td>
<td></td>
<td></td>
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<tr>
<td>Combinations</td>
<td></td>
<td>Distal</td>
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<td></td>
<td></td>
<td>Rotary</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Combinations</td>
<td></td>
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</tr>
</tbody>
</table>

* This category also includes the concept of severity.
† Irreducible or reducible; ease of reducibility and degree of displacement may also be considered.
‡ Degree of load required to cause displacement may also be considered.
§ CIC. Combination of CID and CIND. Example: perilunate and axial injuries include both capsular (CIND) and intercarpal (CID) components.
ǁ CIA, apparent carpal instability; a carpal instability pattern that exists because the carpal bones have adapted to an extended deformity (eg, a distal radius malunion).
VISI, volar flexion intercalated segment instability (palmar flexion instability); DISI, dorsiflexion intercalated segment instability.

Figure 1.16 Analysis of Carpal instability.
Reproduced with permission from Elsevier (Larsen et al., 1995)
1.3 Wrist osteoarthritis

The types of wrist osteoarthritis can be classified according to the cause of the disease:

1. Idiopathic
2. Traumatic.

Idiopathic causes of wrist osteoarthritis are untreated cases of Kienböck’s disease (avascular necrosis of lunate) or Preiser’s disease (avascular necrosis of the scaphoid). Osteoarthritis of the carpometacarpal joint of the thumb and the scapho trapezium-trapezoid joint is usually idiopathic in origin. The distal radioulnar and ulnocarpal joint and some congenital abnormalities like Madelung’s deformity can also lead to osteoarthritis. Idiopathic causes do not form part of this study.

Traumatic causes of wrist osteoarthritis form the main focus of this study. These are (1) Scapholunate ligament injuries leading to progressive wrist osteoarthritis (Scapho-Lunate Advanced Collapse, SLAC wrist) and (2) Scaphoid fracture with subsequent nonunion leading to progressive arthrosis (Scaphoid Nonunion Advanced Collapse, SNAC wrist).

Scapho-Lunate Advanced Collapse (SLAC): This was originally described in 1984 (Watson and Ballet, 1984). They described the various stages of progression of wrist osteoarthritis associated with the disruption of scapholunate ligament. The fossa on the radius for scaphoid is elliptical in shape, while the lunate fossa is spherical (Figure 1-2). In a normal wrist, the proximal articular surface of the scaphoid is believed to be like two nested boat hulls sitting congruently with normal compressive loads. In the event of a ligament disruption or fracture, rotary subluxation of the scaphoid causes the incongruity of the boat hulls, which loads the edges of the joint. This leads to osteoarthritis of the radial styloid (Stage I) (Figure 1.16A). As the cartilage shear progresses, the osteoarthritis involves the whole of the radial fossa (Stage II) (Figure 1.16B).
Figure 1.17 Radiographs with changes associated with SLAC wrist.  
(A) Radiograph showing Stage 1 SLAC with osteoarthritis of radial styloid;  
(B) Radiograph showing Stage 2 SLAC with radioscaphoid arthritis.

The eventual separation of the scaphoid and lunate causes the capitate to load against the radial edge of the lunate. The migration of the lunate to the ulnar side point loads the head of the capitate, which shears the cartilage leading to eventual lunocapitate arthritis (Stage III). The spherical shape of the lunate fossa of the radius preserves the cartilage in the radiolunate joint until the very late stages of advanced whole joint osteoarthritis (Stage 1V). This pattern is consistently followed in all cases of SLAC wrist. (Figure 1.17) Even if the lunate displaces into a DISI or a VISI deformity, the perpendicular loading of the radiolunate joint preserves the cartilage in this joint.
Figure 1.18 Stages of SLAC wrist. (A) Radiograph of left wrist showing Stage 3 SLAC wrist with cartilage still appears preserved between lunate fossa of radius and lunate; (B) Radiograph showing Stage 4 disease with cartilage between radius and lunate appears degenerate.

In a Scaphoid Nonunion Advanced Collapse (SNAC) wrist, a similar pattern is observed (Vender et al., 1987). Krakauer described the scaphoid nonunion advanced collapse of the wrist and coined the term SNAC wrist (Krakauer et al., 1994). The natural history is based on the site of fracture. Proximal fracture nonunion rarely develops a DISI deformity unless the proximal fragment resorbs. The onset of symptoms is later if the fracture is in the distal third or in the proximal third. The pattern of osteoarthritis is the same as that for the SLAC wrist. The spherical radiolunate joint is spared in both SLAC and SNAC wrist until later stages of the disease (Stage IV). Vender et al. noted that scaphoid nonunion led to a similar sequence of degenerative changes except for the spherical proximal scaphoid fragment which, when tethered to the lunate, was spared from the arthritic changes (Vender et al., 1987).

In advanced cases of scaphoid nonunion, degenerative changes appear between the radial fossa and the distal scaphoid segment. The proximal portion of the scaphoid remains attached to the lunate with the
The degeneration progresses to the capitolunate joint, while sparing the radiolunate joint (Stage III). This common pattern of degeneration makes the treatment of both these diseases consistent despite differing causes of the disease. (Figure 1.18)

Figure 1.19 Stages of SNAC wrist.
The AP and lateral radiographs of left wrist show stage 3 SNAC wrist deformities, with flexion of scaphoid and associated degenerative changes over the head of the capitate.

The SNAC wrist is due to an unhealed scaphoid fracture leading to subsequent degeneration, whereas the etiology of a SLAC wrist is debatable. In rare cases, the cause may not be traumatic and the deposition of calcium pyrophosphate crystals in the scapholunate ligament could lead to disruption. The SLAC wrist disease may be detected in the contralateral asymptomatic wrist, hence the recommendation to request radiographs of both wrists during clinical review. Watson and Ballet also described osteoarthritis of the triscaphae joint (scaphoid, trapezoid and trapezium), which can be found in 27% of the population (Watson and
Nevertheless, this subtype of arthritis is not part of the present study.

There are other, less common, causes of wrist osteoarthritis. Wrist osteoarthritis is also believed to eventually occur after a proximal row carpectomy due to the abnormal shapes of the lunate fossa and the head of the capitate. The sharper radius of the curvature of the capitate compared to the curvature of the lunate leads to abnormal loads that, over 10 years, will culminate into degeneration between the radius and the articulating head of the capitate in proximal row carpectomy (DiDonna et al., 2004). Wrist osteoarthritis will eventually also develop due to a malunited fracture of the distal radius. The extra-articular fracture with malunion could alter the biomechanics of the wrist joint leading to abnormal joint loading. This could result in radiological osteoarthritis, but symptoms may be unpredictable (Forward et al., 2008). The intraarticular distal radius fracture can also lead to degenerative changes due to step or malunion of the fragments. However, poor fixation can make it even more significant (Jupiter et al., 2009).

1.4 Rheumatoid arthritis

My journey on this project started when I agreed to participate in an ongoing study in Department of Orthopaedics at University Hospitals of Leicester looking at the techniques of assessing grip strength in patients with rheumatoid arthritis. The forces generated in these situations are small and measuring grip strength in the presence of deformities and marked weakness poses a challenge using the conventional Jamar dynamometer. The differences in grip strength between hands with rheumatoid deformities could be studied more easily by measuring the sustainability of grip and use of force time curves could show differences more easily as presence of deformity in rheumatoid hand has a significant effect on grip. This experience using the force time curves in assessing grip strength in patients with rheumatoid arthritis helped me develop this technique to study grip
strength in patients with wrist osteoarthritis. Although the main wrist disease I have studied in this PhD is osteoarthritis, in this section, I describe how rheumatoid arthritis affects the wrist and my role in the project on assessment of grip strength using force time curves in rheumatoid hand. (Dias et al., 2012)

Rheumatoid Arthritis (RA) is a polyarticular inflammatory disease that causes swelling, stiffness, joint destruction and deformity. This autoimmune disease has an effect on the cells that coat and lubricate joints (synovial tissue). Although osteoarthritis may affect a joint on one side of the body, such as hand arthritis or finger arthritis, rheumatoid arthritis usually happens symmetrically. While RA can affect any joint, the small joints in the hands and feet tend to be involved most often. As the pathology progresses, the inflammatory activity leads to tendon tethering, erosion and destruction of the joint surfaces, which impairs range of movement and leads to deformity. The fingers may suffer from almost any deformity depending on which joints are most involved. Specific deformities include ulnar deviation, boutonniere deformity, swan neck deformity and Z-deformity of the thumb. (Figure 1.19)
Escalante et al. (Escalante et al., 2005) recognised two distinct impairments in rheumatoid arthritis, due to joint inflammation and joint deformity, which together contributed strongly to functional limitations caused by this disease. Eberhardt et al. (Eberhardt et al., 1991) in their study on the occurrence of hand deformities in early rheumatoid arthritis found that those hands with deformity had more active disease, less grip strength, more
disability, and markedly greater radiographic changes compared to patients without deformity. They grouped the patients with any deformity together to compare with those with no deformity.

Grip strength is used as a measure of the functional capacity of the Rheumatoid hand but the rate of development of maximum grip is considered a more sensitive indicator of hand dysfunction than maximum grip strength itself (Myers et al., 1980). Also the change in the rate of development of grip serves as a better discriminator in measuring response of patients to anti-inflammatory drug therapy. Power generated during grip provided more information about hand function than maximum grip strength alone (Palmer et al., 1981).

The strength-time curves have been used to study rheumatoid hands before (Helliwell et al., 1987). Maximum grip strength, time to maximum, rate of loss of grip from maximum (fatigue rate) and integral of the force-time curve (power factor) has been previously mathematically calculated to study the difference from normal hands. Smith et al. have analysed the force-time curves for peak force, average force and force variability to discriminate sincere efforts in volunteers from faked weakness in subjects who were asked to fake their weakness (1989). Rheumatoid hands are, however, remarkably weak hands and I felt that the study of force variability in the plateau region of the curve would be useful to develop more understanding in use of force-time curves to distinguish between weak deformed hands.

I was involved in the analysis of the project looking at the use of the force-time curves to assess peak force, average force, total grip time, area under the curve and the variability of the plateau region of the curves to understand the impact of different rheumatoid hand deformities on grip strength. The differences in grip strength between different rheumatoid deformities could be appreciated more easily by assessing sustainability of grip strength. A fluid-filled, non-elastic 6 cm diameter balloon was used to
collect grip strength data by connecting the balloon to a pressure transducer and a charting system, calibrating the readings into Newtons. (Figure 1.23) This technique allowed measurement of grip strength for all the deformities in the rheumatoid hand as the hand could still conform easily around the balloon. Over the required range, there was a linear relationship between an applied force and the recorded pressure, when the volume within the system was constant. The system was calibrated using a 500 g (4.9N) weight. The pressure exerted by the patient’s grip on the balloon was recorded over time on the chart as force-time curves. In this project, a previous researcher (Mr. Manoj Kumar) had already completed data collection.

He had used this system of assessment in 43 patients with established rheumatoid arthritis (disease duration > 3 years) affecting the hand with their consent. No patient had had surgery. Standard technique of assessed was followed in each test with the subject sitting in front of the dynamometer with both arms on the table. Each arm was tested one at a time, while the other arm rested on the table. Patients were asked to squeeze the balloon as hard as possible and for as long as possible up to a maximum of 60 seconds while data was captured onto the chart recorder. The assessments were stopped if patients had any pain. As the fluid volume within the system remained constant, the transducer measured the pressure generated within the system.

I converted the force-time curves obtained (Collins, 2007) into digital curves with Image/J software (National Institutes of Health, Maryland, USA). I transferred the XY coordinates to a spreadsheet to generate digital curves and further analysed them mathematically to obtain several parameters for each force-time curve (Figure 3.20). Peak force was the maximum grip strength achieved on the force-time curve and the average force was calculated from readings in the middle half of the force-time curve, excluding the first and the last quartile, as this represented the force generation and relaxation segments.
Figure 1.21 Force Time curve showing the method of calculation of the various force attributes. Reproduced with permission from SAGE (Dias et al., 2012)

Total grip time was calculated from the x-axis of the force-time curve. The plateau region of the curve was defined as the part of the curve after the peak to the end of the recorded contraction period. Variability of force generated in the plateau region was studied by assessing the standard deviation (SD) of values recorded in this region. SD of the middle half of the plateau region was also calculated to avoid the variation of the beginning and end of the plateau. The “Trapezoid rule” (Atkinson, 1989) was used in
the spreadsheet to calculate the total area under the curve.

The study found that peak force alone might not give a complete assessment of the mechanical capacity of the diseased hand. The small area under the curves confirms the marked weakness caused by swan neck and combined deformities. The area under the curve best predicted disability assessed using the Patient Evaluation Measure (patient rated disability score). Overlaying the curves gives the best visual impression of the differences between the deformity groups. (Figure 1.21)

The hands with ulnar deviation deformity had the greatest area under the curve with a mean of 6214.4 (SE, 2878) Ns, whilst hands with combined deformities had a mean of only 949.4 (SE, 206) Ns. There was a significant difference between groups (p < 0.01) and also an ordered difference on moving from the hands with ulnar deviation deformity to those with combined deformity (p < 0.01).

I therefore felt this technique would be applicable in osteoarthritis and it is the basis of one of my assessments for this thesis.
Figure 1.22 Mean Force Time curves of different deformity groups demonstrating the differences. Reproduced with permission from SAGE (Dias et al., 2012)
1.5  Wrist Assessment

The influence of a disease or surgery on a patient can be estimated using outcome measures and comparing against baseline values. This can be performed before and after surgery comparing normal versus diseased wrist or comparing with normal population. This could help the clinician in making decisions about appropriate treatment and measure the progress of the patient towards normality. However, every condition and treatment of that condition has a unique influence on patient function. Hence, it is important to select suitable outcome measures that provide a complete overall picture of the effect of the disease, or the treatment on the patient.

Outcome instruments used in wrist disorders evaluate the physical function by measuring the range of motion, grip strength, pain and ability to perform daily activities. Nevertheless, few studies use all of these measures in combination to reflect the performance of the wrist or function at an individual level. Traditional outcome measures may fail to show a relationship with an ability to perform daily activities, such as a patient with wrist fusion who may employ compensatory mechanisms to complete the same tasks (Weiss et al., 1995). Newer outcome measures are required to assess a patient’s functional ability. Measuring the difficulty of task performance, or assessing a combination of modalities creates a comprehensive picture of the ability of the patient (Fricke, 1993).
1.5.1 *Clinical Assessment*

A detailed assessment of the wrist is required before deciding upon the appropriate treatment for the patient. Talwalkar et al. published guidelines for assessing a wrist with osteoarthritis (Talwalkar et al., 2008):

- A thorough history, including age, hand/arm/wrist trauma, hand dominance, occupation, sports and recreational functional needs;
- A differential diagnosis; symptomatic patients complain about pain during manual activity or sometimes at rest, usually localised on the radiodorsal side of the radiocarpal joint, stiffness of the wrist and decreased grip strength;
- A physical examination, including testing carpal laxity, locating the area that gives the most tenderness and crepitus to determine whether the arthrosis is in the radiocarpal joint, ulnocarpal articulation or distal radioulnar joint (DRUJ);
- A radiological assessment (postero-anterior, lateral and a clenched-fist view), to evaluate the midcarpal joint, radioscapoid joint, scaphoid non-union (resulting in a SNAC wrist), scapholunate dissociation (resulting in a SLAC wrist), and also to rule out ulnar-sided causes of wrist pain. The radiological assessment is usually sufficient to make the diagnosis and to classify the stage of degeneration of the wrist.

Nagle also recommends a wrist arthroscopy to evaluate the articular surface as midcarpal osteoarthritis is sometimes missed by radiological assessment (Nagle and Benson, 1992). The surgeon must always consider whether a planned surgery would cure the specific complaints of the patient. Osteoarthritis of the carpometacarpal joint of the thumb must always be kept in mind in the differential diagnosis, as it is very common.
1.5.2 Grip strength assessment

Grip strength is achieved by the combined effort of the extrinsic and intrinsic muscles of the hand. Extrinsic muscles originate outside the hand and are inserted in the carpal bones or phalanges, while intrinsics are responsible for finer movements and are attached within the hand and wrist only. Both finger and thumb contribute towards power grip; the palm and the fingers mould around the object being held and the thumb adducts to hold it in space, while the object can be positioned in space and moved freely by the proximal joints (Garcia-Elias, 2011). There are three varieties of power grip which comprise the cylindrical grip, spherical grip and the hook grip (Hertling, 1996), depending on the shape of the object being held. The hook grip does not involve the thumb, while the spherical and cylindrical grip vary in the amount of separation between the fingers. Norkin reported that the more separation there is between the fingers (as in a spherical grip), the greater is the intrinsic strength required (Norkin and Levangie, 1992).

An evaluation of grip strength is critical when measuring the effect of disease on upper extremity function, to monitor treatment and in the prognosis of clinical and functional recovery (Norkin and Levangie, 1992). The four types of instruments available to measure grip strength are:

1) Hydraulic systems that use viscous fluids in a sealed system. A Jamar dynamometer is a typical example that is commonly used in clinical practice, as there is good reliability and validity (Mathiowetz et al., 1984). It is also recommended by the American Society of Hand Therapists as a standard technique to measure grip strength (Fess E, 1981). (Figure 1.22)
2) *Pneumatic instruments* that use the compression of an air or fluid filled balloon and measure pressure in millimetres of mercury or pounds per square inch. However, they are useful when measuring the grasp in painful hands as a result of rheumatoid arthritis, for example. This technique was used in our study of the use of force-time curves (Section 1.4) in rheumatoid deformities. (Figure 1.23)
Figure 1.24 Photograph showing a fluid-filled compression system. This technique was used for patients with rheumatoid arthritis, as the Jamar is difficult to hold with deformed hands.

3) *Mechanical instruments* are less commonly used due to difficulties in standardisation and reliability of repeated use as they measure the amount of tension placed on a steel spring (Bohannon and Andrews, 1989).

4) *Strain gauges* measure the strain placed on an object with the grasp strength and any deformation of a metallic foil pattern placed in an insulated flexible backing. It causes the electrical resistance to change, which is measured using a wheatstone bridge (adding in a gauge factor) (Helliwell et al., 1987). This technique is used in the MIE digital pinch/grip analyser that was used in this study. This technique is very reliable and a valid way of keeping digital records of resistive/sustainability testing (Massy-Westropp et al., 2004). (Figure 1.24)
Figure 1.25 Photograph showing MIE pinch/grip dynamometer with Digital analyser

Standard position for Grip Strength assessment:

The Jamar dynamometer can measure the static grip strength in five positions with the handles apart by 3.5, 4.8, 6.1, 7.4, 8.7 centimetres. Both for men and women, maximum grip strength usually occurs with handles in the second position (Beaton et al., 1995). It is recommended that an average of three trials is taken, but it is difficult in endurance testing when the measurement is done over one minute. The standard position recommended by the American Society of Hand Therapists for assessment of grip strength is shoulder adducted, elbow at 90°, forearm in neutral rotation, wrist at 0-30° of extension, and slight ulnar deviation (Fess E, 1981). The volunteer is advised to keep both feet flat on the floor, while the examiner should not support the patient. This position is recommended in order to improve reliability and consistency and to allow a comparison.
between studies (Spijkerman et al., 1991) and this position was used in my study.

The various factors that could affect grip strength are body size, age, fatigue, time of day and disability due to inflammatory arthropathy (Roberts et al., 2011) and motivation. No consistent association has been found between the time of the day for assessment and grip strength. Many authors believe a subject's occupation could affect the strength testing, but findings are inconsistent (Nevill and Holder, 2000). The dominant hand is stronger than the non-dominant by 10%, but this may not hold true for left-handed subjects (Petersen et al., 1989). Authors suggest using the same tone of voice and volume for instructions while measuring grip strength in each patient, as an increase in voice volume can influence isometric strength contracture (Innes, 1999). It is also believed that biofeedback regarding the effort in grip strength can influence the result in volunteers and they should not be allowed to see the measurements until after the effort (Weinstock-Zlotnick et al., 2011). The grip strength declines with age, with a significant reduction in maximal force, rate of force production and total force generated, which is reduced when comparing 20-year-old and 75-year-old men (Bemben et al., 1991).

Grip strength is traditionally measured as the maximum force that can be generated by the hand. In rheumatoid disease, the dysfunction of muscles, tendons, nerves and the skeleton of the hand and wrist, as well as local or proximal pain, influence grip strength. Despite the development of indices designed to assess the function of the hand affected by rheumatoid disease, grip strength assessment remains the cornerstone of most longitudinal studies (Duym and Pfurtscheller, 1984). This is used to assess the degree of impairment of the hand in rheumatoid arthritis. Measuring only the peak force misses other attributes of strength of the hand, as it does not assess the speed of generation of strength, the sustainability or change of grip strength over time.
Force-time curves have been used to measure strength and to assess the sincerity of effort (Smith et al., 1989), in order to discriminate between sincere effort and faked weakness. I, initially, used force-time curves in patients with rheumatoid deformities of the hand. I then extended the technique to normal volunteers and patients with wrist osteoarthritis before surgery and after four-corner fusion, three-corner fusion, proximal row carpectomy and wrist arthrodesis.

1.5.3 Range of motion assessment

The measurement of range of motion of the wrist in a patient with osteoarthritis is another useful assessment. It provides an important index of joint function; however, in clinical practice it is measured as a static ability to move the wrist into extremes of wrist flexion, extension and radial-ulnar deviation. (Souer et al., 2008) Methods used to assess the range are visual estimation, a hand-held universal goniometer, an inclinometer or a tape measure to make these assessments. However, these tools have drawbacks in measuring range of motion.

Standard uniplanar goniometry of the wrist is widely used to measure wrist motion in only a single plane and statically during either active or passive motion. Nevertheless, it is difficult to ascertain if these two-dimensional assessments of movement correlate with the function of the musculoskeletal system. Dynamic movement, including combinations of movements used in everyday activities and the velocity of movement, is not captured and so a complete picture of the movement is not obtained. This may be particularly important in the movement of a complex joint, like the wrist joint, where movement is three-dimensional. Two planar motions could be measured simultaneously in a dynamic state to get a true picture of the dynamic ability of the wrist.
In the case of the human wrist, circumduction consists of a circular motion combining flexion, extension, and radioulnar deviation without simultaneous supination or pronation of the forearm. Currently, the most widely used assessment tools for measuring circumduction include biaxial electrogoniometers, which have demonstrated validity, reliability, and clinical utility for the measurement of the range of flexion-extension or circumduction. However, these have not been used for the assessment of speed or the rhythm of movement. It has also been recognised that it is not only total circumductive motion, but also the specific sector or region of motion limitation that influences an individual’s functional outcome.

Measurement of the extremes of flexion-extension and radio-ulnar deviation of the wrist joint provides a limited picture of the static ability of the joint to move in the measured planes. It is also difficult to ascertain the relationship between the function of a complex joint like the wrist and these two-dimensional measurements (Tomaino et al., 1994). In the human wrist, circumduction provides a more accurate representation of the capacity of the wrist function (Ojima et al., 1992, Rawes et al., 1996) as it combines flexion, extension, and radio-ulnar deviation into a single measure. This coupling of motion is used in activities of daily living and involves a physiological oblique plane of wrist motion (Taleisnik, 1985, Wolfe et al., 2006, Moritomo et al., 2007, Palmer et al., 1985) rather than in the flexion-extension or radio-ulnar deviation axis. However, previous literature on the assessment of motion in this plane is limited to complex radiographic measurements (Moritomo et al., 2006) or a study in cadavers (Werner et al., 2004). Moritomo investigated in vivo kinematics of the midcarpal joint with the use of a noninvasive bone registration technique. They suggested that a DTM may be the most stable and controlled wrist motion and that this could be explained by the anatomy and kinematics of the STT joint. Werner et al. measured in vitro scaphoid and lunate motion during 9 variations of wrist motion. The motions ranged from a pure flexion-extension motion to 7
DTMs in which the wrist moved from radial extension to ulnar flexion and finally to a pure radioulnar deviation motion.

The commonly used assessment technique for measuring circumduction includes biaxial electrogoniometers, which are valid and reliable in measuring the range of circumduction (Ojima et al., 1992). However, these have not been used to assess the velocity or the smoothness of wrist circumduction (Rawes et al., 1996). Previous studies indicate that wrist disease or pain may affect a specific quadrant of wrist circumduction (Ojima et al., 1991, Nagy and Buchler, 1997), and ageing mainly affects the radio-dorsal quadrant of wrist circumduction (Ojima et al., 1992). However, these studies have not measured the differences in motion in each of the quadrants of circumduction in normal volunteers, so a comparison is not possible with disease conditions. These differences could be in the velocity or smoothness of movement (Ojima et al., 1992) in the quadrants of wrist circumduction.

1.5.4 Assessment of Function

An assessment of hand function is important when evaluating the effect of treatment and to monitor improvement after surgery. The Sollerman hand function test is a standardised test to assess the overall hand function (Sollerman and Ejeskar, 1995, Weng et al., 2010, van Tuijl et al., 2002). It has been validated and has been found to be reproducible (Sollerman and Ejeskar, 1995, Brogardh et al., 2007). However, its development was based on experience with tetraplegic patients, while its validity and reliability were established by correlating it with the disability rating scale and the international classification for surgery of the hand in tetraplegia (McDowell et al., 1979).
The test measures the ability of the volunteers to do 20 day-to-day tasks to assess overall hand function. The tasks were timed during the original Sollerman test, but the score was summarised on a 5-point scale from 0 (task cannot be performed at all) to 4 (task is completed without any difficulty, within the time frame of 20 seconds and with the prescribed handgrip of normal quality). The final Sollerman score was calculated by adding up the scores from the different tests and ranged from 0 to 80, with the higher score reflecting a better performance. However, this test has been found to be better at picking up differences between severely affected hands rather than those with less severe disorders (Lindqvist et al., 2011). The Sollerman test showed a ceiling effect (Cramer, 2005) with bunching of scores at the upper level. The original authors (Sollerman and Ejeskar, 1995) also felt that the Sollerman test might not be able to capture smaller differences between patients.

In hand surgery, the evaluation of hand function is an important aspect when assessing the ability to perform activities of daily living (ADL) (Sollerman and Ejeskar, 1995, Jonsson and Larsson, 1990). Previous studies compared the functional outcome of the PRC and four-corner fusion (4CF) by assessing the range of motion of the wrist. Other studies have compared the two procedures by using questionnaires, such as the “Disabilities of the Arm Shoulder and Hand” questionnaire (DASH), the “Short Form Health Survey” (SF-36), the “Patient Rated Wrist Evaluation” (PRWE) and the “Visual Analogue Scale” (VAS) pain score (Mulford et al., 2009, Bisneto et al., 2011, Dacho et al., 2008, Baumeister et al., 2005, Richou et al., 2010, Bain and Watts, 2010). To our knowledge, until now the ability to perform tasks of daily living in these two groups has never been assessed with an objective ADL-test.

The Sollerman hand function test also examines the ability to perform different grips used during daily living activities. (Figure 1.26) The 20 tasks are based on seven of the eight most common handgrips (Sollerman and Ejeskar, 1995). This test has been used to evaluate the hand function of
several hand conditions, such as Dupuytren’s contracture, Rheumatoid arthritis, and injuries from powered wood splitters (Sollerman and Ejeskar, 1995, Blomgren et al., 1988, Draviaraj and Chakrabarti, 2004, Brogardh et al., 2007, Lindqvist et al., 2011). However, it has never used to compare functional outcome in wrist osteoarthitis patients after surgery.

Figure 1.26 Tasks included in the Sollerman Hand Function test. (Sollerman and Ejeskar, 1995)

Although the functional outcome for PRC and 4CF patients have been compared in the literature, the focus was never on ADL and the related wrist movement. Knowledge about the effects on ADL after these two types of surgery may lead to a better informed decision making between both salvage procedures.

1.5.5 *Patient Reported Outcome*

Objective approaches to wrist assessment, like range of motion and grip strength, can determine the effect of disease on the joint, but patient reported outcome questionnaires are better at exploring the patient’s perception of the condition and the personal experiences of people with the condition (Garratt et al., 2002). Certain questionnaires measure broad life domains and perception of health, such as SF36 (Stewart, 2007) and EuroQol-5D (Rabin and de Charro, 2001). These are useful when comparing health states across heterogeneous clinical conditions rather
than specific body regions (Patrick and Deyo, 1989). In addition, targeted interventions have a greater effect on specific elements of disability that are better measured with disease-specific questionnaires (Bachmeier et al., 2001) which have a lower risk of the treatment effect becoming diluted due to influences (recall bias) not related to the original disease in this study being wrist osteoarthritis (McPhail and Haines, 2010).

There are nine condition specific patient reported outcome questionnaires used in trials for osteoarthritis of the wrist (McPhail et al., 2012). However, only four of these have reports on the validity, reliability and responsiveness of these questionnaires. The Disabilities of the Arm, Shoulder and Hand (DASH) score and Michigan Hand Questionnaire (MHQ) are the most commonly used for wrist osteoarthritis (McPhail et al., 2012); however, only the MHQ score has been used previously in four-corner fusion patients and has information about the standard deviation of outcomes in patients with wrist osteoarthritis to allow power calculation (Chung et al., 2006). Patient Evaluation Measure (PEM) and Patient Reported Wrist Evaluation (PRWE) also have favourable evidence on validity, reliability and responsiveness. However, PRWE had not been commonly used when the present study was started.

The MHQ evaluates overall hand function, activities of daily living (ADL), pain, work performance, aesthetics, and patient satisfaction. The right and left hand can be assessed individually. This questionnaire is reliable and valid for wrist and hand outcomes (Chung et al., 1998). PEM evaluates not only the process of treatment and the current state of the hand, but also provides an overall assessment of the hand and wrist. This questionnaire is reliable, valid and responsive for assessing wrist disorders (Dias et al., 2001). (Appendix 2)
1.6 Management

Wrist osteoarthritis due to SNAC/SLAC wrist can be managed conservatively with symptom control, splints or injections. However, explanation and reassurance can help the decision-making with a discussion of the pathological process and the long-term prognosis. Patients can be temporarily helped with a period of splint/cast immobilisation, being prescribed non-steroidal anti-inflammatory medications and even corticosteroid intra-articular injections. However, when the disease is more advanced, nonsurgical options may be insufficient. Commonly, the goal of surgery is to eliminate the pain and preserve as much motion as possible.

Historically, most posttraumatic wrist disorders were treated by total wrist arthrodesis, which would eliminate all movement between the radiocarpal and intercarpal joints without affecting the distal radioulnar joints. However, surgical options have evolved based on the four stages of SNAC/SLAC wrist, which can be divided into those allowing no wrist motion (total wrist fusion) and those preserving motion (proximal row carpectomy, partial fusion and total wrist replacement).

In stage I, reconstructive methods are still possible. Scaphoid nonunion reconstructions using a bone block, screw fixation or scaphoid implant are commonly used in combination with a resection of the radial styloid for a SNAC wrist. Scapholunate ligament reconstruction or scaphotrapezial-trapezoid arthrodesis (STT arthrodesis), in combination with a resection of the radial styloid, can be offered in a stage 1 SLAC wrist.

O’Meeghan et al. have found that arthroscopically-proven scapholunate injuries (Grade I or 2) might not radiographically progress to osteoarthritis (SLAC wrist), although there were ongoing clinical symptoms of pain and limitation of range of motion at seven years post diagnosis (O’Meeghan et
al., 2003). At present, it is still not certain whether a reconstruction or repair of the scapholunate ligament can prevent degeneration in the wrist joint. Previous studies have found an association of asymptomatic contralateral SLAC wrist with pseudogout (calcium pyrophosphate crystal arthropathy) (Doherty and Lovallo, 1993).

The management of wrist osteoarthritis associated with a Stage 2 or more SNAC (Vender et al., 1987) or SLAC (Watson and Ballet, 1984) wrists remains a challenge. Historically, total wrist fusion was the standard procedure for arthritis of the wrist from whatever cause. This aimed to reduce pain and allow a return to work. However, the use of total wrist fusion for post-traumatic conditions can be associated with a high complication rate and poor hand function (Field et al., 1996). There increasing interest in preserving a small range of wrist movement to improve functional outcome after surgery by allowing certain activities of daily living such as perineal care, dressing and combing hair. Presently, this procedure is used more commonly when other surgeries have failed to provide pain relief.

The two most preferred motion preserving surgical options are scaphoid excision with Four-Corner Fusion (4CF) and Proximal Row Carpectomy (PRC). (Details of these operations will follow, Page 72) However, it remains unclear, which of these two procedures has the better outcome (Cohen and Kozin, 2001, Mulford et al., 2009). Grip strength is greater after a 4CF, but it carries a higher risk of nonunion or complications secondary to failure of hardware (Wyrick et al., 1995). PRC is a technically simpler procedure but could lead to radiological osteoarthritis without significant clinical symptoms at follow up at minimum 10 years (Stern et al., 2005). A recent article (Bain and Watts, 2010) showed little deterioration in function 10-year after 4CF.

PRC surgery, excising the scaphoid, lunate, triquetrum and radial styloidectomy, creates a new joint between the distal carpal row (capitate)
and the radius and is a technically less demanding surgery (Blankenhorn et al., 2007, Imbriglia et al., 1990, Inglis and Jones, 1977). The initial description of proximal row carpectomy dates back to 1944, when Stamm described the removal of a proximal row of bones in the wrist, converting the complex link joint into a simple hinge (Stamm, 1944). The distal carpal row will move proximally so that the capitate will articulate with the distal radius. This newly created joint results in significant biomechanical changes, which are non-physiological. Zhu et al. studied these changes in cadavers and found that the mismatch of the radio-capitate articulation was mainly caused by the contour of the proximal capitate being smaller than the radial articulation (Zhu et al., 2010). There is a reduction in the contact area, which causes the PRC to produce a “hinge-and-roll” motion instead of a “ball-and-socket” motion. When there is already degeneration of the capitate head, as in Stage III SNAC or SLAC wrist, proximal row carpectomy is contraindicated; nevertheless, surgeons have tried interposition of soft tissues or capitate head replacement for this stage with variable results.

Whilst SLAC Stage III is considered to be a theoretical contraindication to PRC, there is no consensus. If central 50% of cartilage over the head of the capitate is lost, then PRC is contraindicated and a loss of cartilage of less than 50% can be treated with interposition. It has been shown that the interposition of capsule between the head of the capitate and radius gives similar results to PRC alone. (Salomon and Eaton, 1996) Pin fixation is also considered unnecessary after PRC as it increases the risk of infection (Jacobs et al., 2008).

Four studies compared the outcome of PRC after SLAC/SNAC or Kienbock's disease over the long term and found similar results with 70% of the flexion-extension arc and 80% of grip strength compared to the contralateral side (DiDonna et al., 2004, Jebson et al., 2003, Lumsden et al., 2008, Croog and Stern, 2008). However, in these studies more than
18% of patients required a conversion to total wrist fusion. Failures over a 10 year period after PRC were found to be more common in those 35 years or younger and a reduction in the joint space between the radiolunate joint, but the symptoms don’t correlate with the degree of narrowing (DiDonna et al., 2004).

A 15-year follow-up study in 13 patients after proximal row carpectomy also showed good clinical outcome, with 75% of range of motion and 90% of grip strength compared to the uninvolved side (Lumsden et al., 2008). Radiological changes of osteoarthritis were noted in the capitate articulation, but clinical symptoms didn’t correlate with radiological degeneration. The authors’ indications for PRC were SLAC/SNAC, advanced Kienbock's disease, failed lunate prostheses or chronic scapholunate dislocation. Other contraindications to PRC are rheumatoid arthritis and the excessive wear of the capitate head cartilage.

A number of biomechanical studies have looked at the impact of proximal row carpectomy on the cartilage between the capitate and radial fossa. Hogan et al. (Hogan et al., 2004) studied wrist loading after proximal row carpectomy in a cadaver model. They looked at the changes in radiocarpal contact area, and pressure and location after proximal row carpectomy in a fresh cadaver wrist model. They found that the load usually borne by the combination of the scaphoid and lunate is transmitted entirely through the new radiocapitate articulation. In addition, the proximal capitate radius of the curvature is approximately two thirds that of the radius of the curvature of the proximal lunate, leading to incongruity in the lunate fossa of the radius and further increasing the stress placed on this joint.

Blankenhorn (Blankenhorn et al., 2007) developed a cadaveric model to study the carpal kinematics after proximal row carpectomy. Wrists were positioned dynamically by varying the forces applied to the wrist tendons, and held statically in each position by clamping the spring scales to the base of the test fixture. Biomechanical testing showed that in PRC, radial
deviation is restricted due to the impingement of the trapezoid to the radial styloid. There is some translation as well as rotation in the radiocapitate joint after PRC. Mainly, translation occurs in radioulnar deviation; however, in flexion and extension, both in normal wrist and after PRC, the main component of motion was flexion and extension. During radio-ulnar deviation in a normal wrist, however, the lunate continued to flex and extend while the capitate rotated into ulnoradial directions within the distal articular facet of the lunate.

4CF surgery involves excision of the scaphoid and fusion of the capitate, lunate, triquetrum and hamate, restores midcarpal stability and preserving the anatomical joint (Merrell et al., 2008, Baratz and Towsen, 1997, Watson and Ballet, 1984). Before completing the four-corner arthrodesis, the lunate should be reduced out of its DISI position. After this is completed, the carpus will be fixated by either a dorsal plate, pin, staple or screw techniques. The range of motion (ROM) of the wrist after a four-corner fusion comes from the radiocarpal joint, so flexion-extension of the wrist stays physiological, but the radial-ulnar deviation is non-physiological. It is favourable for the mobility of the wrist to ensure the lunate is fixed in a neutral position. In the original description (Watson and Ballet, 1984), the scaphoid was replaced with a silastic joint implant and the four bones were fused with wires and bone graft from the distal radius.

The technical points that are important when achieving optimal results in four-corner fusion (Merrell et al., 2008) are the use of distal radius bone graft, careful hand debridement of adjacent joint surfaces, adequate removal of cartilage debris, and sufficient screw numbers with at least two in each bones. Use of high-speed burrs was discouraged due to the risk of thermal necrosis. Initially, silicone was used to replace the scaphoid to fill in the void, but this was later abandoned due to the risk of silicone synovitis. K-wires used initially to fix the four bones were removed at six weeks; however, the percutaneous wires increased the risk of infection. In the
recently published 10-year follow-up with no deterioration in function 10 years after four-corner fusion (Bain and Watts, 2010), authors advocated the use of memory staples and iliac crest bone grafts, but many other techniques like circular or square plates have been described for this procedure.

Three-corner fusion (van Riet and Bain, 2006) has been advocated for Stage 3 SLAC and SNAC wrists to give better range of motion but the risk of altering carpal kinematics and loading patterns exists (Cohen et al., 2012). Three-corner fusion differs from four-corner fusion where in addition to excision of scaphoid, the triquetrum is also excised with arthrodesis of lunate, capitate and hamate. This is believed to allow greater ulnar deviation by reducing the impaction between triquetrum and ulna. (van Riet and Bain, 2006)

A study comparing three-corner fusion with four-corner fusion in cadavers with additional excision of triquetrum has been shown to improve the range of radio-ulnar deviation by additional 6 degrees. (Bain et al., 2009) However, this has not been confirmed in clinical situation. It is believed to improve motion at the cost of increased radiolunate contact pressure. The scarring, oedema, and immobilisation associated with surgery could limit motion despite good results shown in studies in cadavers. (Scobercea et al., 2009)

Despite the controversy, many authors have found that four-corner fusion and proximal row carpectomy give similar clinical results. A systematic review by Mulford et al. in 2009 compared the 4CF with PRC in patients with SNAC or SLAC wrists. (Mulford et al., 2009) It compared 27 articles with a total of 625 wrists treated with PRC, 36 articles with a total of 1,173 wrists treated with 4CF, and 8 articles that compared the outcomes of the two procedures. They used weighted averages based on the number of patients that were included in each study to compare grip strength, ROM, demographic features, subjective scores and postoperative complications.
They concluded that grip strength, pain relief and subjective outcomes were similar in the PRC and the 4CF patients, that the range of motion was slightly less after 4CF; however, 4CF patients had more complications due to nonunion and impingement due to hardware.

Previous cohort studies (Cohen and Kozin, 2001, Dacho et al., 2008) have also attempted to compare the 4CF and PRC and discussed the differences in peak grip strength and extremes of range of motion. But this provides an incomplete picture of the total capacity and ability of the hand (Dias et al., 2012). Uniplanar range of motion measurements may not accurately determine velocity and smoothness of functional motion of the wrist after surgery. None have used dynamic assessments of grip strength or range of motion. These formed the main aims and objectives of this study.
1.7 Operative techniques

The 4CF is usually performed through a longitudinal dorsal incision with a ligament splitting Berger’s approach to the joint. The posterior interosseous nerve is dissected and divided proximal to the joint. After confirming that the cartilage over the lunate and the lunate fossa of the radius is intact, the scaphoid is excised and the cartilaginous surface between the four carpal bones was removed. The DISI deformity is corrected and maintained temporarily with K-wires when a bed was created for the selected fusion plate. The specially designed Spider (Integra® Spider™ Fusion System, Osteotec, UK) plate, or Hubcap (Hubcap four-corner fusion plate, Acumed, UK), is used for the limited wrist fusion. (Figure 3.14) The plate is fixed to each carpal bone with screws.

![Radiographs taken after insertion of spider plates for Four Corner fusion.](image)

The screw placement is confirmed with radiographs and the K-wires were removed. Bone grafts taken from the iliac crest are placed between the four bones and into the center of the fusion area through the plate. After surgery, the patient's wrists is immobilised in a plaster cast for 6-8 weeks. Once
fusion is satisfactory, wrist mobilisation is allowed, sometimes needing the supervision of a hand therapist.

The PRC is also performed through a dorsal longitudinal incision. The posterior interosseous nerve is divided. The proximal carpal row is approached with an inverted T-shaped capsular incision. While protecting the palmar ligaments and cartilage on the surface of the capitate and lunate fossa of the radius, the scaphoid, lunate, and triquetrum are excised. (Figure 3.15) The radial styloid is resected to avoid impingement. Postoperatively, all patients have their wrists immobilised in a plaster cast for 2-3 weeks, followed by mobilisation.

![Figure 1.28. Radiographs taken after Proximal Row Carpectomy.](image)

Wrist fusion is performed with standard dorsal approach to the wrist with AO wrist fusion plate. (Figure 3.20) The posterior interosseous nerve is dissected and divided proximal to the joint. The disease cartilaginous surface between the carpal bones is removed. The wrist joint is maintained temporarily with K-wires when a bed is created for the selected fusion plate. The specially designed AO wrist fusion is used for the total wrist fusion. (Figure 3.1) The plate is fixed to third metacarpal, capitate and the radius
with screws after ensuring the cartilage at the base of third metacarpal is denuded to achieve union in the joint.

Figure 1.29 Radiograph of a patient with fusion of radiocarpal joint for osteoarthritis of the wrist joint. The breakage of the distal screws required removal of the plate.

Three-corner fusions are performed through a dorsal longitudinal incision. A Berger's ligament splitting approach is used to identify the joint. The posterior interosseus nerve is divided proximal to the joint line when a one-centimetre segment of the nerve was excised. The scaphoid and triquetrum is excised piecemeal and cartilage integrity is confirmed over the radial fossa and the head of the lunate. Cartilage surfaces between lunate, capitate and hamate are denuded and the DISI deformity is corrected by using K-wires as a joystick. Further K-wires are used for preliminary bony fixation. Arthrodesis is performed with memory staples (Depuy, Warsaw, IN). Two staples are used, one across the luno capitate joint and the other
across the lunate and hamate. The position of the staples is confirmed with
dynamic fluoroscopy, particularly to identify impingement of the staples on
the dorsal radius. (Figure 2.323) Standard closure is performed when the
capsule is closed over the staples with absorbable sutures to skin. The
forearm is placed in a palmar cast, which is reapplied at one week after
satisfactory wound healing and further extended for 4 to 6 weeks
postoperatively. Radiological union is confirmed before forceful gripping is
permitted and a return to sports is allowed.

![Postoperative radiographs show complete resection of the scaphoid and triquetrum and position of Memory staples.](image)

Figure 1.30 Postoperative radiographs show complete resection of the scaphoid and triquetrum and position of Memory staples.
1.8 Deficiencies in the literature

1. Measuring only flexion-extension and radio-ulnar deviation provides a very limited representation of total capability of the wrist joint. Circumduction captures a more accurate picture of the functional ability of the joint as it symbolizes wrist movement as coupled motion in two dimensions. Flexible electrogoniometer has been used before to quantify the range of wrist motion but has not been used to measure velocity and smoothness of circumduction in normal volunteers. Measuring range, velocity and smoothness of circumduction in four quadrants of wrist (flexion-extension and radio-ulnar deviation quadrants) would allow better description of the dynamic capability of wrist. This method could also be used to explore the oblique functional plane of wrist circumduction and to establish the reproducibility and reliability of these measures of circumduction.

2. Peak grip strength is traditionally used to measure the maximum force that can be generated by the hand, and it is used to assess the degree of impairment of the hand due to disease. Measuring only the peak force misses other attributes of hand strength, as the speed of generation of strength, or sustainability or variability of grip. Force–time curves have been used previously to measure grip strength and assess sincerity of effort to discriminate between sincere effort and faked weakness but not used to depict the sustainability of grip. Force-time curves have never been used to assess peak force, average force, total grip time, area under the curve, and variability of the plateau region of the curves in order to understand the impact of wrist osteoarthritis on grip strength.

3. The Sollerman Hand Function test was designed to evaluate the quality of grip and the ability to complete 20 day-to-day tasks within one minute, however, its development was based on experience in
tetraplegic patients and its validity and reliability were established by correlating it with the disability rating scale and the international classification for surgery of the hand in tetraplegia. In addition, this test shows a ceiling effect with bunching of scores at the upper level making it difficult to capture small differences between patients. It has not been investigated whether measuring only the time taken to complete each of the Sollerman tasks without summarisation of continuous time data into the categorical 5-point scale can still identify differences in hand function. It has not been used to describe the application of the timed Sollerman hand function test in normal volunteers and the association between age, gender, dominance and handedness and the timed Sollerman hand function test. The Sollerman test was developed for tetraplegics and may not be a useful test for other hand problems.

4. These dynamic techniques of measuring wrist range of motion with electrogoniometry, grip strength with force-time curves and timed Sollerman hand function test have not been applied to patients with wrist osteoarthritis (SLAC and SNAC wrist) before surgery and after four-corner fusion, proximal row carpectomy, three-corner fusion, and total wrist fusion. These denote the main aims of this dissertation.
1.9 Aims and Objectives

The aim of my study was to assess wrist function and to understand the disability experienced by the patients with traumatic wrist osteoarthritis in greater detail. The aim was also to apply dynamic methods of evaluating wrist range of motion, grip strength and hand function to patients with wrist osteoarthritis (SLAC and SNAC wrist) before surgery and after four-corner fusion, proximal row carpectomy, three-corner fusion, and total wrist fusion.

The objectives of the dissertation were:

• To measure the wrist range of motion with a biaxial electrogoniometer to measure rate, rhythm and range of circumduction and to study grip strength with a digital dynamometer over one minute in Normal Volunteers. The aim was also to develop the Sollerman hand function test to measure the time taken to complete each task.

• To apply these techniques of assessment to patients with wrist osteoarthritis (SLAC and SNAC wrist) before surgery and after four-corner fusion, proximal row carpectomy, three-corner fusion and total wrist fusion.

• Finally, to compare the range of motion and grip strength variables between normal volunteers and all the patients in the surgical groups including wrist osteoarthritis (before surgery), four corner fusion, proximal row carpectomy, three corner fusion and total wrist fusion.
2 Methods

This chapter describes the equipment and experiments used to gather the range of motion, grip strength, Sollerman hand function test and questionnaire data for this study:

2.1 *Project Initiation* describes how I became interested in this study.

2.2 *Project Logistics* includes initial sample size calculation and how this study became into a multicenter project. It also defines the ethic committees that supported the study and the other approvals from the hospitals and local trusts that were required in order for this study to commence. It further describes the bodies that supported the study, with grants for purchase of the equipment and travel grants for visits to units in other countries for collection of data.

2.3 *Patients and volunteers* describe the patients and normal volunteer subjects who underwent the wrist assessments.

2.4 *Equipment* describes the equipment used, and also justifies the use of the chosen equipment.

2.5 *Experimental protocol* defines the equipment checks and the data gathered from each subject during the experiments.

2.6 *Data handling* describes the uploading and manipulation of the raw data, and the custom MATLAB programs used to handle the data.

2.7 *Analysis* describes the techniques used for data analysis and presentation.
2.1 Project Initiation

While exploring the use of force time curves for assessing grip strength in an ongoing project in the University Hospitals of Leicester on patients with rheumatoid arthritis (Dias et al., 2012), I got an opportunity to extend this method of analysis to patients with wrist osteoarthritis. On further research on this topic, I identified that traumatic osteoarthritis of wrist behaves very differently from rheumatoid arthritis. It is a disabling disease that affects middle aged active adults in prime working life. This usually occurs after scaphoid fracture nonunion or ligament injuries of wrist. When the pain is not controlled with non-operative methods of treatment, consideration has to be given to surgery. Surgery aims to reduce pain and disability by improving grip strength and range of motion. The available surgical options are total wrist fusion, motion preserving surgery (four-corner fusion and proximal row carpectomy) or wrist arthroplasty (replacement). As wrist arthroplasty is still largely experimental and results very unpredictable, the main choice is between total wrist fusion, proximal row carpectomy (PRC) and four-corner fusion surgery (4FC).

Arthrodesis (fusion) of wrist reduces pain and improves strength but restricts motion so is considered very disabling. Proximal row carpectomy (PRC) and scaphoid excision with four-corner fusion (4CF) or three-corner fusion (3CF) are common motion-preserving procedures for symptomatic osteoarthritis. PRC involves excision of proximal row of bones in the wrist and 4CF involves fusion of four bones (capitate, lunate, triquetrum and hamate) in wrist with excision of scaphoid. Advocates of PRC claim that the simpler surgical technique gives a greater range of motion without the risk of nonunion or complications secondary to hardware associated with fusion. Advocates of 4CF claim greater grip strength and a lower chance of progression of radiocarpal arthritis. But there is no clear evidence to suggest which of these procedures has a better outcome for the patients. A 3CF differs from 4CF by excision of both the scaphoid and the triquetrum.
and with arthrodesis of lunate, capitate and hamate. This may allow greater ulnar deviation by reducing impingement between the triquetrum and ulna.

I approached Prof Joseph J Dias, Mr. Bhaskar Bhowal, Ms. Clare Wildin and Mr. Aamer Ullah in University hospitals of Leicester to allow me to access their patients to extend the technique of using force time curves to patients with wrist osteoarthritis (SNAC and SLAC wrist) who had undergone a 4CF.

Traditional methods of assessment of hand function provide limited information about the dynamic abilities of the wrist. They provide an incomplete picture of limitations experienced by the patients, as sustainability of the grip and circumduction of wrist is not assessed. Functional assessment like Sollerman hand function test is also not used routinely for these patients due to time constraints. For a comprehensive picture of the dynamic capacity of hand, I have included objective assessment of range of motion with an electrogoniometer, assessment of function with Sollerman Hand function test and subjective assessments with patient reported outcome scores including the Michigan Hand Questionnaire and Patient Evaluation Measure in addition to the grip strength assessment with force time curves.
2.2 Project Logistics

The research question for this study was to document how the wrist performs in patients with wrist osteoarthritis (SLAC/SNAC) before surgery and after each of the operations. A randomized trial would have required a long follow-up to discern differences in function after surgery based on previous literature. (Bain and Watts, 2010, Stern et al., 2005) A cross-sectional clinical outcomes study was therefore considered appropriate. The primary outcome measure for the study was chosen as the Michigan Hand Questionnaire with secondary outcomes measures of grip strength, range of Motion and timed Sollerman hand function test.

Sample size calculation was difficult for this thesis, as the methods used for assessment have never used before for this study group. Chung et al in 2006 had used Michigan hand questionnaire to study patients after four-corner fusion surgery so this was used as the primary outcome measure for the sample size calculation ($\alpha = 5\%$, $\beta = 80\%$). A prospective observational study was chosen as the suitable method to assess the disabilities as there is little evidence in literature available to guide the patients what to expect after motion preserving procedures like four corner fusion.

The hypothesis for the study was that the four-corner fusion (4CF) does not lead to any clinically relevant difference in the functional outcome of the patients with post-traumatic osteoarthritis of wrist when compared to total wrist fusion or proximal row carpectomy. Variability of measure ($\sigma$) was taken as standard deviation (preoperative and postoperative) from Chung et al (2006) article with an improvement of 12 points in Michigan hand questionnaire value as clinically relevant difference with alpha error of 0.05 and beta error of 0.20 (80% power) giving an sample size requirement of 24 patients in each group. Since the numbers of 3CF were very small, I have not performed a power calculation for this group.

Four corner fusion patients: I identified forty-eight patients who had a four-
corner fusion (4CF) of the wrist in the Orthopaedic department at Glenfield Hospital, Leicester, from 1998 to 2011. Twenty-four patients with scaphoid excision and four-corner fusion agreed to attend the research clinic and were assessed. I was successful in obtaining a research grant from the Leicester Hospitals Foxtrot charity that allowed the purchase of the equipment used in the data collection and the manufacture of the Sollerman hand function equipment for this study. Ethics approval was obtained from Leicestershire, Northamptonshire and Rutland Research Ethics committee 1 (reference: 08/HO406/221) (Appendix 3). (Chief investigator: Prof Joseph J Dias, Principal investigator: Harvinder pal Singh, Sponsor: University Hospitals of Leicester NHS Trust; Reference UHL 10636). Ethics committee application required a finalized protocol of the project where formal procedures to be followed for recruitment, data collection and analysis were agreed. The documents included in the application are reproduced in Appendix 2.

*Proximal row carpectomy patients:* I was unable to identify sufficient patients in the databases in Leicester hospitals, who had undergone primary proximal row carpectomy for wrist osteoarthritis. I was unable to identify one centre in the UK with sufficient patients with proximal row carpectomy to include in this study and I approached Prof Steven Hovius in Rotterdam who finally identified a cohort in the plastic Surgery department of the “Diakonessenhuis” hospital Zeist, Netherlands. Dr. Thybot Moojein and Dr. Reinier Feitz of the Xpert clinics, Netherlands had a cohort of fifty-nine patients who had a primary proximal row carpectomy (PRC) for SLAC/SNAC wrist from 2006 to 2010. Fifteen were excluded due to multiple operations on the same wrist or hand, major surgical procedure(s) or pathology on the opposite wrist, as these wouldn’t allow comparison with no affected hand. Excluded patients were similar demographically to the patients included in the study.
I obtained the Federation of European Societies for Surgery of the Hand (FESSH) 2010 junior travel grant and the British Orthopaedic Association (BOA) 2011 travelling fellowship grants that allowed me to visit the hospitals in the Netherlands for this study. Due to leave restrictions, I visited Netherlands three times for two weeks each time for setting up this study and for data collection in the next visits. A research Student, Dr. Michelle Brinkhorst was identified from the research group in Netherlands to help with interpretation and approaching the patients for clinic visits for this study. During my first visit to Netherlands, I transported all the equipment and trained the research student in the study protocol and use of all the equipment. Twenty-six patients agreed to attend research clinics, but two were unable to attend due to illness. The remaining 24 patients were assessed. Two patients had SLAC on the other wrist, hence could not be included in comparison between PRC and 4CF for ROM and grips strength assessment but were included for comparison with Sollerman function test. I assessed 12 patients in Netherlands jointly with Dr. Michelle Brinkhorst. She also helped in translation of the patient information sheet, questionnaires and consenting of the patients in the Netherlands. Patients review in clinics was staggered to my visits to Netherlands from the UK but due to time constraints and need for me to travel to Netherlands every time patient agreed to participate in the study; Dr. Michelle Brinkhorst reviewed the other 12 PRC patients alone when I was not in the Netherlands as per the agreed protocol. This was closely reviewed for consistency by another researcher (Dr. Harm Slijper). Dr. Brinkhorst further assessed patients with wrist arthroplasty and 4CF with biodegradable fusion plates with the same equipment and similar research protocol for her PhD project but this data is not included in the document. Ethics approval was also obtained for the Dutch study from the ethics committee in Erasmus Hospital, Rotterdam, Netherlands. (Medische Etische Toetsings Comissie, Erasmus MC; Reference MEC-2010-295).

In Netherlands, I also met Dr. Harm Slijper who at that time was working with the department of plastic surgery in Rotterdam. He previously had
experience in the MATLAB software. He agreed to write the code for the software to analyse the data from the assessment of grip strength and range of motion. This required multiple face-to-face and Skype meetings to create the code as per the study protocol.

Unfortunately, halfway through this study, Dr. Harm Slijper changed his job and was unable to support the completion of the code for analysis. As the code was only partly complete to allow analysis of the force-time curves and calculation of range of wrist circumduction variables and it was very essential for the future of this study, I had to personally learn coding using MATLAB software. I attended multiple training sessions on the Mathworks website and training course in University of Leicester to acquire sufficient knowledge to complete the code not just to measure the range of wrist circumduction but also to calculate the rate and rhythm of wrist circumduction in the four quadrants of the wrist. (Singh et al., 2011)

*Three corner fusion patients:* While reviewing the previous literature on this topic, I also identified that some surgeons prefer to perform three-corner fusion (3CF) for wrist osteoarthritis. A 3CF differs from 4CF where in addition to excision of scaphoid, the triquetrum is also excised with arthrodesis of lunate, capitate and hamate. This is believed to allow greater ulnar deviation by reducing impingement between the triquetrum and ulna. (van Riet and Bain, 2006) A cadaveric study (Bain et al., 2009) reported that the additional excision of the triquetrum (3CF), improves the range of radio-ulnar deviation by an additional 6°, however, another study reported that excision of the triquetrum increased radiolunate contact pressure. (Scobercea et al., 2009)

Any advantage seen in a cadaveric model may not necessarily be replicated in the clinical settings, as a consequence of postoperative oedema and contracture. The advantages seen in range of motion may not lead to an increase in patient satisfaction or function of the wrist. I felt that
assessing patients with 3CF would also further the knowledge of surgical outcomes after wrist osteoarthritis. Hence I approached Dr Gregory Bain from Adelaide in the Federation of European Societies of Surgeons of the hand annual conference, 2010 in Bucharest to allow me to assess his patients with three-corner fusion. I was also successful in obtaining a Capener travelling fellowship with the Royal College of Surgeons of England in 2011 that allowed me to visit the hospitals in Australia in order for me to complete this study.

Initially it was planned that one of Dr Bain’s research nurses will identify and approach the patients of 3CF for inclusion in the study so less time is required for assessments and I can collect all the data in three weeks in Australia. Unfortunately due to illness, this plan fell through and I had to identify, approach and assess the patients in the three weeks in Australia. I identified 24 patients who had three-corner fusion for stage 2/3 SLAC/ SNAC wrists performed by Dr Greg Bain at the Royal Adelaide Hospital and Modbury Public Hospital, Australia, from September 2004 to October 2011. These patients were invited to participate in the study that involved clinical assessments one year after surgery. Twelve agreed to attend and were assessed.

**Normal Volunteers:** When I had completed the data collection for patients with 4CF, I realised that we did not have normal values of these measures of function using techniques of dynamic assessment of range of motion and grip strength applied in this study. Previous literature also had no data to allow comparison. Hence I needed to apply these techniques to normal volunteers so I could have the normal values that I could use to compare against patients with wrist osteoarthritis. This project was hence extended to normal volunteers was the same techniques of assessment. The Ethics committee that initially approved by study (Leicestershire, Northamptonshire and Rutland Research Ethics committee 1, reference: 08/HO406/221) had advised me to use the norms data from literature to compare my surgical groups, but since there was no such data available in literature I had to
resubmit a substantial amendment to the ethics application to allow inclusion of normal volunteers in the study groups.

Volunteers were recruited from the hospital staff and the patients’ relatives attending the outpatients’ clinics in Glenfield Hospital, Leicester. The sample size calculation was based on the pilot of the first 10 volunteers, as the variability of the Sollerman score in normal volunteers was not previously available. The total time taken to complete the Sollerman tasks with each hand was taken as the primary outcome measure. To detect a difference of 20 seconds (one point on the Sollerman scale) between the dominant and nondominant hand, with standard deviation (SD) of 32 seconds in a 2-sided test at 80% power and false positive (type I error) rate of 0.05, the sample of 90 volunteers was required. For the other variables (age groups, handedness and gender), I planned to present the confidence intervals as an estimate of how close the sample mean is to the population mean.

One hundred volunteers (200 hands) were assessed in this study with the agreed protocol. I ensured an equal gender distribution by recruiting 10 men and 10 women in each decade from 20 to 70 years. I included volunteers who were able to understand and participate in the study and were able to give consent. The volunteers were excluded if they had a history of injury, deformity or disease of the upper limb and systemic arthropathy. I assessed the suitability of the volunteers for the study and invited them to participate. I provided the volunteers with an information sheet detailing the study protocol and the method of data collection. Participation was voluntary and, if the volunteers agreed to participate in the study, they were asked to sign a consent form. (Appendix 2)

**Wrist Osteoarthritis patients**

Four-corner fusion (4CF) for Scapholunate Advanced Collapse (SLAC) and Scaphoid Nonunion Advanced Collapse (SNAC) has been reported to
consistently lead to good function after fusion with satisfactory pain relief. However it is unclear whether surgery improves range of motion or grip strength. To clarify this question, I identified twenty patients on the waiting lists of Glenfield Hospital with Grade 2/3 SNAC and SLAC wrist between the period January 2010 and April 2012 and invited them to take part in the study. Sixteen agreed to participate and attended research clinics and the data was included in this study.

*Total Wrist Fusion patients*

I also identified 17 patients with total wrist fusion for wrist osteoarthritis in databases at Glenfield Hospital, Leicester and invited them for this study to allow comparison between results of 4CF with total wrist fusion. Twelve attended the research clinics and were assessed.
2.3 Equipment

2.3.1 MIE Grip/Pinch dynamometer

This Digital Dynamometer is available in the Orthopaedic department of University Hospitals of Leicester and is a very reliable tool (Allen and Barnett, 2011) for measurement of grip strength, hence it was chosen for the study. The components of this device are: (Appendix 1)

1. Digital analyser (Figure 2.1)
2. Pinch/grip transducer
3. Mains cable
4. WinCAS Software
5. Bayonet Neill–Concelman (BNC) to 9-pin connector
6. R 232 to USB cable to connect display unit to the PC.

Figure 2.1 Photograph showing MIE digital analyser (right) with Grip/Pinch transducer (left).
The instruments are assembled by connecting the pinch/grip handle to the back of the digital analyser and into the input marked 'Transducer'. The plug should be seated fully and locking rings are tightened till fully engaged with the BNC connector. The mains cable is connected the display unit to activate the display on the device. The display is set to zero by pressing the 'zero' button for a few seconds. (Figure 2.2)

Figure 2.2 Picture of Front and Rear of the MIE Digital Analyser. Zeroing button is on the upper right hand corner of the front display and the attachments for the cables are at the rear section.

This device is designed to improve the repeatability of grip strength data collection. In the past, a sphygmomanometer was used to measure grip strength, but this measured pressure and not force. When force is applied onto the rubber bulb, the pressure depends on the contact area between the hand and the rubber bulb and also on how the rubber bulb is held, which makes it unreliable. In addition, the minimum grip measurement with
The pneumatic device is 2.5 kg or higher; it translates to 25N. Some weak hands have difficulty gripping more than a few Newtons, hence I choose the MIE dynamometer to measure grip strength, as it is more accurate in measuring grip strength.

MIE WinCAS Software. This software is specifically written for use with the dynamometer by MIE Medical Research Limited. It was installed on a laptop PC and the digital analyser unit was connected to the laptop using a serial R232 to USB connector as the digital analyser has a serial port.

The software allows some statistical calculations for endurance analysis in the test (Figure 2.3). There were inaccuracies between visual results and calculations displayed on screen so I chose to analyse the raw data with MATLAB software directly. The software displays a statistical table with the following parameters:

- Maximum value (maximum grip strength)
- Target Value (default at 50% maximum force)
- Elapsed time (total time of endurance test)
- Grip rate
- Average value of the slope (excluding the first and last 10%)
- Fatigue rate (average of the curve between maximum and end value)
- Fatigue (the drop in grip over the maximum grip as percentage)
- Release rate (the average of the slope excluding first and last 10%)
- Integrated area (the total area under curve as measure of work done).
Figure 2.3 Photograph showing WinCAS software used for data collection with MIE dynamometer.

Each component of the force-time curve was analysed to measure (1) Slope of first 10%, (2) Peak force, (3) Release rate, (4) Last 10% and (5) Integral (Area) of force-time curve.

This device allows the collection of grip strength data up to 1000 Newtons with a resolution of one Newton. Accuracy is approximately 1% and it allows both hardware and the software calibration. The operating temperature is from +5°C to +45°C. This device is designed to minimise inaccuracies as the grip strength can vary due to physiological and psychological factors, which can be minimised using standard testing procedures that were followed in this study. A formal protocol was developed to avoid variation.

1. Limb position: The patient sits on a chair with arms; the shoulder is kept in neutral, elbow at 90° and forearm in midprone position. This is to prevent any mechanical advantage as grip strength can vary with different elbow & wrist positions (Dorf et al., 2007).
2. Diurnal variation: The test procedures were all performed during working hours from 9 am to 4 pm (Wright, 1959).
3. Size of Handle: The handle width was kept standard, which was at size 2, the same as that used for the Jamar Dynamometer.
4. Pain: Pain can influence the patient's grip strength and endurance so the patient/volunteer was advised to stop the test as soon as the pain became severe or intolerable. The patient was advised to retake the test or repeat the test with a slightly different grip position that was less painful.

The handle is made from a lightweight aerospace alloy that is as strong as steel. This has been found to be reliable for use in subjects with a strong grip or with poor grip strength (Allen and Barnett, 2011). Its sensors are designed in such a way that, no matter where the handle is held, within the black area below the red mark line (Figure 2.1), the reading is always correct and is not dependent on site of grip placement. A scale is attached to the handle to accommodate for the different hand sizes. The width in my experiments was set to number 2, which is equivalent to the width of the handle in the Jamar dynamometer. The digital display can be adjusted to indicate force in Newton, kilograms or pounds. This was set to Newton throughout the experiment.

2.3.2 Biometrics Electrogoniometer

The strain gauge based goniometer consists of a sensing element with a flexible core (0.3mm diameter) with four resistive wires, which are equally spaced around the core and run along its entirety. The flexible core is a steel beam with four small resistive wires (Figure 2.4). Each pair of resistive wires are placed diametrically opposite each other and form a half bridge strain gauge transducer, which has been calibrated to measure flexion and extension in one plane and radial and ulnar deviation in the opposite plane.
Figure 2.4 Photograph showing Biometrics electrogoniometer. Data logger is connected to the green coloured Strain Gauge (SG65) that has plastic end blocks with the sensing element and flexible core in the middle section. Base Unit has attachments at the back for the power cable, data logger and computer cable.

A protective spring metal sleeve protects the sensing element from crushing while maintaining flexibility. A SG65 electrogoniometer (Figure 2.4) was used for this study. It is composed of two-sensor end blocks made of plastic measuring 55 mm in length and 18 mm in breadth. One end of the sensing element is fixed to the proximal end block, while the distal end block uses a slide mechanism to allow translation of the block from 30 mm to 65 mm. (Figure 2.5) This is to allow translation to adapt to the changes in length during limb movements. The end blocks provide a skin attachment point with double-sided adhesive tape and also act as a reference points for calibration of angular displacement.
Figure 2.5 Placement of the distal block of the biaxial flexible electrogoniometer.

Left: Distal block is placed on the dorsum of the hand over the third metacarpal and the proximal block is placed over the middle of the forearm in a straight line with the distal block. Right: Placement of the proximal block of the biaxial flexible electrogoniometer. Before attachment of the proximal block, the wrist is flexed as much as possible and central sensing element is pulled to its maximum length before fixing with a double-sided adhesive tape.

The electrogoniometer allows the measurement of flexion/extension on one channel and radial/ulnar deviation on the other channel. These were recorded simultaneously at a sampling rate of 200Hz. The electrogoniometer was attached with two cables to the data logger. (Figure 2.4) This Data Logger can take up to four channels, but only two were used - one for flexion/extension and other for radial/ulnar deviation. The data from the logger is amplified and presented to a computer through a USB connection.

The wrist angles are calculated using the data analysis program (Data Link) provided with the hardware. The software presents the goniometer data to the user in the form of a graph (Figure 2.6) that can further be uploaded and stored as a log file (for use again with Data Link software) or can be
converted to a text file for ease of data handling in other software. When a channel is used in a goniometer, the displayed output is from -180 to +180 degrees. The actual values stored in the data output file are, however, in the range of -4000 to +4000, where -4000 corresponds to -180 degrees and +4000 corresponds to +180 degrees. The main window of the data link display provides a real time view of data received from the hardware to check accuracy. (Figure 2.6)

![Image](image.png)

**Figure 2.6.** The output trace as seen on the Data Link display. (A) Orange line indicates the flexion extension and blue line indicated the radial-ulnar deviation. (B) This was plotted in a trace-trace graph of circumduction with x-axis (radioulnar deviation) and y-axis (extension flexion).

The channel trace on the Data Link software can be used to check the accurate collection of data. Each analogue input channel has a vertical scale showing the maximum and minimum value of 90°. During the setup of the electrogoniometer, two of the available channels were chosen to study the angles; channel A (orange trace) was set to flexion and extension and channel B (blue trace) was set to display radial and ulnar deviation. (Figure 2.6A)

The sensors were zeroed using the standard protocol in the software. Neutral wrist position and wrist angles were measured using the methods described by the American Academy of Orthopaedic Surgeons (AAOS) (Greene, 1994). Putting the subject's wrist in a neutral flexion/extension and
radial/ulnar deviation positions, I recorded the zero position by entering the position as the neutral position. The positive direction for each channel was set for each task by moving the sensor towards the desired positive direction. In this experiment, it was set to show positive direction in channel A as extension and positive direction in channel B as radial deviation. These conventions were used throughout the experiments and data handling. (Figure 2.6B)

Calibration: The manufacturer states an accuracy of ±2 degrees over a range of 90 degrees from the neutral position. The goniometer output values displayed on the software were checked against the protractor measurement to determine the accuracy. A measurement range between 90 degrees of flexion/extension and 60 degrees of radial/ulnar deviation was considered accurate.

Crosstalk between the two channels: The strain-gauge electrogoniometers have a problem of cross-talk between channels due to torsion movements in one channel, which affects the movement in the other channel. The manufacturer claims that the instruments have been calibrated to an accuracy of 3 degrees of crosstalk over 90 degrees of movement in either planes if the standard method of attachment of the end blocks is followed, as per the protocol that was followed for this study. (Figure 2.5 and 3.2) All our experiments were performed in standard pronated position of forearm, hence minimising the potential of rotational skin movement errors. Johnson et al. (Johnson et al., 2002) compared two wrist goniometer systems for accuracy and suggested that a goniometer be calibrated in the pronation position, as this is most likely to be maintained during data collection. It is also suggested that forearm rotation should be eliminated as far as possible during in-vivo wrist joint motion measurements (Leonard et al., 2005).

Equipment checks: Before the experiment was undertaken, the equipment was checked for function. The sensors were moved through 90 degrees in a positive and negative direction of both X and Y planes and confirmed on the
display on the software to indicate exact angle measurements with a protractor.

Sample Rate: During physiological activities, the frequency of movements are considered to be around 4 Hz (McAuley and Marsden, 2000). The sample rates available for this test in the software are 1000Hz, 500Hz, 200Hz, 50Hz and 20Hz. However, slower rates are associated with aliasing, which is an effect that causes different signals to become indistinguishable when sampled especially due to noise from electrical machines. The high sample rates require bigger hard drives for data storage and faster processor for analysis. So, a rate of 200Hz was decided, as it would allow for measurement of the rate of circumduction in each quadrants of wrist movement.

Instrument: The system of flexible electrogoniometry included an electrogoniometer (Biometrics®: XM-65, Biometrics Ltd, Gwent, UK) with a twin axis sensor to measure the relative angles between the two end blocks. The strain gauge (SG65) was located between the two end blocks and was protected by a spring. This electrogoniometer had two separate output channels that permitted the simultaneous measurement of angles in two orthogonal planes: wrist flexion-extension and radio-ulnar deviation. The strain gauge measured the angular movement of the wrist joint and sent signals to a notebook computer through sensor adapters. The angular signal input range was from –180 degree to +180 degree. The sampling rate was 200 Hz. The signals produced by the electrogoniometer as a result of wrist movement were amplified and converted to a digital form, while the real-time data were displayed on the monitor for error checking (Figure 2.7a & 2.7b).
Figure 2.7 Monitor display of the Biometrics Electrogoniometer. It shows (2.7a) real-time data trace in flexion extension axis (orange) and radio-ulnar deviation axis (blue). This was plotted in a trace-trace graph (2.7b) of circumduction with x-axis (radioulnar deviation) and y-axis (extension flexion). MATLAB software was used to generate angle-angle figures (2.7c) to measure extension flexion arc (1), radio-ulnar deviation arc (2), oblique plane of the circumduction curve (3), circumference of circumduction (4), maximum vertical distance (5) for oblique plane, and maximum horizontal distance (6) for the oblique plane. The ellipse overlay method (2.7d) was used to measure the area of circumduction curve (1). Red line (2) correlates with oblique plane of circumduction curve and ellipse (3) overlaid 85% of the data points of the curve.

The telescopic end block of the electrogoniometer was attached to the dorsal skin surface of the third metacarpal (Buchholz and Wellman, 1997), which was the most suitable area on which to attach the end block. Both end blocks were fixed to the skin using double-sided adhesive tape. Elastic adhesive tape was also applied over the blocks. Subjects sat on a chair and
held their shoulders in a neutral position, with their upper arms relaxed, the elbows in 90° of flexion, and the wrist in full pronation. (Figure 2.8)

![Electrogoniometer on forearm](image)

Figure 2.8 Photograph showing the electrogoniometer and its position on the forearm. The fixed proximal electrode is taped to the middle of the forearm, and the flexible distal electrode is taped to the dorsum of third metacarpal.

The subjects were asked to form a light fist during the examination. The amplifier output was calibrated to zero before the examination of each subject to ensure zero degrees would correspond to a neutral position of the wrist in both the flexion-extension and the radio-ulnar deviation. The subject then performed maximum excursion of flexion-extension, radio-ulnar deviation, and circumduction of the wrist. The direction of circumduction
was clockwise for the right hand and counterclockwise for the left hand, beginning at the 12 o’clock position. Each movement was repeated five times, so each hand performed a total of 15 movements. Subjects were instructed to perform the movements at a speed they felt comfortable with. Both hands were measured. The specifications of this goniometer has previously been examined and validated in a laboratory study (Ojima et al., 1991), and the system was reliable and accurate (Rawes et al., 1996).

The repeat measurement of range of movement was done at the beginning and the end of the hour-long session due to the time required for these sessions and the need for the volunteers to travel to the clinics. The researchers removed the electrogoniometer from the forearm and reapplied it between each test-retest session, as the main source of variation between observers for the electrogoniometers is the site of application of the goniometer on the volunteer’s forearm (Moriguchi et al., 2009, Szulc et al., 2001).

2.3.3 Sollerman Hand function test kit

The Sollerman Hand Function Test (SHFT) is composed of 20 tasks; the selection is based on representation of important activities of daily living (Sollerman and Ejeskar, 1995). (Figure 1.26) The task selection by Sollerman was based on the percentage use of handgrips during daily activities, and hence reflects a picture of overall handgrip function, utilising the most common handgrips used on a day-to-day basis (Figure 2.10).
The percentage use of the eight most common hand-grips in activities of daily living. (Sollerman and Ejeskar, 1995)

<table>
<thead>
<tr>
<th>Pinches (Fingers)</th>
<th>%</th>
<th>Grips (Hand)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulp pinch</td>
<td>20</td>
<td>Diagonal volar grip</td>
<td>15</td>
</tr>
<tr>
<td>Lateral pinch</td>
<td>20</td>
<td>Transverse volar grip</td>
<td>14</td>
</tr>
<tr>
<td>Tripod pinch</td>
<td>10</td>
<td>Spherical volar grip</td>
<td>4</td>
</tr>
<tr>
<td>Five-finger pinch</td>
<td>15</td>
<td>Extension grip</td>
<td>2</td>
</tr>
</tbody>
</table>

The Sollerman test kit comprises a vertical piece of wood, locked within a wooden tray, with an edge of 5 cm in height. The vertical piece of wood has various props attached to it, including the tops of two jars, door handle on both sides, a Yale lock, two purses, screws and bolts (Figure 2.11 and 2.12).

This test has been found to be reliable and reproducible in tetraplegic patients, chronic stroke patients and burn injuries (Sollerman and Ejeskar, 1995, Brogardh et al., 2007, Weng et al., 2010).
Additional items for the SHFT include an iron, two wooden cubes, pen, paper, envelope, plate, knife, fork, Play-Doh, Tubigrip sleeve, cup, jug, “Pure-Pak”, and a wooden board with material and buttons covering it. The order in which the tasks were carried out was decided by how the kit was set up in front of the volunteer; side A of the vertical board, followed by side B, (Figure 2.10) and then followed by the tasks that do not require the vertical board or tray. The volunteers were instructed to move the position of the equipment, within limits, for comfort whilst completing the tasks. The Sollerman kit was placed in front of the volunteers on a table whilst they sat in a chair placed approximately 15 cm from the edge of the table. This protocol was followed for all volunteers.
Volunteers were instructed to complete the Sollerman hand function test (Sollerman and Ejeskar, 1995). Originally, it was created and used to compare the hand function before and after reconstructive hand surgery. It has been found to be reliable and reproducible in tetraplegic patients, chronic stroke patients and burn injuries (Sollerman and Ejeskar, 1995, Brogardh et al., 2007, Weng et al., 2010). The test measured the ability to do 20 day-to-day tasks that assessed overall hand function, in a quick and easy manner. The tasks were timed during the original Sollerman test, but the score was summarised on a 5-point scale. The final Sollerman score ranged from 0 to 80, with the higher score reflecting the better performance. In this study, I also measured the time taken to complete each task but, instead of using the ordinal scale, I collated the time taken to complete all tasks in the timed Sollerman hand function test.

A single researcher who was conversant with the Sollerman hand function test collected all the data. Custom-built equipment was used to perform the

Figure 2.11 Photograph showing other side (B) of the Sollerman Hand function kit.
Sollerman hand function test. The equipment required for this test could be easily dismantled and packed compactly into a travel suitcase. This allowed the researcher to carry out the hand function test efficiently and maintain the sequence of the tasks in different locations using the same equipment. The Sollerman test equipment is composed of a vertical piece of wood, with the props required for some tasks attached to each side, locked within a wooden tray that had a 5 cm high edge. The equipment also included an iron, two wooden cubes, pen, paper, envelope, plate, knife, fork, Play-Doh, Tubigrip sleeve, cup, jug, a Pure-Pak and a wooden board covered with a cloth and buttons.

To perform the tasks, the volunteer was seated in front of the equipment that was set up on a standard office desk 28-30″ in height. The tasks were explained in detail before the test and the volunteers were instructed to stay seated while carrying out the tasks. For each of the tasks, only one hand could be used except for the three activities (task 11, cut Play-Doh; task 14, fold paper and put into envelope; and task 15, put paper-clip on envelope), where the other hand could support the props. All the activities were timed separately (Table 3.5). Data were collected for both the dominant and the nondominant hand. Each assessment took around thirty minutes.

A spreadsheet program was written to allow continuous collection of the data and to measure the time taken to complete each task. The program gave a verbal instruction to the volunteer to start the task, when the researcher pressed the spacebar tab to start the timer. The researcher pressed the spacebar again as soon as the task was completed and the time taken to complete the task was recorded in the spreadsheet. The sequence of the tasks depended on the position of the Sollerman test props and the side of the equipment where the test item was located. This reduced interruptions during the test and avoided the need to turn the equipment around, thus allowing smooth completion of all the tasks. The position of the test equipment was the same for each individual and could
be adjusted to a certain extent to ease the completion of the tasks, but volunteers were discouraged from standing up or using two hands unless stated.

The Sollerman test is based on seven of the eight handgrips used commonly in everyday activities. All tasks were completed based on the normal and permitted handgrips for each test as listed in the instructions provided in the original publication (Sollerman and Ejeskar, 1995). Volunteers were discouraged from diverting from the permitted grip and were asked to repeat the test if this was observed. The type of grip used during each of the 20 tasks in the Sollerman test was studied closely by analysing the videos of five volunteers, while the average time spent in each grip during one task was estimated (Table 3.6). This allowed measurement of the total time spent on each to the seven grips and this was compared between the dominant and the nondominant hands. The percentage use of the main grips in the Sollerman hand function test was calculated to give a picture of the grip function in activities of daily living; it could then allow comparison in disease conditions that affect specific types of grip, like thumb base osteoarthritis, which would affect key pinch.
<table>
<thead>
<tr>
<th>Task Description</th>
<th>Pulp pinch</th>
<th>Lateral pinch</th>
<th>Tripod pinch</th>
<th>Five-finger pinch</th>
<th>Diagonal volar grip</th>
<th>Transverse volar grip</th>
<th>Spherical volar grip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Put key into Yale lock, turn 90°</td>
<td>70</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pick coins up from flat surface, put into purses mounted on wall</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open/ Close zip</td>
<td>50</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pick up coins from purses</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lift wooden cubes over edge 5 cm in height</td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lift iron over edge 5 cm in height</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turn screw with screwdriver</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pick up nuts</td>
<td>20</td>
<td>40</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unscrew lid of jars</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do up buttons</td>
<td>50</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cut Play-Doh with knife</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 Percentage of time taken for each task in relation to Handgrips.
<table>
<thead>
<tr>
<th>Activity</th>
<th>Score 1</th>
<th>Score 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>and fork</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Put on Tubigrip stocking on the other hand</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Write with pen</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Fold paper, put into envelope</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Put paper-clip on envelope</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Lift telephone receiver, put to ear</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Turn door-handle 30°</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Pour water from Pure-Pak</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Pour water from jug</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Pour water from cup</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>
2.3.4 Questionnaires

The Michigan Hand Questionnaire (MHQ) has originated from the University of Michigan in 1998 (Chung et al., 1998) and has been validated using psychometric principles. The questionnaire evaluates the overall hand function, activities of daily living, pain, work performance, aesthetics, and patient satisfaction with the hand function. It consists of 63 questions with five possible answers, divided into six scales (overall function, activities of daily living, work, pain, appearance and satisfaction). (Appendix 2) The scoring system for the MHQ is complex. For the pain scale, a higher score indicates more pain. For the other five scales, higher scores indicate better hand performance. The raw score per scale is converted to a score ranging from 0-100. The overall MHQ score can be obtained by summing the scores for all six scales after reversing the pain scale and then dividing this by six. If 50% or more of the items in a scale are missing, then that particular scale cannot be scored. The right and left hand can be assessed individually. This questionnaire was found reliable and valid by the originators (Chung et al., 1999).

The patient evaluation measure (PEM) was first described in 1995 (Macey et al., 1995). The questionnaire evaluates the process of treatment, the current state of the hand, and also provides an overall assessment. It consists of three parts, with a total of 19 questions with seven possible answers, presented as a categorised visual analogue scale. (Appendix 2) The questions relate to symptoms, the impact of the disorder on the patient, the satisfaction and general disability/handicap. The PEM score is calculated by summing the values for each item in parts two and three of the questionnaire and expressing it as a percentage of the maximum possible score from 0 to 100. The higher the score, the greater is the disability. The first part, which assesses the patient’s view of the
consultation, is excluded from the scoring. This questionnaire is reliable, valid and responsive for assessing wrist disorders (Dias et al., 2001).

The Beighton score (Beighton and Horan, 1969) was used to assess hypermobility as this could impair function (Wolf et al., 2011). It uses a simple 9-point system, where the higher the score, the higher the laxity. The threshold for joint laxity in a young adult is 4 to 6.

I also assessed the handedness of volunteers using a questionnaire (McManus, 2009). This one page handedness questionnaire documents the volunteer’s preference for use of either hand in activities of daily living. The laterality score was calculated as the mean of the first eleven items in this questionnaire. (Appendix 3) The total time taken to complete all the Sollerman tasks with the dominant hand was subtracted from the time taken when using the nondominant hand and this difference was plotted against the laterality score to study the effect of handedness on the time taken to perform the 20 tasks of the Sollerman test.
2.4 Experimental Protocol

All assessments were done in special research clinics. Each session of assessment took approximately one hour. The repeat measurement of range of movement was performed on 20 normal volunteers to assess the repeatability of the analysis. This was done at the beginning and the end of the hour-long session rather than repeating the assessment on another day. This was due to the time required for these sessions and the need for the volunteers to travel to the clinics. I removed the electrogoniometer from the forearm of the volunteer and reapplied it between each test-retest session, as the main source of variation between observers for the electrogoniometers is the site of application of the goniometer on the volunteer’s forearm. The marking of the position of the electrogoniometers was not permitted and there was a minimum interval of 40 minutes between the test and retest of both hands of the subjects.

The subject was provided with a “Letter to participate” (Appendix 3) and a “Patient information sheet” (Appendix 3) by post (for patients) or by hand (for normal volunteers) detailing the purpose of the study, methodology, the type of study and the study procedure. On the day of the interview, the subject was welcomed and registered to the study. The study was explained to them again and any further questions were answered as required. They were then asked to sign the consent form (Appendix 3). Michigan Hand Questionnaires (Chung et al., 1999) and the Patient Evaluation Measure (Macey et al., 1995) (Appendix 3) were provided to the subjects in paper form to complete. A handedness questionnaire and Beighton score were completed as well.

In case of normal volunteers, after introductions and an explanation of the project, each volunteer read through the information and were asked to complete the consent form if they agreed to participate. The handedness questionnaire was completed and their demographic data was collected.
The information letter included details of the purpose, methodology, and type of study and the study procedure. All documents given to the volunteers can be found in the Appendix. Each volunteer was required to perform the positions required in order to calculate a Beighton score.

Grip strength data was collected with a MIE pinch and grip analyser (MIE, Medical Research, Leeds, UK) to analyse the grip strength and endurance of the affected and unaffected hand. This device, once calibrated, has been found to be very reliable and repeatable (Allen and Barnett, 2011). The patient was seated on a chair with arms. The shoulder was adducted, forearm was placed in a mid-prone position along a flat chair arm; with the elbow flexed 90 degrees and the wrist overhanging the end of the chair arm, to allow free movement. Before starting the test, I ensured the grip handle was adjusted to position 2 and the subject was asked to hold the handle at the base unaided and without touching the two lever arms. The WinCAS Software can be launched from the desktop icon. The main application window appears, where a new patient data can be entered (Figure 2.11). It also allows the analysis of an existing patient data by using the 'Find patient' or 'List all patients' toolbar.
A 'New patient' button creates a welcome wizard, where patient details (Name, Date of Birth, Gender, Date of test and Dominance) are entered and saved on the computer (Figure 2.12).
Once a new file is created for the patient, it can be opened to perform a 'new test'. Two options are presented when the 'test tab' is selected in the welcome wizard. Either an endurance test or a strength test can be performed. When using a digital analyser with pinch grip (not the Myometer, which is used for knee or ankle assessment), the endurance test measures a subject's ability to maintain a constant force within a given range for only certain duration of time (Figure 2.13).
Figure 2.14 Step-by-step wizard to enter patient information and the new endurance test.

The endurance test built in the provided software (WinCAS) is designed more for differentiating between faked submaximal effort and true weakness in strength based on whether a pre-specified target is achieved. This, however, was not the research question in this study. Hence, I chose to use the MATLAB software to calculate the sustainability, as I wanted to look at the drop in strength over time. The software allowed the settings to be changed to allow the endurance test to be run over one minute. After creating a new strength test, (Figure 2.14) the software took the volunteers through onscreen instructions within the test session wizard.
I chose to perform a single assessment per subject in the grip strength test although three assessments are commonly recommended. The reason was the time patients were required to strongly grip was over one minute and patients with wrist osteoarthritis would not be able to repeat the test due to pain. Hence, to keep a standard protocol for all patients and volunteers, they were asked to take the grip strength assessments only once at the end of the session.

I made sure patients understood the instructions clearly and were asked to repeat their understanding of the steps of the assessment before commencing the test. The step-by-step wizard standardises the process to follow so different operators can easily repeat this experiment. The cycle duration option was set to 60 seconds, (Figure 2.15) the time that each exertion cycle would last.
The 'Next' button leads to the calibration process for this device. It is a two-step process. Firstly, the hardware must be zeroed and, secondly, removing any remaining offset would zero the software. The 'zero' button on the front panel of the digital analyser unit was pressed and held for a couple of seconds to allow the hardware to be calibrated to zero. The current software offset value of -0.41 N was displayed on the screen. This was within the normal operating range for this device of -5N to +5N. Ensuring that no load was applied to the transducer, the 'Next' button was clicked to calibrate the software and proceed to the actual strength measurement stage.
The software prompts the subject through the steps of the test using a set of traffic lights. (Figure 2.16) The wizard starts in the amber ‘ready’ mode, indicating the software is ready for the patient to exert a force on the transducer. When the software gives a verbal prompt to start exerting the maximum force on the transducer, the light turns to green. When a minute has elapsed, the light turns to red with a verbal prompt to relax, when the measurements are stopped. The two clocks on the screen; display the cycle time remaining and the total elapsed time, while a ‘progress bar’ shows the test is proceeding. (Figure 2.16)

As the software gives a verbal prompt at the start and culmination of the test, I ensured subjects were not able to see the measured force displayed on the digital analyser (Figure 2-17) to prevent bias in the results (Weinstock-Zlotnick et al., 2011). The subject was asked to maintain the force at their maximum until the traffic light turned red, or on the verbal prompt to relax, or if the patient experienced unbearable pain and he/she
could no longer participate in the test. The test cycle was not repeated unless there was any obvious flaw in the technique.

![MIE digital grip/pinch analyser](image)

**Figure 2.18** MIE digital grip/pinch analyser showing the grip strength in Newtons on the display screen.

The subjects were encouraged to maintain the maximum force throughout the whole cycle. The biofeedback was unchecked; therefore, the subjects could not see the current force being applied so as to avoid a conscious or subconscious bias to control the amount of force being applied. At the end of the cycle, the computer made a short bleep and the software prompted the subject to relax, when the software automatically progressed to the next stage of saving the data. At this point, the subject was asked to let go of the handle as quickly as possible, preferably without leaving any residual load on the transducer. The data collected was saved on the computer as a graph of force to time curves and stored in a separate folder with a unique identifier for each subject.
The final page of the wizard allows the analysis of the data, when any errors can be checked and the test repeated, if required. The ‘finish’ button automatically closes the test session and saves the patient data. The 'Patient Search' button allows the search for a specific patient’s data saved on the PC when their test could be re-analysed.

It was noted in the first few curves generated when measuring grip strength in patients that the calculated values of the maximum force were not correct, as identified from the graphs. It was, therefore, decided to use MATLAB Software for the mathematical calculation of the force-time curve characteristics, as explained in the analysis section. The software also saves the test/data files on the computer as a backup on disk. The data can be exported into an Excel file, where the collected data can be stored for later analysis in other software. The software also prompts the user to back up the patient data every fortnight onto a disk to allow restoration of data in case any of the files get corrupted.

During the analysis stage of the experiment, five patients' force time curves showed large blips in the data, where there was a sharp rise in the values to more than 1000N for a few seconds followed by a sudden drop in value below zero. I discussed this with the company (MIE digital). They thought it was due to a loose connection between the cables, but they were unable to rectify the data errors that were already collected. As this was noted in only five patients, I used the MATLAB software to discount these blips, as explained in the analysis section. Changing the cable rectified problem with the loose connection.

*Electrogoniometry*

Range of motion data was collected with a Biometrics digital electrogoniometer. In 1991, Ojima et al. examined and validated the specifications of this electrogoniometer in a laboratory study (Ojima et al.,
1991). In a clinical validation, the system was found reliable and highly accurate (Rawes et al., 1996).

Attachment of sensor: Initially, the patient was told about the procedure and was asked if he/she had any questions. The subjects were initially informed about the movements they were supposed to perform and were verbally prompted through each of the movements. The sensor was attached to each subject’s arm, which was placed on a horizontal armrest of the chair on which the patient sat, (Figure 2.5) with their shoulder in neutral position, elbow at 90 degree and wrist in full pronation, with hand held in a light fist. Positions of the two sensor blocks were chosen to be the back of the hand on the third metacarpal and on the back of the forearm, as suggested in the goniometer manufacturer’s manual. The blocks were axially aligned by eye, but the marking of the arm was not allowed. The sensor blocks were attached to the skin using medical double-sided adhesive tape, and the forearm sensor was held onto the arm and fixed with a medical grade adhesive tape to prevent movement between the skin and block (Figure 3.2). Once the electrogoniometer was attached, volunteers were instructed to place their hands flat, palms down, and forearms on the table. In this pronated position, the wrist was considered to be at zero degrees in both flexion extension and radial ulnar deviation planes. In order to identify when volunteers were performing tasks when analysing the data, each volunteer was instructed to return to this neutral position between tasks. The electrogoniometer was zeroed to each volunteer’s neutral position.

The subjects were informed about the movements they were supposed to perform and were verbally prompted through each of the movements. The demographic data was entered at that stage into the Data Link software (Figure 2.18) They were asked to perform four maximal uniplanar movements of flexion-extension and ulno-radial deviation, followed by four maximal circumduction movements in the direction of pronation (anticlockwise right hand, clockwise left hand from patient’s viewpoint).
Movements were also assessed during the dart-throwing movement by asking the patient to perform a movement from radial-dorsal to ulno-palmar direction. The forearm was kept fully pronated and the subjects were asked to aim for an imaginary point over the ulno-palmar aspect on the floor as if the subject was hammering in that direction. The subjects then performed four sets of circumduction movements with the fist clenched tightly and a dart-throwing motion with a tight clenched fist. The reason for the use of clenched fist during circumduction and dart throwing was the suggestion that muscle contraction decreased the range of motion of the wrist (Gehrmann et al., 2008). Constraining fingers in static flexion posture reduced wrist flexion and ulnar deviation without decreasing extension and radial deviation. This was the reason I used a gentle fist posture as the standardized finger joint configuration during all circumduction assessments. Once the measurement of the left wrist of a volunteer was completed, the electrogoniometer was placed on the right arm and the process was repeated after zeroing the electrogoniometer again. The traces could be visualised on the Data Link software and checked for accuracy. (Figure 2.6 and 2.18)
Figure 2.19 Print screen of Data link analysis software. It displays the tabs for entry of patient information for use with Biometrics electrogoniometer.

Data handling and analysis: At the end of each test, the data was uploaded from the data logger using the Biometrics software supplied with the electrogoniometer. Each uploaded test was converted to an ASCII file using the biometrics software and then converted to a text file (.txt) in Microsoft Excel. This format could allow handling with MATLAB for data analysis. The angular values from each channel stored in the data logger were converted to degrees by the formula:

\[ \text{Angle in degrees} = \text{Raw value} \times 0.045. \]

This was done for each channel, using this calibrated value.

Standard data display: The standard way of displaying the data from the tests was a Cartesian plane, being a simple X-Y plot of two planes of motion. (Figure 2.7) Flexion and extension were placed on the vertical axis, with extension positive, while radial and ulnar deviation were placed on the horizontal axis, with radial deviation positive for left hand and vice versa. This allowed consistency with sign conventions as well as an understanding of the data, with positive extension direction occurring vertically in both physical and graphic terms.

I used MATLAB software to further analyse the data generated by electrogoniometer. The key steps followed in the MATLAB codes to calculate the range of motion parameters from the biaxial wrist goniometer were:

1. Set the frequency of data collections (200Hz) and the number of conditions for processing (conditions are flexion extension, radial ulnar deviation, circumduction of wrist, dart throwing motion, circumduction with tight clenched fist, dart throwing with tight clenched fist).

2. Enter the text files in the Matlab software (Figure 2.19).
3. Convert voltages to degrees using the calibration factor (Angle in degrees = Raw value * 0.045) and apply the Butterworth filter to reduce noise. This technique of applying a filter is used in all standard data processing techniques used in MATLAB. Butterworth filter is one of the commonly used filters to reduce the effect of background noise on data analysis. It filters out high frequencies to allow collection of the useful data for analysis.

4. Indicate the start of the first trial until the end of the last trial. (Figure 2.20 and 2.21)

5. Count the number of full cycles of the trials you want to extract. (Figure 2.22)

Figure 2.20 The display in MATLAB is maximised to identify the gaps between each of the conditions.
Figure 2.21 The Hair cursor in the MATLAB. It is used to indicate the beginning and end of each of the cycles, which are further analysed to calculate the different variables of range of motion.

6. Calculation of the different variables of range of motion data as discussed in the analysis section later in this chapter. (Section 2.6)
**Timed Sollerman Hand Function test**

A custom-built equipment was used to perform the Sollerman hand function test (Figure 2.23). It could be easily dismantled and packed into a travel suitcase to allow me to carry out the hand function test efficiently and maintain the sequence of the tasks in different locations. To perform the tasks, the volunteer was seated in front of the equipment that was set up on a table. The volunteers were instructed to carry out the tasks without hurrying and to stay seated. For each of the tasks, only one hand could be used, except for the three activities (tests 11, 14, and 15), where the other hand could support the props. All the activities were timed separately. Data was collected for both the dominant and the nondominant hand. Each assessment took around thirty minutes.

![Figure 2.22. Photograph showing the props for the Sollerman hand function test on side A.](image)

A spreadsheet program (Appendix 5) was written to allow continuous collection of the data and measure the time taken to complete each task. The program gave a verbal instruction to the volunteer to start the task,
when the researcher pressed the spacebar tab to start the timer. The researcher pressed the spacebar again as soon as the task was completed and the time taken to complete the task was recorded in the spreadsheet. The sequence of the tasks depended on the position of the Sollerman test props and the side of the equipment where the test item was located. This reduced interruptions during the test and avoided the need to turn the equipment around, thus allowing smooth completion of all the tasks. The position of the test equipment was the same for each individual and could be adjusted to a slight extent to ease the completion of the tasks, but volunteers were discouraged from standing up or using two hands unless stated.

All tasks were completed based on the normal and permitted handgrips for each test as listed in the instructions provided in the original publication. (Figure 2.8) Volunteers were discouraged from diverting from the permitted grip and were asked to repeat the test if this was observed. The type of grip used during each of the 20 tasks in the Sollerman test was studied closely by analysing the videos of five volunteers, and the average time spent on each grip during one task was estimated. This allowed measurement of the total time spent on each to the seven grips, which was compared between the dominant and the nondominant hands.
Timed Sollerman Hand Function test (Tasks and instructions) (Figure 2.11, 2.12, 2.23)

Task 1: Put a key into a Yale lock and turn 90 degrees. The Yale lock with bolt was attached to the vertical board about 30 cm from the table surface. The volunteer was instructed to pick up the key from the table surface and insert it into the Yale lock and rotate the key 90 degrees until the bolt disappeared.

Task 2: Pick two coins from flat surface and put into two purses mounted on vertical board. Two coins were placed in front of the volunteers, 5 cm from the edge of the vertical board. The two purses was placed on the vertical board about 20 cm from the table surface. Volunteers were instructed to pick up the coins from the table surface one at a time and place them into the purses. They had to do this without sliding the coin to the edge of the table, but were asked to pick the coins up with a pulp pinch grip.

Task 3: Open and close a zip. Two purses were attached to the vertical board 20 cm from the surface with two different zip sizes. The volunteers were instructed to open and close the zip once for both purses. The volunteers were allowed to stabilise the purse with their other hands whilst unzipping and zipping.

Task 4: Pick up coins from purses. The two coins used in task 2 were picked out of the same purses attached to the board. The volunteers were instructed to take the coins out of the purses one at a time and place them at the bottom of the board in front of them.

Task 5: Lift wooden cubes over edges 5 cm in height. Two wooden blocks, size 7.5 cm and 10 cm, were placed on the bottom of the vertical board and placed in a box with a 5 cm edge. Volunteers were instructed to pick up the blocks, lift them over the edge and place them on the table in front of the box and then return them into the box by lifting them over the edge.
Task 6: Lift iron over edges 5 cm in height. The box holding the vertical board was used as the edge, being 5 cm in height in this task. An iron weighing 3 kg was placed on the bottom of the box with edges of 5 cm. The volunteers were instructed to lift the iron over the edge with a pronated handgrip and place it on the table in front of the box, and return it to the same position in the box.

Task 7: Turn a screw with a screwdriver. Two screws with nuts were mounted in the vertical wall, one with spring resistance and the other without resistance. A screwdriver with a handle 2.5 cm in diameter was used for this task. Volunteers were asked to pick up the screwdriver and turn the screw with one turn in supination for both the screws.

Task 8: Pick nuts from the surface and put on the bolts. Four bolts of different sizes were mounted on the vertical board. Four nuts were placed on the bottom of the box on the table in front of the volunteers. The volunteers were instructed to pick up the nuts, one at a time, and put them on the appropriate bolts until they were fully engaged. The forearm was in the pronated position for this task.

Task 9: Unscrew the lids of two jars. Two jars with screw-lids sized 7.5 and 10 cm respectively, mounted on the vertical board, at around 20 cm height, from the bottom of the board. The lids were screwed on with moderate force. Volunteers were instructed to unscrew the lids and place them on the table and screw them back on.
Figure 2.23 Photograph showing props for Sollerman hand function test on side B.

Task 10: Do up buttons. Four buttons with buttonholes of different sizes on pieces of cloth were mounted on a wooden board and placed in front of the volunteer on the table. The volunteers were asked to do up the four buttons, allowing the volunteers to work from big to small, or vice versa. The volunteers were required to complete the task one-handed, with the forearm in the pronated position.

Task 11: Cut Play-Doh with knife and fork using a plate, knife and fork of commercial design. A lump of Play-Doh was placed on the plate. Volunteers were asked to pick up the knife and fork and cut the lump of Play-Doh into four pieces.

Task 12: Put a Tubigrip stocking on to the other hand. One Tubigrip stocking was available. Volunteers were instructed to pick up the stocking with the tested hand and place the sleeve on the opposite arm to the one being recorded and to pull the distal end past their hand.
Task 13: Write with a pen: Each volunteer was instructed to write his or her name on an unfolded A4 piece of paper. Volunteers were allowed to stabilise the paper with their other hand.

Task 14: Fold the paper, put into an envelope. The volunteers were asked to fold the A4 piece of paper from task 13 and to fit it into a C6 envelope. They had to fold the paper twice and put it into the envelope. The volunteers were allowed to use the non-tested hand when folding the paper and to hold the envelope.

Task 15: Put a paperclip on to the envelope. Two paper clips of different sizes were available. Volunteers were instructed to use the measured hand to place the paperclip on the envelope while the other hand could be used to hold the envelope.

Task 16: Lift a telephone receiver and put to the ear. A telephone of commercial design was placed on the table. This task required the volunteer to lift the telephone receiver to their ear, on the same side as the hand being used, and return to the base after pausing at the ear for a few seconds.

Task 17: Turn a door handle 30 degrees. The vertical board was fitted with door handles on both sides so the left-handed handle was used when recording movement of the left wrist, and the right-handed handle for the right wrist. The volunteers were instructed to rotate the door handle by 30 degrees from the horizontal position downwards. The forearm was in the pronated position when turning the door handle.

Task 18: Pour water from a Pure-Pak. A Pure-Pak®, size 1 litre, filled with water was placed on the table. The volunteers were instructed to lift the Pure-Pak and pour the water into the empty water jug.
Task 19: Pour water from a jug. A water jug with handle, size 1 litre, filled with water and teacup, size 200 ml, was available for this task. The volunteer was instructed to lift the jug by the handle and pour the water into the cup.

Task 20: Pour water from the cup. A teacup with a handle without a hole, size 200 ml, filled with water was used for this task. The volunteer was instructed to lift the cup by the handle and pour water back into the jug.
2.5 Data Handling

The electrogoniometer traces for each volunteer are displayed in the Data link software as the movement of the wrist using two separate traces; the orange trace relates to movement in the FE plane, while the blue trace refers to the RUD plane (Figure 2.6). Each movement of the wrist is portrayed as a trace movement in the y-axis directions, and time along the x-axis, with the trace moving from left to right. The y-axis ranges from 180° to -180°, and time is counted in seconds along the x-axis.

Movement in the positive direction in the FE plane indicates flexion of the wrist, and movement in the negative direction indicates extension of the wrist. The direction of movement within the RUD plane changes between wrists. As the RUD trace moves in the positive direction, the wrist is moving to the right of the volunteer; for the left hand, this is the radial deviation, while the right hand is in the ulnar deviation. When the RUD trace moves in the negative direction, the wrist is moving towards the left of the volunteer; for the left hand, this is the ulnar direction and for the right hand this is the radial deviation (Figure 2.25). The adjustment for this difference between hands was built into the MATLAB codes when the analyses for the data were performed.
Figure 2.24. Picture of the wrist shows the movements of flexion, extension, radial and ulnar deviation. The relationship of radial-ulnar deviation varies for left and right hand and also its relationship to Dart Throwers’ Motion plane (DTM).

By using two separate codes in MATLAB, Lissajous’ figures and calculations for the predominant axis can be generated for each task correcting for hand from which the data originated. The angle can be measured from a vertical line in the 12 o’clock position to the axis of that task (Figure 2.26 and 2.27).
Figure 2.25. MATLAB software was used to generate angle-angle figures. It measured flexion extension arc (1), radio-ulnar deviation arc (2), oblique plane of the circumduction curve (3), circumference of circumduction (4), maximum vertical distance (5) for oblique plane, and maximum horizontal distance (6) for the oblique plane.

Figure 2.26. Ellipse overlay method. It was used to measure area of circumduction curve (1). Red line (2) correlates with oblique plane of circumduction curve and ellipse (3) overlaid 85% of the data points of the curve.
2.6 Analysis

The electrogoniometer recordings were processed with a commercial software package (MATLAB 7.8, The Math Works Inc., Natick, Massachusetts, 2009) to derive summary measures from the data collected. MATLAB code was written to allow the extraction of the following parameters (Figure 2.26 and 2.27):

1. Flexion-extension arc based on maximum values of flexion and extension.
2. Radio-ulnar deviation arc based on maximum values of radial and ulnar deviation.
3. Area under circumduction curve: MATLAB software was used to fit an ellipse to the circumduction x-y curve to calculate the area of the ellipse that contained more than 85% of data points generated by the electrogoniometer. This is described in a 2-dimensional measurement, degree-degrees (°°). This measurement could be understood as the angle subtended at the apex of the cone and represented the area within the irregular shape (much like the area of the continents on a globe can be measured by the angle of the cone subtended at the center of the earth).
4. Circumference of circumduction curve: Sum of angular changes between all the data points within a single movement measured (i.e. the path length).
5. Velocity of the movement: Circumference of the circumduction curve/time to complete one cycle.
6. Quadrant analysis: Data from the circumduction curve were divided into four quadrants based on the four parts of the bounding box around the data (Figure 2.28). The bounding box was defined by the maximum extents of the movement in two orthogonal directions, and the two diagonals divide the box into four separate quadrants. As the deviation quadrants were different for right and left hands, the radio-ulnar deviation data for the left hand were inverted after the quadrant analysis was performed. This way, all sectors from both hands could be compared. The velocity and smoothness of the motion were calculated for each quadrant.

Figure 2.27 Circumduction curve shows quadrant analysis for left hand. Black markers indicate the radial deviation quadrant, red markers indicate the flexion quadrant, green markers indicate ulnar deviation quadrant and magenta markers indicate extension quadrant.
7. Smoothness of movement: This was measured by the number of zero crossings of the acceleration signal of the circumduction curve. Zero crossing/point was whenever the acceleration signal changed to deceleration and vice versa. The green circles in Figure 2.29 indicated acceleration, and red circles indicate deceleration, while changes from green to red or vice versa indicate a zero point. Width of the overlay green or red circles indicated the amount of acceleration or deceleration respectively. This indicated how many times the patient slowed down or sped up while performing a movement. These data were divided by the duration of the movement, yielding the number of zero points per second. This was expressed as a frequency (Hz) of changes in direction of acceleration signal.

![Circumduction curve envelope (Overlay markers)](image)

Figure 2.28 Circumduction curve with overlay of unfilled coloured markers. It indicates the velocity of movement with green markers indicating acceleration, red markers showing deceleration, and transition indicating the zero point of change in direction of velocity. The distance between each data point was used to measure the diameter of the unfilled circle, i.e. marker size depended on the path length that is the distance between each individual data points. Acceleration was the change in velocity along the path length.
8. Orientation of the oblique circumduction plane: The circumduction curves of all the normal wrists were oval-shaped, and the ends of the long axes of the curve resided in ulna-palmar and radio-dorsal directions (J Chang, 2005). A line was plotted between the farthest points of the circumduction curves within each cycle. This line indicated the orientation plane of the circumduction curve. The angle between this oblique line and horizontal line (Figure 2.26) was mathematically calculated using MATLAB. This angle showed a high correlation with the orientation angle of the fitted ellipse used for calculation of the area (Figure 2.22).

The mathematical steps used to calculate the variables from the electrogoniometer text file using the MATLAB software were:

- Open the parameter in text file
- Set the number of conditions for processing to three: flexion-extension, radioulnar deviation, circumduction
- Calculate range of motion parameters from biaxial wrist goniometer
- Convert angle from voltages to degrees and fill in the calibration factor
- Plot the data to divide it into six conditions so it can be analysed further
- Sample frequency is set as 200 HZ
- Variables to be extracted are:
  - Radio-ulnar deviation range
  - Flexion-extension range
  - Maximum distance
  - Angle between maximum distance line and Cartesian angles
  - Area of Ellipse
  - Circumduction of Ellipse
- Velocity of movements
- Number of zeros per second in circumduction
- Measurements are taken in each channel: radioulnar deviation direction and flexion-extension
- Number of repetitions entered and each variable calculated for extremes of radial deviation, ulnar deviation, flexion and extension

- Pythagoras theorem used to calculate the path of the trial.
- Time taken for each cycle was measured.
- Path length of the whole trial gives the circumference.
- Velocity was calculated from the path length and time taken to complete one cycle.
- Acceleration profile measured by measuring differences in the path changes with number of changes in the sign of the acceleration profile (+ to − or − to +).
- Ellipse fitting method used to extract angle of circumference.
- Data saved as SPSS and Excel file with the parameters.
- Data is cut into four parts based on direction of movement.
- Each quadrant is analysed for all the above variables, velocity, and number of zeros in each quadrant.

**Data analysis**

The computer displayed the values for the uniplanar movements in degrees and circumduction as a 2-dimensional x-y curve with radio-ulnar deviation on x-axis and flexion-extension on y-axis. The area of circumduction was measured in a 2-dimensional measurement, degree-degrees (°°). A commercial software package (MATLAB 7.8, The Math Works Inc., Natick, Massachusetts, 2009) was used to analyse the shape, size, and orientation of the circumduction curves.

Data collected with the flexible electrogoniometers were divided into three movement groups (flexion-extension, radio-ulnar deviation, and
circumduction). The MATLAB code was written to allow extraction of the parameters from the output of the electrogoniometer, as discussed in the analysis section. (Figure 3.3)

**Reliability**
Test-retest reliability was assessed by performing repeated measurements of range of movement at the beginning and the end of the hour-long session (Kocher and Zurakowski, 2004). Repeated measurements were made in 20 volunteers by one researcher. The reliability of the measurements was examined with the intraclass correlation coefficient (ICC) to express both interobserver reliability and intraobserver reliability for repeat measurements. This value, known as the intraclass correlation coefficient, can range from 0 to 1 (Landis and Koch, 1977).

I also used the Bland and Altman approach (Bland and Altman, 1995), based on graphical techniques and simple calculations, for reliability. The Bland and Altman plot helped clarify if any relationship existed between the initial and repeat result. Horizontal lines were drawn at the mean difference and at the limits of agreement, which were defined as the mean difference plus and minus 1.96 times the standard deviation of the differences (Institution, 1979).
Figure 2.29 Circumduction curves.

(A) Circumduction curve with overlay of unfilled coloured markers indicating the velocity of movement, with green markers indicating acceleration and red markers showing deceleration and transition indicating the zero point of change in direction of velocity. The distance between each data point was used to measure the diameter of the unfilled circle, i.e. marker size depended on the path length that is the distance between each individual data points. Acceleration was the change in velocity along the path length.

(B) Circumduction curve shows quadrant analysis for left hand. Black markers indicate the radial deviation quadrant, red markers indicate the flexion quadrant, green markers indicate the ulnar deviation quadrant and magenta markers indicate the extension quadrant. For the left hand, black markers indicate the radial deviation quadrant, red markers indicate the flexion quadrant, green markers indicate the ulnar deviation quadrant and magenta markers indicate the extension quadrant.

I assessed the grip strength with a MIE pinch/grip analyser (MIE, Medical Research, Leeds, UK). The MIE pinch and grip analyser has been shown to produce reliable and repeatable results (Helliwell et al., 1987). The patient was asked to perform a maximum grip and sustain it for 60 seconds. (Figure 2.30)
Figure 2.30. MATLAB software was also used to represent the output from the WinCAS text files. It was used to present the data into force-time curves that were further analysed to derive grip strength variables. Data collected with the MIE grip strength analyser was also processed with MATLAB software. For both hands, the variables derived from the trace were peak force, slope of the force-time curve, area under the curve and SD of the fitted line (Figure 2.31).
Figure 2.31 Force-time curve parameters were selected to quantify the grip strength.
1: Slope of the grip strength calculated from the 60s of force data indicating level of fatigue occurring during the 60 seconds (steeper slope = more fatigue). 2: Area under the force curve (force-time integral) is a measure of overall grip force performance. 3: Peak force is a measure of maximum grip strength. 4: Standard deviation of data around the fitted line (STD detrended),

Statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS, version 16, Chicago). Mean values and standard deviation of data collected from objective and subjective measures were calculated. For the range of motion, the mean score across all movement cycles was used. The differences in the MHQ score, PEM score, grip strength and ROM between 4CF and PRC were analysed using the Student’s t-test, as data for these items were normally distributed. Other special statistical techniques used for individual experiments are explained in the results section. The value of statistical significance was set at P≤0.05.
3 Results

This chapter presents the results of the experimental work undertaken as part of this thesis.

3.1 describes the range of active circumduction of the wrist and force time curves to develop summary descriptors of the data in normal volunteers. It also explains the application of the timed Sollerman Hand Function test in normal volunteers.

3.2 describes the range of motion and grip strength variables in patients with wrist osteoarthritis due to stage 2/3 SLAC and SNAC wrist.

3.3 describes the range of motion, grip strength and Timed sollerman Hand function test in patients with Four-corner fusion.

3.4 describes the range of motion, grip strength and Timed sollerman Hand function test in patients with proximal row carpectomy.

3.5 describes the range of motion and grip strength variables in patients with Three-corner fusion.

3.6 describes the range of motion, and grip strength variables in patients with Total wrist fusion.

3.7 presents the comparison of range of motion and grip strength variables between all surgical groups and compares to the Normal Volunteers.
3.1 Normal Volunteer group

The mean age of 100 volunteers (200 Hands) was 45 (range 21 to 69) years. There were 50 men and 50 women. A total of 88 volunteers were right-handed and 12 were left-handed.

In normal volunteers, the mean area of circumduction (4600°°) and circumference (267°) of the circumduction curve indicated the total range of circumduction. The average arc of uniplanar flexion and extension was greater than the flexion and extension component of the circumduction curve, but the mean uniplanar radio-ulnar deviation arc was similar to the radio-ulnar deviation component of the circumduction curve. The mean area of circumduction and circumference of the circumduction curve was used to measure the total range of circumduction, and this was similar in both hands (p=0.81) (Table 3.1).
Table 3.1 Measurements of range of motion variables in 100 normal volunteers relative to dominance of hand.

<table>
<thead>
<tr>
<th>Range of Circumduction</th>
<th>Dominant Hand Mean</th>
<th>Dominant Hand SD</th>
<th>Nondominant Hand Mean</th>
<th>Nondominant Hand SD</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion-extension arc</td>
<td>122.5</td>
<td>17.6</td>
<td>128.6</td>
<td>18.1</td>
<td>0.17</td>
</tr>
<tr>
<td>Flexion-extension in circumduction (degrees)</td>
<td>100.9</td>
<td>19.4</td>
<td>104.9</td>
<td>17.6</td>
<td>0.08</td>
</tr>
<tr>
<td>Radial ulnar deviation arc</td>
<td>63.6</td>
<td>10.8</td>
<td>62.2</td>
<td>10.3</td>
<td>0.23</td>
</tr>
<tr>
<td>Radial ulnar deviation in circumduction (degrees)</td>
<td>62.3</td>
<td>10.9</td>
<td>59.2</td>
<td>13.4</td>
<td>0.57</td>
</tr>
<tr>
<td>Area of circumduction (degree-degrees)</td>
<td>4613.4</td>
<td>1473.2</td>
<td>4506.5</td>
<td>1504.6</td>
<td>0.81</td>
</tr>
<tr>
<td>Circumference of circumduction (degrees)</td>
<td>267.5</td>
<td>43.8</td>
<td>267.7</td>
<td>42.8</td>
<td>0.12</td>
</tr>
<tr>
<td>Angle of Oblique circumduction plane (degrees)</td>
<td>27.6</td>
<td>12.4</td>
<td>29.3</td>
<td>14.7</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Units of variable in Italics
The velocity of circumduction (mean 186°/s) and the time (1.6s) taken to complete one cycle of circumduction were similar in both hands (Table 3.9). The velocity of circumduction and the time taken to complete one cycle of circumduction was similar in both hands (p<0.16) (Table 3.2). The four quadrants for the velocity of circumduction showed that the velocity was faster in the radio-ulnar deviation quadrants compared to flexion and extension. (Table 3.2)

Table 3.2 Measurement of velocity of circumduction in 100 normal volunteers and relationship to dominance of hand.

<table>
<thead>
<tr>
<th>Velocity of Circumduction</th>
<th>Dominant Hand</th>
<th>Nondominant Hand</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (degrees/second)</td>
<td>185.4 91.9</td>
<td>189.6 70.3</td>
<td>0.08</td>
</tr>
<tr>
<td>Velocity in flexion</td>
<td>45.3 23.3</td>
<td>44.3 21.7</td>
<td>0.09</td>
</tr>
<tr>
<td>Velocity in radial deviation</td>
<td>27.9 14.4</td>
<td>26.2 10.9</td>
<td>0.14</td>
</tr>
<tr>
<td>Velocity in extension</td>
<td>53.5 31.2</td>
<td>50.7 20.1</td>
<td>0.17</td>
</tr>
<tr>
<td>Velocity in ulnar deviation</td>
<td>27.5 12.4</td>
<td>21.3 14.8</td>
<td>0.04</td>
</tr>
<tr>
<td>Time taken for one cycle</td>
<td>1.7 0.8</td>
<td>1.6 0.6</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Units of variable in Italics
Smoothness of circumduction, measured by the average number of zero points in one circumduction cycle, was 9.2 zero points per second (Hz). This indicated changes in acceleration of the movement and was not necessarily apparent visually. Quadrant analysis showed the smoothness was greater in the radio-ulnar deviation components compared to flexion and extension quadrants (Table 3.3).

Table 3.3 Measurements of smoothness of circumduction in 100 normal volunteers and relationship to dominance of hand.

<table>
<thead>
<tr>
<th>Smoothness of Circumduction (Number of zeros per second)</th>
<th>Dominant Hand</th>
<th>Nondominant hand</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoothness</td>
<td>11</td>
<td>10</td>
<td>0.14</td>
</tr>
<tr>
<td>Smoothness Flexion</td>
<td>3</td>
<td>3</td>
<td>0.09</td>
</tr>
<tr>
<td>Smoothness Radial deviation</td>
<td>2</td>
<td>2</td>
<td>0.07</td>
</tr>
<tr>
<td>Smoothness Extension</td>
<td>3</td>
<td>4</td>
<td>0.13</td>
</tr>
<tr>
<td>Smoothness Ulnar deviation</td>
<td>2</td>
<td>2</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Units of variable in Italics
The graphical representation of the changes in the acceleration signal captured the changes in the velocity of motion, when the wrist went from ulnar deviation to flexion and from radial deviation to extension. The oblique planes of the circumduction curves of all the normal wrists resided in ulno-palmar and radio-dorsal directions, with a mean angle of 28 (SD 16) degrees to the flexion and extension plane. This obliquity was counterclockwise for right hands and clockwise for left hands in relation to the 12 o’clock position. (Figure 3.1)

Figure 3.1 Circumduction curve with overlay of unfilled coloured markers. It indicates the velocity of movement with green markers indicating acceleration, red markers showing deceleration, and transition indicating the zero point of change in direction of velocity. The distance between each data point was used to measure the diameter of the unfilled circle, i.e. marker size depended on the path length that is the distance between each individual data points. Acceleration was the change in velocity along the path length.
The peak grip strength was greater in the dominant hand than nondominant hand by 10%. The area under the force-time curve was also greater in the dominant hand (13144 Ns) compared to the nondominant hand (11097Ns). Dominant hands showed a greater drop in strength over 60 seconds as the slope was steeper. The variability of force (SD of slope) was similar in both hands. (Table 3.4)

Table 3.4 Measurements of grip strength (Force time curves) in 100 normal volunteers and relationship to dominance of hand.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Dominant Hand</th>
<th>Nondominant Hand</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Peak strength (Newtons)</td>
<td>283.6</td>
<td>83.1</td>
<td>253.6</td>
</tr>
<tr>
<td>Area under the curve (Newton-seconds)</td>
<td>13143.6</td>
<td>4837.1</td>
<td>11096.9</td>
</tr>
<tr>
<td>Slope of curve</td>
<td>-1.9</td>
<td>1.0</td>
<td>-1.7</td>
</tr>
<tr>
<td>Standard deviation of slope</td>
<td>9.7</td>
<td>3.9</td>
<td>9.7</td>
</tr>
<tr>
<td>Intercept (Newtons)</td>
<td>210.5</td>
<td>74.6</td>
<td>195.7</td>
</tr>
<tr>
<td>Time (Seconds)</td>
<td>55.5</td>
<td>1.8</td>
<td>55.8</td>
</tr>
</tbody>
</table>

Units of variable in Italics
Our volunteers were able to complete the tasks 20 seconds quicker with the dominant hand than with the nondominant hand, and the time taken to perform certain tasks was significantly different ($P<0.001$) (Table 3.5). The volunteers could complete each of the Sollerman tasks within 20 seconds except for the task of doing up the buttons, which took 20.2 seconds (Table 3.5). The volunteers completed 16 tasks in less than 10 seconds. According to the original Sollerman hand function test, these volunteers would have scored 79-80 for both men and women with either the dominant or the nondominant hand based on our data.
Time taken to complete each Sollerman task was compared between dominant and nondominant hand using t-test as the data was normally distributed. *Differences between dominant and nondominant hand were significant, even after Bonferonni adjustment of p-values adjusting for 20 tasks. With permission sage publications (Singh et al., 2015).

Table 3.5 Time taken to complete each task by 100 Normal Volunteers.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Time taken to complete task</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dominant</td>
<td>Nondominant</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Put key into Yale lock, turn 90°</td>
<td>5.8</td>
<td>2.2</td>
</tr>
<tr>
<td>Pick coins up from flat surface, put into purses mounted on wall</td>
<td>5.6</td>
<td>2.2</td>
</tr>
<tr>
<td>Open/Close zip</td>
<td>6.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Pick up coins from purses</td>
<td>7.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Lift wooden cubes over edge 5 cm in height</td>
<td>4.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Lift iron over edge 5 cm in height</td>
<td>4.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Turn screw with screwdriver</td>
<td>8.4</td>
<td>2.7</td>
</tr>
<tr>
<td>Pick up nuts</td>
<td>11.4</td>
<td>5.8</td>
</tr>
<tr>
<td>Unscrew lid of jars</td>
<td>14.8</td>
<td>4.6</td>
</tr>
<tr>
<td>Do up buttons</td>
<td>20.2</td>
<td>8.6</td>
</tr>
<tr>
<td>Cut Play-Doh with knife and fork</td>
<td>14.1</td>
<td>6.8</td>
</tr>
<tr>
<td>Put on Tubigrip stocking on the other hand</td>
<td>5.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Write with pen</td>
<td>7.7</td>
<td>4.4</td>
</tr>
<tr>
<td>Fold paper, put into envelope</td>
<td>8.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Put paper-clip on envelope</td>
<td>6.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Lift telephone receiver, put to ear</td>
<td>2.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Turn door-handle 30</td>
<td>2.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Pour water from Pure-Pak</td>
<td>6.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Pour water from jug</td>
<td>5.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Pour water from cup</td>
<td>5.1</td>
<td>2.6</td>
</tr>
<tr>
<td>Total time (Seconds)</td>
<td>165.6</td>
<td>25.6</td>
</tr>
</tbody>
</table>

Total time (Minutes)                          | 2.7     | 0.4         | 3.1   | 0.4         | 0.001*|

Time taken to complete each Sollerman task was compared between dominant and nondominant hand using t-test as the data was normally distributed. *Differences between dominant and nondominant hand were significant, even after Bonferonni adjustment of p-values adjusting for 20 tasks. With permission sage publications (Singh et al., 2015).
Volunteers took less time for the tasks in each of the seven handgrips with the dominant hand compared to the nondominant hand \((P<0.001)\) (Table 3.6).

Table 3.6 Time spent in each handgrip in timed Sollerman hand function test.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Time taken in each hand grips (seconds)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dominant Hand</td>
<td>Nondominant Hand</td>
<td>P Value</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Pulp pinch</td>
<td>38.4</td>
<td>7.3</td>
<td>43.7</td>
</tr>
<tr>
<td>Lateral pinch</td>
<td>32.8</td>
<td>7.6</td>
<td>37.6</td>
</tr>
<tr>
<td>Tripod pinch</td>
<td>18.6</td>
<td>6.7</td>
<td>24.1</td>
</tr>
<tr>
<td>Five finger pinch</td>
<td>18.2</td>
<td>3.2</td>
<td>23.7</td>
</tr>
<tr>
<td>Diagonal volar grip</td>
<td>18.4</td>
<td>4.3</td>
<td>22.3</td>
</tr>
<tr>
<td>Transverse volar grip</td>
<td>12.3</td>
<td>2.9</td>
<td>19.3</td>
</tr>
<tr>
<td>Spherical volar grip</td>
<td>14.7</td>
<td>4.6</td>
<td>17.3</td>
</tr>
</tbody>
</table>

Total time taken during all tasks by the particular volunteer in each pinch/grip type was calculated using the percentage shown in Table 3. For example, the time taken by a volunteer in a transverse volar grip was calculated by adding 100 per cent of time taken during tasks 6, 17 and 19. The dominant and nondominant hands were compared using t-test as the data was normally distributed.

*Differences between dominant and nondominant hand were significant, even after Bonferonni adjustment of p-values adjusting for 20 tasks. With permission Sage Publications (Singh et al., 2015).
Age could predict the change in total time taken to complete all tasks for the dominant hand as the null hypothesis of the same distribution over age groups was rejected and with less time taken by volunteers between the age groups 30 to 40 years (Figure 3.2).

Figure 3.2 Distribution of time taken to complete Sollerman tasks with dominant (left) hands. With permission Sage Publications (Singh et al., 2015).
3.2 Wrist Osteoarthritis group.

The mean age for the patients with wrist osteoarthritis due to Grade 2/3 SNAC and SLAC wrist (Figure 3.19) was 54 years. Ten were men and six were women. In 14 patients, the dominant hand was the right side, while it was the left hand in two patients. In six patients, the operated side was the dominant side and, in 10 patients, the operated side was the nondominant. (Table 3.21)

Figure 3.3 Radiographs showing SNAC wrist with significant joint destruction between radiocarpal joints. Patient opted for wrist fusion.
Table 3.7 Demographic characteristics of patients with wrist osteoarthritis.

<table>
<thead>
<tr>
<th></th>
<th>Wrist osteoarthritis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Mean</strong></td>
</tr>
<tr>
<td>Number</td>
<td>16</td>
</tr>
<tr>
<td>Age (years)</td>
<td>54</td>
</tr>
<tr>
<td>Sex</td>
<td>Male</td>
</tr>
<tr>
<td></td>
<td>Female</td>
</tr>
<tr>
<td>Dominant side</td>
<td>Right</td>
</tr>
<tr>
<td></td>
<td>Left</td>
</tr>
<tr>
<td>Affected side</td>
<td>Right</td>
</tr>
<tr>
<td></td>
<td>Left</td>
</tr>
</tbody>
</table>
The results for the range of motion variables in patients with wrist osteoarthritis are presented in Table 3.22.

Table 3.8 Range of motion variables in patients with wrist osteoarthritis

<table>
<thead>
<tr>
<th>Demographics</th>
<th>Wrist osteoarthritis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Flexion-extension in Circumduction</td>
<td>64.9\textsubscript{b}</td>
</tr>
<tr>
<td>Radial-Ulnar deviation in Circumduction</td>
<td>36.0\textsubscript{b}</td>
</tr>
<tr>
<td>Area of Ellipse</td>
<td>1993.0\textsubscript{b}</td>
</tr>
<tr>
<td>Angle of Oblique Circumduction plane</td>
<td>14.2\textsubscript{a}</td>
</tr>
<tr>
<td>Time for Circumduction cycle</td>
<td>1.9\textsubscript{a}</td>
</tr>
<tr>
<td>Circumference of Circumduction</td>
<td>166.5\textsubscript{b}</td>
</tr>
<tr>
<td>Velocity of Circumduction</td>
<td>99.7\textsubscript{b}</td>
</tr>
<tr>
<td>NZRP Smoothness of Circumduction</td>
<td>11.8\textsubscript{a}</td>
</tr>
</tbody>
</table>
The grip strength variables for patients with wrist osteoarthritis are presented in Table 3.23.

Table 3.9 Force-time grip strength characteristics in patients with wrist osteoarthritis.

<table>
<thead>
<tr>
<th>Force time characteristics</th>
<th>Wrist osteoarthritis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Area under force-time curve</td>
<td>7129.3$_b$</td>
</tr>
<tr>
<td>Peak force</td>
<td>161.1$_b$</td>
</tr>
<tr>
<td>Time</td>
<td>55.8$_a$</td>
</tr>
<tr>
<td>Intercept</td>
<td>138.1$_b$</td>
</tr>
<tr>
<td>Slope</td>
<td>-1.1$_b$</td>
</tr>
<tr>
<td>Mean force</td>
<td>102.1$_b$</td>
</tr>
</tbody>
</table>
The MHQ score, compared to the nonoperated wrist, was 79% in the wrist osteoarthritis group. PEM score was 49% nearly half of normal.

Table 3.10. Michigan Hand Questionnaire and Patient Evaluation measure (patient reported outcome) in patients with Wrist Osteoarthritis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Wrist osteoarthritis</th>
<th>Median</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michigan Hand Questionnaire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Operated Hand)</td>
<td></td>
<td>79</td>
<td>43-99</td>
</tr>
<tr>
<td>(Nonoperated Hand)</td>
<td></td>
<td>90</td>
<td>59-100</td>
</tr>
<tr>
<td>Patient Evaluation Measure</td>
<td></td>
<td>49</td>
<td>21-88</td>
</tr>
</tbody>
</table>
3.3 Four Corner Fusion group

Mean age of patients with 4CF was 49 years. There were 17 men and 7 women. Time since surgery was 72 months for patients with 4CF. (Table 3.7)

Table 3.11 Demographic Characteristics of patients with four-corner fusion.

<table>
<thead>
<tr>
<th></th>
<th>Four corner fusion (Follow-up 10-148 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>24</td>
</tr>
<tr>
<td>Age at surgery (years)</td>
<td>49 (10.5)</td>
</tr>
<tr>
<td>Age at Follow-up (years)</td>
<td>55 (10.3)</td>
</tr>
<tr>
<td>Time since surgery (months)</td>
<td>72.3 (10-148)</td>
</tr>
<tr>
<td>Immobilization in plaster (weeks)</td>
<td>6.2</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>17</td>
</tr>
<tr>
<td>Female</td>
<td>7</td>
</tr>
<tr>
<td>Hand dominance</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>22</td>
</tr>
<tr>
<td>Left</td>
<td>2</td>
</tr>
<tr>
<td>Side of surgery</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>15</td>
</tr>
<tr>
<td>Left</td>
<td>9</td>
</tr>
<tr>
<td>Side of surgery is dominant</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>15</td>
</tr>
<tr>
<td>No</td>
<td>9</td>
</tr>
</tbody>
</table>
Flexion-extension component in circumduction in the operated wrist was 51% of the nonoperated side in the 4CF group. (Table 3.8) The mean area of circumduction of the operated wrist compared to the non-operated wrist was 35% in the 4CF group. The circumference of circumduction compared to the nonoperated wrist was 53% in the 4CF group. (Table 3.8)

Table 3.12 Range of Circumduction variables in operated hand of patients with four-corner fusion and relationship to nonoperated hand.

<table>
<thead>
<tr>
<th>Range of Circumduction</th>
<th>Four corner fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Operated hand</td>
<td></td>
</tr>
<tr>
<td>Flexion- extension in circumduction (degrees)</td>
<td>46.7</td>
</tr>
<tr>
<td>Radio ulnar deviation in circumduction (degrees)</td>
<td>29.1</td>
</tr>
<tr>
<td>Area of circumduction (degree-degrees)</td>
<td>1233.2</td>
</tr>
<tr>
<td>Circumference of circumduction (degrees)</td>
<td>125.1</td>
</tr>
<tr>
<td>Angle of Oblique circumduction plane</td>
<td>12</td>
</tr>
<tr>
<td>Nonoperated Hand</td>
<td></td>
</tr>
<tr>
<td>Flexion- extension (degrees)</td>
<td>92.0</td>
</tr>
<tr>
<td>Radio ulnar deviation (degrees)</td>
<td>50.6</td>
</tr>
<tr>
<td>Area of circumduction (degree-degrees)</td>
<td>3572.6</td>
</tr>
<tr>
<td>Circumference of circumduction (degrees)</td>
<td>234.9</td>
</tr>
<tr>
<td>Angle of Oblique circumduction plane</td>
<td>18</td>
</tr>
</tbody>
</table>
The smoothness of movement of the wrist during circumduction (measured by number of zero-crossings per second) after a 4CF was less (more than double the number of zero-crossings per second) compared to the nonoperated side after a 4CF (Table 3.9).

Table 3.13 Velocity of Circumduction in operated hand of patients with four-corner fusion and relationship to nonoperated hand.

<table>
<thead>
<tr>
<th>Velocity of Circumduction</th>
<th>Four corner fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td><strong>Operated hand</strong></td>
<td></td>
</tr>
<tr>
<td>Velocity (degrees/second)</td>
<td>53.5</td>
</tr>
<tr>
<td>Velocity in flexion (degrees/second)</td>
<td>50.0</td>
</tr>
<tr>
<td>Velocity in radial deviation (degrees/second)</td>
<td>22.5</td>
</tr>
<tr>
<td>Velocity in extension (degrees/second)</td>
<td>60.2</td>
</tr>
<tr>
<td>Velocity in ulnar deviation (degrees/second)</td>
<td>17.9</td>
</tr>
<tr>
<td>Time taken for one cycle (seconds)</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>Nonoperated hand</strong></td>
<td></td>
</tr>
<tr>
<td>Velocity (degrees/second)</td>
<td>151.7</td>
</tr>
<tr>
<td>Time taken for one cycle (seconds)</td>
<td>1.7</td>
</tr>
</tbody>
</table>
The smoothness of movement of the wrist during circumduction (measured by number of zero-crossings per second) after a 4CF was more than double the nonoperated side. (Table 3.10)

Table 3.14 Smoothness of Circumduction in operated hand of patients with four-corner fusion and relationship to nonoperated hand.

<table>
<thead>
<tr>
<th>Smoothness of Circumduction (Number of zeros per second)</th>
<th>Four corner fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Operated Hand</td>
<td></td>
</tr>
<tr>
<td>Smoothness</td>
<td>28</td>
</tr>
<tr>
<td>Smoothness Flexion</td>
<td>7</td>
</tr>
<tr>
<td>Smoothness Radial deviation</td>
<td>7</td>
</tr>
<tr>
<td>Smoothness Extension</td>
<td>9</td>
</tr>
<tr>
<td>Smoothness Ulnar deviation</td>
<td>6</td>
</tr>
<tr>
<td>Nonoperated Hand</td>
<td></td>
</tr>
<tr>
<td>Smoothness</td>
<td>11</td>
</tr>
</tbody>
</table>
The peak grip strength on the operated side was 59% in the 4CF group compared to the nonoperated side (Table 3.19). The area under the force time curve compared to the nonoperated wrist was 58% in the 4CF group. The variability of force (SD of slope) was similar in the 4CF to the opposite hand (Table 3.19).

Table 3.15 Grip strength (Force time curves) variables in operated hand of patients with four-corner fusion and relationship to nonoperated hand.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Four corner fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Peak strength (Newtons)</td>
<td></td>
</tr>
<tr>
<td>(Operated)</td>
<td>165.1</td>
</tr>
<tr>
<td>(Nonoperated)</td>
<td>281.2</td>
</tr>
<tr>
<td>Area under the curve (Newton-seconds)</td>
<td></td>
</tr>
<tr>
<td>(Operated)</td>
<td>8776.9</td>
</tr>
<tr>
<td>(Nonoperated)</td>
<td>15312.3</td>
</tr>
<tr>
<td>Slope of curve (Operated)</td>
<td>-0.8</td>
</tr>
<tr>
<td>Standard deviation of slope (Operated)</td>
<td>9.7</td>
</tr>
<tr>
<td>Intercept (Operated) (Newtons)</td>
<td>126.7</td>
</tr>
<tr>
<td>Time (Operated) (Seconds)</td>
<td>52.4</td>
</tr>
</tbody>
</table>
The MHQ score, compared to the nonoperated wrist, was 77% in the 4CF group. PEM score was 48% nearly half of normal.

Table 3.16 Michigan Hand Questionnaire and Patient Evaluation Measure in patients with proximal row carpectomy.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Four-Corner fusion</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Range</td>
</tr>
<tr>
<td>Michigan Hand Questionnaire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Operated Hand)</td>
<td>70</td>
<td>18-99</td>
</tr>
<tr>
<td>(Nonoperated Hand)</td>
<td>91</td>
<td>55-100</td>
</tr>
<tr>
<td>Patient Evaluation Measure</td>
<td>48</td>
<td>17-82</td>
</tr>
</tbody>
</table>
The center of circumduction ellipse for a patient with a 4CF was located in the flexion and radial deviation area. The orientation of the plane of circumduction was more vertical after a 4CF the plane was more vertical (12°), which is closer to the plane of flexion-extension. The obliquity was clockwise or anticlockwise from the vertical flexion and extension plane depending on whether the left or right hand was assessed.

Figure 3.4 Circumduction curves (Lissajous’ XY figures) for four-corner fusion.
The width of the overlay green (acceleration) and red (deceleration) circles indicate the velocity of motion. The grey lines indicate the center of the axes.
The median time to complete the timed Sollerman hand function test with the affected hand was 241 seconds for 4CF patients. The 4CF patients unscrewed the lids with their affected hand significantly quicker (Table 3.33), which corresponds to a better spherical volar grip.
Table 3.17 Results, in seconds, to complete the subtasks of the modified timed Sollerman hand function test for the affected hand, and unaffected hand for patients with 4CF.

<table>
<thead>
<tr>
<th>Subtask</th>
<th>Median (SD) Affected</th>
<th>Median (SD) Unaffected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Put key into Yale lock, turn 90°</td>
<td>8.2 (9.2)</td>
<td>5.3 (7.1)</td>
</tr>
<tr>
<td>Pick coins from flat surface, put into purses mounted on wall</td>
<td>6.2 (5.3)</td>
<td>3.9 (3.0)</td>
</tr>
<tr>
<td>Open/close zip</td>
<td>10.9 (10.6)</td>
<td>9.4 (6.5)</td>
</tr>
<tr>
<td>Coins out of purse</td>
<td>9.4 (14)</td>
<td>6.3 (5.3)</td>
</tr>
<tr>
<td>Wooden blocks</td>
<td>5.3 (6.4)</td>
<td>4.4 (3.4)</td>
</tr>
<tr>
<td>Lift iron</td>
<td>5.2 (4.8)</td>
<td>3.1 (2.4)</td>
</tr>
<tr>
<td>Turn screwdriver</td>
<td>8.5 (4.3)</td>
<td>9.1 (10.0)</td>
</tr>
<tr>
<td>Nuts on bolts</td>
<td>28.9 (24.2)</td>
<td>26.5 (27.2)</td>
</tr>
<tr>
<td>Unscrew lids</td>
<td>13.6 (7.9)</td>
<td>16.5 (10.4)</td>
</tr>
<tr>
<td>Do up buttons</td>
<td>36.0 (33)</td>
<td>23.4 (23.2)</td>
</tr>
<tr>
<td>Cut Play-Doh</td>
<td>15.1 (15.3)</td>
<td>16.7 (24.9)</td>
</tr>
<tr>
<td>Put on Tubigrip on other hand</td>
<td>7.2 (7.0)</td>
<td>5.1 (7.5)</td>
</tr>
<tr>
<td>Writing+ Fold paper put in envelope+ Paperclip*</td>
<td>38.2 (30.4)</td>
<td>38.2 (20.4)</td>
</tr>
<tr>
<td>Pick up telephone</td>
<td>3.6 (3.4)</td>
<td>2.9 (4.2)</td>
</tr>
<tr>
<td>Turn door-handle</td>
<td>3.0 (2.7)</td>
<td>2.1 (2.2)</td>
</tr>
<tr>
<td>1L Pure-Pak to jug + jug to cup + cup to jug*</td>
<td>34.1 (24.3)</td>
<td>29.4 (19.2)</td>
</tr>
<tr>
<td>Total time to complete test</td>
<td>239.9 (170.0)</td>
<td>203.6 (32.8)</td>
</tr>
</tbody>
</table>

*I have combined subtasks 13-15 (writing, fold paper and put in envelope, and put paperclip on envelope) and subtasks 18-20 (pack to jug, jug to cup, and cup to jug) because they consisted of similar wrist movements, resulting in a total of 16 subtasks.
3.4 Proximal Row Carpectomy group

This mean age at the time of surgery for the patients with PRC was 51 years and there were 18 men and 4 women. Time since surgery was 47 months for patients with a PRC. (Table 3.14)

Table 3.18 Demographic characteristics of patients with proximal row carpectomy.

<table>
<thead>
<tr>
<th>Proximal row carpectomy</th>
<th>Mean (SD)</th>
<th>Count/ Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Age at surgery (years)</td>
<td>53 (11.6)</td>
<td></td>
</tr>
<tr>
<td>Age at Follow-up (years)</td>
<td>55 (11.9)</td>
<td></td>
</tr>
<tr>
<td>Time since surgery (months)</td>
<td>27.9</td>
<td>(6-47)</td>
</tr>
<tr>
<td>Immobilization in plaster (weeks)</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Hand dominance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Side of surgery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Side of surgery is dominant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>
Flexion-extension component in circumduction in the operated wrist was 65% of the nonoperated wrist after a PRC. The radioulnar deviation component in circumduction in the operated wrist was similar to the nonoperated wrist after a PRC. The mean area of circumduction of the operated wrist compared to the non-operated wrist was 58% after PRC. The circumference of circumduction compared to the nonoperated wrist was 63% after PRC (Table 3.15).

The orientation of the plane of circumduction was 22° to the vertical flexion extension plane after a PRC. The obliquity was clockwise or anticlockwise from the vertical flexion and extension plane depending on whether the left or right hand was assessed. The mean angle of plane of the circumduction ellipse of the opposite wrist was 13-14° to the vertical flexion extension plane (Table 3.15).
Table 3.19 Range of Circumduction variables in operated hand of patients with proximal row carpectomy.

<table>
<thead>
<tr>
<th>Range of Circumduction</th>
<th>Proximal row carpectomy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td><strong>Operated hand</strong></td>
<td></td>
</tr>
<tr>
<td>Flexion- extension in circumduction (degrees)</td>
<td>60.1</td>
</tr>
<tr>
<td>Radio ulnar deviation in circumduction (degrees)</td>
<td>28.9</td>
</tr>
<tr>
<td>Area of circumduction (degree-degrees)</td>
<td>1302.4</td>
</tr>
<tr>
<td>Circumference of circumduction (degrees)</td>
<td>149.5</td>
</tr>
<tr>
<td>Angle of Oblique circumduction plane</td>
<td>22</td>
</tr>
<tr>
<td><strong>Nonoperated Hand</strong></td>
<td></td>
</tr>
<tr>
<td>Flexion- extension (degrees)</td>
<td>91.9</td>
</tr>
<tr>
<td>Radio ulnar deviation (degrees)</td>
<td>55.3</td>
</tr>
<tr>
<td>Area of circumduction (degree-degrees)</td>
<td>3842.6</td>
</tr>
<tr>
<td>Circumference of circumduction (degrees)</td>
<td>238.9</td>
</tr>
<tr>
<td>Angle of Oblique circumduction plane</td>
<td>14</td>
</tr>
</tbody>
</table>
The mean velocity of wrist circumduction compared to the nonoperated wrist was 52% after PRC. The time taken to complete one wrist circumduction cycle was similar to the nonoperated wrist after a PRC. (Table 3.9)

Table 3.20 Velocity of Circumduction in operated hand of patients with proximal row carpectomy.

<table>
<thead>
<tr>
<th>Velocity of Circumduction</th>
<th>Proximal row carpectomy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td><strong>Operated hand</strong></td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>90.4</td>
</tr>
<tr>
<td><em>(degrees/second)</em></td>
<td></td>
</tr>
<tr>
<td>Velocity in flexion</td>
<td>84.6</td>
</tr>
<tr>
<td><em>(degrees/second)</em></td>
<td></td>
</tr>
<tr>
<td>Velocity in radial deviation</td>
<td>59.0</td>
</tr>
<tr>
<td><em>(degrees/second)</em></td>
<td></td>
</tr>
<tr>
<td>Velocity in extension</td>
<td>94.9</td>
</tr>
<tr>
<td><em>(degrees/second)</em></td>
<td></td>
</tr>
<tr>
<td>Velocity in ulnar deviation</td>
<td>58.7</td>
</tr>
<tr>
<td><em>(degrees/second)</em></td>
<td></td>
</tr>
<tr>
<td>Time taken for one cycle</td>
<td>1.7</td>
</tr>
<tr>
<td><em>(seconds)</em></td>
<td></td>
</tr>
<tr>
<td><strong>Nonoperated hand</strong></td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>172.2</td>
</tr>
<tr>
<td><em>(degrees/second)</em></td>
<td></td>
</tr>
<tr>
<td>Time taken for one cycle</td>
<td>1.5</td>
</tr>
<tr>
<td><em>(seconds)</em></td>
<td></td>
</tr>
</tbody>
</table>
The smoothness of movement of the wrist during circumduction (measured by number of zero-crossings per second) after a PRC was similar to the nonoperated side. (Table 3.10)

Table 3.21 Smoothness of Circumduction in operated hand of patients with proximal row carpectomy.

<table>
<thead>
<tr>
<th>Smoothness of Circumduction</th>
<th>Proximal row carpectomy</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Number of zeros per second)</td>
<td>Mean</td>
</tr>
<tr>
<td>Operated Hand</td>
<td></td>
</tr>
<tr>
<td>Smoothness</td>
<td>11</td>
</tr>
<tr>
<td>Smoothness Flexion</td>
<td>3</td>
</tr>
<tr>
<td>Smoothness Radial deviation</td>
<td>3</td>
</tr>
<tr>
<td>Smoothness Extension</td>
<td>5</td>
</tr>
<tr>
<td>Smoothness Ulnar deviation</td>
<td>1</td>
</tr>
<tr>
<td>Nonoperated Hand</td>
<td></td>
</tr>
<tr>
<td>Smoothness</td>
<td>11</td>
</tr>
</tbody>
</table>
In comparison to the nonoperated side, the peak grip strength on the operated side was 81% after a PRC. The area under the force time curve compared to the nonoperated wrist was 82% after a PRC. The variability of force (SD of slope) was similar to the nonoperated side in the PRC. (Table 3.11)

Table 3.22 Grip strength (Force time curves) variables in operated hand of patients with proximal row carpectomy

<table>
<thead>
<tr>
<th>Variable</th>
<th>Proximal row carpectomy</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Peak strength (Newtons)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Operated)</td>
<td>229.6</td>
<td>69.6</td>
<td></td>
</tr>
<tr>
<td>(Nonoperated)</td>
<td>284.2</td>
<td>97.3</td>
<td></td>
</tr>
<tr>
<td>Area under the curve (Newton-seconds)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Operated)</td>
<td>12835.5</td>
<td>3929.8</td>
<td></td>
</tr>
<tr>
<td>(Nonoperated)</td>
<td>15930.1</td>
<td>5461.8</td>
<td></td>
</tr>
<tr>
<td>Slope of curve (Operated)</td>
<td>-1.6</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Standard deviation of slope (Operated)</td>
<td></td>
<td>7.7</td>
<td>3.1</td>
</tr>
<tr>
<td>Intercept (Operated) (Newtons)</td>
<td>194.9</td>
<td>59.2</td>
<td></td>
</tr>
<tr>
<td>Time (Operated) (Seconds)</td>
<td>55.8</td>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>
The MHQ score was 92% of the nonoperated side after a PRC. PEM score after PRC was 27 but the range was quite wide (Table 3.20).

Table 3.23 Michigan Hand Questionnaire and Patient Evaluation Measure in patients with proximal row carpectomy.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Proximal row carpectomy</th>
<th>Median</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michigan Hand Questionnaire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Operated Hand)</td>
<td>87</td>
<td>61-100</td>
<td></td>
</tr>
<tr>
<td>(Nonoperated Hand)</td>
<td>95</td>
<td>78-100</td>
<td></td>
</tr>
<tr>
<td>Patient Evaluation Measure</td>
<td>27</td>
<td>14-40</td>
<td></td>
</tr>
</tbody>
</table>
The center of the circumduction ellipse for a patient with a PRC was in the extension and ulnar deviation quadrant (Figure 3.2). The orientation of the plane of circumduction was 22° to the vertical flexion extension plane after a PRC. The obliquity was clockwise or anticlockwise from the vertical flexion and extension plane depending on whether the left or right hand was assessed.

![Circumduction curves for proximal row carpectomy](image)

Figure 3.5 Circumduction curves (Lissajous’ XY figures) for proximal row carpectomy. They indicate the obliquity of the plane in proximal row carpectomy. The velocity of movement was faster after proximal row carpectomy, as indicated by the width of the overlay green (acceleration) and red (deceleration) circles. The grey lines indicate the center of the axes.
The median time to complete the timed Sollerman hand function test with the affected hand was 221 seconds in PRC patients. PRC patients were significantly quick in tasks 1, 2, 6, 9, 10, 12, 15 and 16, which corresponds to better function of the pulp pinch, the transverse volar grip, the combination of the pulp pinch and lateral pinch, the combination of the tripod pinch and the five-finger pinch, and the combination of the tripod pinch and the diagonal volar grip (Table 3.13).
Table 3.24 Results, in seconds, to complete the subtasks of the modified timed Sollerman hand function test for the affected hand, and unaffected hand for patients with PRC.

<table>
<thead>
<tr>
<th>Subtask</th>
<th>PRC Affected Median (SD)</th>
<th>PRC Unaffected Median (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Put key into Yale lock, turn 90°</td>
<td>5.0 (16.9)</td>
<td>4.3 (9.3)</td>
</tr>
<tr>
<td>Pick coins from flat surface, put into purses mounted on wall</td>
<td>4.0 (5.4)</td>
<td>3.7 (3.0)</td>
</tr>
<tr>
<td>Open/close zip</td>
<td>10.6 (26.9)</td>
<td>10.9 (12.5)</td>
</tr>
<tr>
<td>Coins out of purse</td>
<td>7.6 (13)</td>
<td>6.6 (10.0)</td>
</tr>
<tr>
<td>Wooden blocks</td>
<td>4.3 (6.6)</td>
<td>3.7 (4.1)</td>
</tr>
<tr>
<td>Lift iron</td>
<td>3.3 (3.7)</td>
<td>2.7 (2.2)</td>
</tr>
<tr>
<td>Turn screwdriver</td>
<td>8.8 (21.3)</td>
<td>9.6 (14.7)</td>
</tr>
<tr>
<td>Nuts on bolts</td>
<td>22.3 (70.1)</td>
<td>24.0 (38.3)</td>
</tr>
<tr>
<td>Unscrew lids</td>
<td>18.0 (40.6)</td>
<td>15.1 (21.6)</td>
</tr>
<tr>
<td>Do up buttons</td>
<td>24.0 (72)</td>
<td>20.6 (40.7)</td>
</tr>
<tr>
<td>Cut Play-Doh</td>
<td>15.1 (15.3)</td>
<td>16.7 (24.9)</td>
</tr>
<tr>
<td>Put on Tubigrip on other hand</td>
<td>5.1 (10.8)</td>
<td>4.1 (6.7)</td>
</tr>
<tr>
<td>Writing+ Fold paper put in envelope+ Paperclip*</td>
<td>34.1 (34.8)</td>
<td>44.2 (51.1)</td>
</tr>
<tr>
<td>Pick up telephone</td>
<td>3.0 (3.4)</td>
<td>2.5 (4.5)</td>
</tr>
<tr>
<td>Turn door-handle</td>
<td>2.1 (3.0)</td>
<td>1.8 (2.2)</td>
</tr>
<tr>
<td>1L Pure-Pak to jug + jug to cup + cup to jug*</td>
<td>28.8 (20.6)</td>
<td>28.8 (14.9)</td>
</tr>
<tr>
<td>Total time to complete test</td>
<td>205.4</td>
<td>198.0 (182.5)</td>
</tr>
</tbody>
</table>

* I have combined subtasks 13-15 (writing, fold paper and put in envelope, and put paperclip on envelope) and subtasks 18-20 (pack to jug, jug to cup, and cup to jug) because they consisted of similar wrist movements, resulting in a total of 16 subtasks.
3.5 Three-corner fusion group

Twelve patients with 3CF were included in the review. There were eight men and four women with a mean age of 60 (range 34-75) years at the time of follow-up who underwent surgery on 12 wrists. Five patients had surgery on the right wrist, which was their dominant hand, and seven had surgery on the left wrist of nondominant hand. (Table 3.24)

Table 3.25 Distribution of demographic variables between group of patients after Three-corner fusion and Four-corner fusion (Groups matched for Age and Gender)

<table>
<thead>
<tr>
<th></th>
<th>Three-corner fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Number</td>
<td>12</td>
</tr>
<tr>
<td>Age at Follow-up (years)</td>
<td>60 (10)</td>
</tr>
<tr>
<td>Age at Surgery (years)</td>
<td>55 (10)</td>
</tr>
<tr>
<td>Months since surgery</td>
<td>68</td>
</tr>
<tr>
<td>Sex</td>
<td>Male</td>
</tr>
<tr>
<td></td>
<td>Female</td>
</tr>
<tr>
<td>Hand Dominance</td>
<td>Right</td>
</tr>
<tr>
<td></td>
<td>Left</td>
</tr>
<tr>
<td>Side of Surgery</td>
<td>Right</td>
</tr>
<tr>
<td></td>
<td>Left</td>
</tr>
</tbody>
</table>
Total flexion-extension arc in the operated wrist was similar after a 4CF compared to a 3CF (p>0.05). However, radioulnar deviation arc in the operated wrist was greater after a 3CF compared to a 4CF, when the measurements were taken at extremes of flexion and extension (Table 3.27). This difference was not seen in the flexion extension or radioulnar deviation measurement taken during circumduction curves, when the wrist was held in a light fist. The mean area of circumduction of the operated wrist was similar after both a 3CF (1276ºº) and a 4CF (1233ºº). The circumference of circumduction was also similar after both operations (Table 3.25).

Table 3.26 Distribution of Circumduction Variables in the operated hand between patient after Three-corner fusion and Four-corner fusion

<table>
<thead>
<tr>
<th>Variable</th>
<th>Three-corner fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Flexion Extension arc</td>
<td>62.2 (18.2)</td>
</tr>
<tr>
<td>Radial-Ulnar deviation arc</td>
<td>38.3 (5.1)</td>
</tr>
<tr>
<td>Flexion Extension in Circumduction</td>
<td>53.9 (13.6)</td>
</tr>
<tr>
<td>Radial-Ulnar deviation in Circumduction</td>
<td>29.3 (10.3)</td>
</tr>
<tr>
<td>Area of Circumduction Ellipse</td>
<td>1276.0 (627.5)</td>
</tr>
<tr>
<td>Axis of Circumduction</td>
<td>19 (10)</td>
</tr>
<tr>
<td>Circumference of Circumduction</td>
<td>140.5 (38.3)</td>
</tr>
</tbody>
</table>
The mean velocity of wrist circumduction was faster after a 3CF than a 4CF. In addition, after a 3CF, the velocity was greater in all the quadrants of the ellipse, especially in flexion and ulnar deviation quadrants (Table 3.28). The smoothness of movement of the wrist during circumduction (measured by the number of zero points/ second) was greater after a 3CF compared to a 4CF in the flexion and ulnar deviation quadrants (Table 3.26).

Table 3.27 Distribution of Smoothness of Movement (NZRP) and Velocity in each quadrant of circumduction in operated hands for patients after Three-Corner fusion.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Three corner fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZP (Smoothness of Circumduction)</td>
<td>11 (7)</td>
</tr>
<tr>
<td>NZRP in Radial Deviation</td>
<td>3 (3)</td>
</tr>
<tr>
<td>NZRP in Extension</td>
<td>4 (3)</td>
</tr>
<tr>
<td>NZRP in Ulnar Deviation</td>
<td>2 (1)</td>
</tr>
<tr>
<td>NZRP in Flexion</td>
<td>2 (2)</td>
</tr>
<tr>
<td>Velocity of Circumduction</td>
<td>94.9 (53.3)</td>
</tr>
<tr>
<td>Velocity in Radial Deviation</td>
<td>26 (12)</td>
</tr>
<tr>
<td>Velocity in Extension</td>
<td>59 (25)</td>
</tr>
<tr>
<td>Velocity in Ulnar deviation</td>
<td>24 (15)</td>
</tr>
<tr>
<td>Velocity in Flexion</td>
<td>35 (16)</td>
</tr>
</tbody>
</table>
The peak grip strength after a 3CF was 170N. Similarly, the area under the force-time curve after a 3CF was 9030 Ns. (Table 3.27)

Table 3.28 Distribution of Grip Strength Variables in Force-Time Curves in the operated hand for patients after Three-corner fusion.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Three corner fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area under the Curve (Operated Hand)</td>
<td>9030.0 (3117.5)</td>
</tr>
<tr>
<td>Peak Force (Operated Hand)</td>
<td>170.5 (46.7)</td>
</tr>
<tr>
<td>Slope of Force Time Curve (Operated Hand)</td>
<td>-1.4 (0.9)</td>
</tr>
<tr>
<td>Intercept (Operated Hand)</td>
<td>143.4 (63.4)</td>
</tr>
<tr>
<td>Standard Deviation Detrended Line (Operated hand)</td>
<td>11.1 (8.3)</td>
</tr>
<tr>
<td>Time (Operated Hand)</td>
<td>53.8 (11.9)</td>
</tr>
<tr>
<td>Peak Force (Non-operated Hand)</td>
<td>207.4 (96.0)</td>
</tr>
<tr>
<td>Area under the Curve (Non-operated Hand)</td>
<td>11773.2 (5414.4)</td>
</tr>
</tbody>
</table>
The MHQ was higher in the unaffected hand compared to the operated hand, signifying better function (Table 3.28). The means PEM score after 3CF was 33.

Table 3.29 Distribution of Michigan Hand Questionnaire and Patient Evaluation Measure for patients with Three-corner fusion.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Three corner fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHQ Affected Hand</td>
<td>84</td>
</tr>
<tr>
<td>MHQ Unaffected hand</td>
<td>93</td>
</tr>
<tr>
<td>PEM Score</td>
<td>33</td>
</tr>
</tbody>
</table>
The center of the ellipse for a patient with a 3CF was close to the center of the centre of planes of motion (Figure 3.6). The orientation of the plane of circumduction was $19^\circ$ to the vertical flexion extension plane after a 3CF (Figure 3.6). The obliquity was clockwise or anticlockwise from the vertical flexion and extension plane, depending on whether the left or right hand was assessed.

Figure 3.6 Figure showing the circumduction curve (Lissajous' XY figure) for three-corner fusion.
The mean age for patients who had wrist arthrodesis for osteoarthritis was 58 years. Six were men and six women. In 11 patients, the right side was the dominant side and, in one patient, the dominant side was the left side. In six patients, the operated side was dominant and, in six patients, the operated side was the nondominant. (Table 3.29) The wrist fusion group was assessed for only grip strength as the wrists were completely fused with no motion across the radiocarpal joint.

Table 3.30  Demographic characteristics of patients with wrist osteoarthritis.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Dominant side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Affected side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>
The grip strength characteristics for patients with wrist arthrodesis for stage 2/3 SLAC and SNAC wrist are presented in Table 3.30. Two patients required removal of the AO plates due to pain and breakage of screws.

Table 3.31 Grip strength variables in patients with wrist fusion for stage 2/3 SLAC and SNAC wrist.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Wrist fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Area under force-time curve</td>
<td>8489.3</td>
</tr>
<tr>
<td>Peak force</td>
<td>161.0</td>
</tr>
<tr>
<td>Time</td>
<td>53.1</td>
</tr>
<tr>
<td>Intercept</td>
<td>125.9</td>
</tr>
<tr>
<td>Slope</td>
<td>-1.1</td>
</tr>
<tr>
<td>Mean force</td>
<td>95.6</td>
</tr>
</tbody>
</table>
Michigan hand questionnaire was 69% and PEM score was 42% in the wrist fusion group.

Table 3.32 Michigan Hand questionnaire and Patient Evaluation Measure for patients with wrist fusion

<table>
<thead>
<tr>
<th>Variable</th>
<th>Wrist Fusion</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Range</td>
<td></td>
</tr>
<tr>
<td>Michigan Hand Questionnaire (Operated Hand)</td>
<td>69</td>
<td>21-95</td>
<td></td>
</tr>
<tr>
<td>(Nonoperated Hand)</td>
<td>89</td>
<td>54-98</td>
<td></td>
</tr>
<tr>
<td>Patient Evaluation Measure</td>
<td>42</td>
<td>28-84</td>
<td></td>
</tr>
</tbody>
</table>
3.7 Comparison between groups

In this section, I have compared the range of motion and grip strength variables between normal volunteers, patients with wrist osteoarthritis (SLAC/SNAC wrist), four-corner fusion, three-corner fusion, proximal row carpectomy and total wrist fusion. Age at the time of surgery was similar in the groups although numbers are different in the groups (Table 3.31)
Table 3.33 Demographic characteristics of normal volunteers and patients with wrist osteoarthritis, four-corner fusion, wrist fusion, three corner fusion, and proximal row carpectomy.

<table>
<thead>
<tr>
<th>Study Groups</th>
<th>Normal volunteer</th>
<th>Wrist osteoarthritis</th>
<th>Four-corner fusion</th>
<th>Wrist fusion</th>
<th>Three Corner Fusion</th>
<th>Proximal Row Carpectomy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Mean</td>
<td>Count</td>
<td>Mean</td>
<td>Count</td>
<td>Mean</td>
</tr>
<tr>
<td>Number</td>
<td>100</td>
<td>16</td>
<td>24</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Age (years)</td>
<td>45</td>
<td>54</td>
<td>49</td>
<td>58</td>
<td>55</td>
<td>51</td>
</tr>
<tr>
<td>Sex</td>
<td>Male</td>
<td>50</td>
<td>10</td>
<td>17</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>50</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Dominant side</td>
<td>Right</td>
<td>88</td>
<td>14</td>
<td>22</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>12</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Affected side</td>
<td>Right</td>
<td>0</td>
<td>6</td>
<td>15</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>0</td>
<td>10</td>
<td>9</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>
Range of motion variables were similar amongst the surgical group but were nearly half of the range in normal volunteers. Wrist became slightly stiffer after surgery compared to patients with osteoarthritis before surgery. (Table 3.33)

Table 3.34 Range of motion variables in normal volunteers and patients with four-corner fusion, wrist osteoarthritis, three-corner fusion and proximal row carpectomy.

<table>
<thead>
<tr>
<th>Study Groups</th>
<th>Normal volunteer</th>
<th>Four Corner Fusion</th>
<th>Wrist osteoarthritis</th>
<th>Three Corner Fusion</th>
<th>Proximal Row Carpectomy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td>Flexion-extension</td>
<td>101.0&lt;sub&gt;a&lt;/sub&gt;</td>
<td>55.0&lt;sub&gt;b&lt;/sub&gt;</td>
<td>64.9&lt;sub&gt;b&lt;/sub&gt;</td>
<td>62.2&lt;sub&gt;b&lt;/sub&gt;</td>
<td>60.1&lt;sub&gt;b&lt;/sub&gt;</td>
</tr>
<tr>
<td>Radial-Ulnar deviation</td>
<td>64.2&lt;sub&gt;a&lt;/sub&gt;</td>
<td>31.1&lt;sub&gt;b&lt;/sub&gt;</td>
<td>36.0&lt;sub&gt;b&lt;/sub&gt;</td>
<td>38.3&lt;sub&gt;b&lt;/sub&gt;</td>
<td>28.9&lt;sub&gt;b&lt;/sub&gt;</td>
</tr>
<tr>
<td>Area of Ellipse</td>
<td>4613.4&lt;sub&gt;a&lt;/sub&gt;</td>
<td>1529.6&lt;sub&gt;b&lt;/sub&gt;</td>
<td>1993.0&lt;sub&gt;b&lt;/sub&gt;</td>
<td>1276.0&lt;sub&gt;b&lt;/sub&gt;</td>
<td>1302.4&lt;sub&gt;b&lt;/sub&gt;</td>
</tr>
<tr>
<td>Angle of Oblique Circumduction plane</td>
<td>19.8&lt;sub&gt;a&lt;/sub&gt;</td>
<td>12.6&lt;sub&gt;a&lt;/sub&gt;</td>
<td>14.2&lt;sub&gt;a&lt;/sub&gt;</td>
<td>19.1&lt;sub&gt;a&lt;/sub&gt;</td>
<td>22.1&lt;sub&gt;a&lt;/sub&gt;</td>
</tr>
<tr>
<td>Time for Circumduction cycle</td>
<td>1.7&lt;sub&gt;a&lt;/sub&gt;</td>
<td>3.9&lt;sub&gt;b&lt;/sub&gt;</td>
<td>1.9&lt;sub&gt;a&lt;/sub&gt;</td>
<td>2.7&lt;sub&gt;b&lt;/sub&gt;</td>
<td>3.9&lt;sub&gt;b&lt;/sub&gt;</td>
</tr>
<tr>
<td>Circumference of Circumduction</td>
<td>267.5&lt;sub&gt;a&lt;/sub&gt;</td>
<td>142.7&lt;sub&gt;b&lt;/sub&gt;</td>
<td>166.5&lt;sub&gt;b&lt;/sub&gt;</td>
<td>140.5&lt;sub&gt;b&lt;/sub&gt;</td>
<td>149.5&lt;sub&gt;b&lt;/sub&gt;</td>
</tr>
<tr>
<td>Velocity of Circumduction</td>
<td>185.4&lt;sub&gt;a&lt;/sub&gt;</td>
<td>58.1&lt;sub&gt;b&lt;/sub&gt;</td>
<td>99.7&lt;sub&gt;b&lt;/sub&gt;</td>
<td>94.9&lt;sub&gt;b&lt;/sub&gt;</td>
<td>90.4&lt;sub&gt;b&lt;/sub&gt;</td>
</tr>
<tr>
<td>Smoothness of Circumduction (NZRP)</td>
<td>11.0&lt;sub&gt;a&lt;/sub&gt;</td>
<td>34.8&lt;sub&gt;b&lt;/sub&gt;</td>
<td>11.8&lt;sub&gt;a&lt;/sub&gt;</td>
<td>11.6&lt;sub&gt;b&lt;/sub&gt;</td>
<td>11.0&lt;sub&gt;b&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

Note: Values in the same row not sharing the same subscript are significantly different at p< .05 in the two-sided test of equality for column means. This method of presenting significance was used, as there were multiple groups. Tests assume equal variances.
The two-dimensional Lissajous’ figures (circumduction ellipse) plotted using the results of the output from the electrogoniometer could display the difference between groups more significantly. The locations of the circumduction ellipses in the x-axis and the y-axis were different for the different surgical groups (Figure 3.7) compared to normal volunteers. The center of the circumduction ellipse for a patient with a PRC was in the extension and ulnar deviation quadrant, while the center of circumduction ellipse for a patient with a 4CF was located in the flexion and radial deviation area. The center of the ellipse for a patient with a PRC was closer to the center of the circumduction ellipse of the opposite wrist while it was not concentric with a nonoperated wrist in a patient with a 4CF. The center of the circumduction ellipse for Three-corner fusion and wrist osteoarthritis groups was nearly concentric with the normal volunteers. (Figure 3.7)
Figure 3.7 Circumduction curves (Lissajous’ XY figures) of the surgical groups overlaid on the circumduction curve of a normal volunteer, showing the difference in the area of circumduction.
The peak grip strength showed no difference between surgical groups and also for patients with wrist osteoarthritis before surgery but area under the curve showed that PRC group had highest sustainability but was 80% of normal volunteers. Other grip strength variables were identical between groups. (Table 3.33) However difference could be identified on graphical overlay of these curves to allow comparison with normal volunteers.

Table 3.35 Grip Strength variables in normal volunteers and patients with four-corner fusion, wrist osteoarthritis, three-corner fusion and proximal row carpectomy.

<table>
<thead>
<tr>
<th>Study Groups</th>
<th>Normal volunteer</th>
<th>Four Corner Fusion</th>
<th>Wrist osteoarthitis</th>
<th>Three Corner Fusion</th>
<th>Wrist Fusion</th>
<th>Proximal Row Carpectomy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Area under force-time curve</td>
<td>15709.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7769.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7129.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9030.0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>8489.3&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean</td>
<td>Peak Force</td>
<td>283.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>152.9&lt;sup&gt;b&lt;/sup&gt;</td>
<td>161.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>170.5&lt;sup&gt;b&lt;/sup&gt;</td>
<td>161.0&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean</td>
<td>Time</td>
<td>55.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>50.4&lt;sup&gt;b&lt;/sup&gt;</td>
<td>55.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>53.8&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>53.1&lt;sup&gt;a,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean</td>
<td>Intercept</td>
<td>210.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>113.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>138.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>143.4&lt;sup&gt;b&lt;/sup&gt;</td>
<td>125.9&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean</td>
<td>Slope</td>
<td>-2.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.8&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-1.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-1.4&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>-1.1&lt;sup&gt;a,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean</td>
<td>Mean Force</td>
<td>148.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>89.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>102.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>107.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>95.6&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Note: Values in the same row not sharing the same subscript are significantly different at \( p < .05 \) in the two-sided test of equality for column means. This method of presenting significance was used, as there were multiple groups. Tests assume equal variances.
Figure 3.8 Overlay of the Force time curves in normal volunteers and patients with four-corner fusion, wrist osteoarthritis, three-corner fusion and proximal row carpectomy.
4 Discussion

4.1 Development of Techniques

I firstly developed the technique of dynamic measurement of the range of motion of the wrist with biaxial electrogoniometer to measure rate, rhythm and range of circumduction. I used a flexible electrogoniometer with a twin axis sensor to measure the relative angles between the 2 end blocks while the subject performed maximum excursion of flexion-extension, radio-ulnar deviation, and circumduction of the wrist held in a standardized, fully pronated position. A software package was used to further analyse the characteristics of the circumduction curves such as the shape, size, rate, smoothness, and orientation.

Measurement of the extremes of flexion-extension and radio-ulnar deviation of the wrist joint provides a limited picture of the static ability of the joint. It is also difficult to ascertain the relationship between the function of a complex joint like the wrist and these 2-dimensional measurements (Tomaino et al., 1994). In the human wrist, circumduction provides a more accurate representation of the capacity of the wrist function (Ojima et al., 1992, Rawes et al., 1996) as it combines flexion, extension, and radio-ulnar deviation into a circular motion without simultaneous supination or pronation of the forearm. This coupling of motion is vital in activities of daily living.

Currently, the most widely used assessment tools for measuring circumduction include biaxial electrogoniometers, which are valid and reliable in measuring the range of circumduction (Ojima et al., 1991). However, these have not been used to assess the velocity or the smoothness of wrist circumduction (Rawes et al., 1996). Previous studies indicate that wrist disease or pain may affect a specific quadrant of wrist circumduction (Ojima et al., 1991, Nagy and Buchler, 1997), while ageing
mainly affects the radio-dorsal quadrant of wrist circumduction (Ojima et al., 1992). Nonetheless, these studies have not measured the differences in motion in each of the quadrants of circumduction in normal volunteers, so a comparison is not possible with disease conditions. These differences could be in the velocity or smoothness of movement (Ojima et al., 1992) in the quadrants of wrist circumduction.

The biometric electrogoniometer has previously been used to quantify the range of circumduction (Ojima et al., 1992, Salvia et al., 2000) of the wrist. The current study also measured the velocity and smoothness of circumduction in the quadrants of the wrist. This is important, as wrist disease or pain may affect a specific quadrant of wrist circumduction (Ojima et al., 1991, Nagy and Buchler, 1997). Wrist partial fusions, like four-corner fusion and radioscapolunate fusion tend to limit motion in some quadrants of wrist motion, and the new methods discussed in this thesis could be used to compare with preoperative measurements. This also allows the visual presentation of the physiologic axis of wrist motion (Taleisnik, 1985, Wolfe et al., 2006). This axis is vital in activities of daily living and is in an oblique plane (Moritomo et al., 2007, Palmer et al., 1985) rather than in the traditional flexion-extension or radio-ulnar deviation axis.

I also designed the experimental set-up to study grip strength with a digital dynamometer to measure the peak strength, variability and sustainability of grip. The subject was asked to exert maximum grip and sustain it for 60 seconds. This allowed assessment of peak grip strength and endurance of the hand. Data collected were also processed with a software package. The variables derived from the trace were peak force, slope of the force time curve, area under the curve, and SD of the fitted line.

Grip strength is used as a measure of the functional capacity of the hand, but the rate of development of maximum grip is considered a more
sensitive indicator of hand dysfunction than maximum grip strength itself (Myers et al., 1980). In addition, the change in the rate of development of grip serves as a better discriminator in measuring the response of patients to drug therapy (Palmer et al., 1981). The power generated during grip provides more information about hand function than maximum grip strength alone (Palmer et al., 1981).

The force-time curves have previously been used to study rheumatoid hands (Helliwell et al., 1988) and to discriminate between sincere efforts and faked weakness (Smith et al., 1989). Maximum grip strength, time to maximum, rate of loss of grip from maximum (fatigue rate) and the integral of the curve (power factor) have been used also to study the difference between diseased and normal hands. I have extended the use of force-time curves to characterise differences between normal volunteers and patients with wrist osteoarthritis. Rheumatoid hands are remarkably weak hands and I felt that the study of force variability in the plateau region of the curve could be used to distinguish between weak, deformed hands and this would give us a good understanding to extrapolate the method to patients with wrist osteoarthritis.

I further developed the Sollerman hand function test to measure the time taken to complete each task to design the timed Sollerman hand function test. I investigated whether measuring the time taken to complete each of the Sollerman tasks can identify differences in hand function in a normal population.

The Sollerman hand function test was proposed to assess seven common grips used during 20 everyday activities of daily living (Sollerman and Ejeskar, 1995). The original Sollerman test has been validated and found to be reliable for use in tetraplegic patients (Sollerman and Ejeskar, 1995). However, among the high-level tetraplegic patients, especially those without sensation, the original authors felt that the test may not identify small differences. This could be due to the 5-point ordinal scale that
makes it difficult to score reliably (van Tuijl et al., 2002). Moreover, the results in less severe injuries (Lindqvist et al., 2011, Lindqvist and Nilsson, 2010) or in severe incapacity (Weng et al., 2010, Limaye et al., 2001) could be misleading. While the test can resolve broad functional differences across groups of patients, it may not detect differences within specific populations, as the description of the data on a 5-point scale causes a loss of significant amounts of information. If this method were employed on our volunteers, all would have scored 79-80 with both the dominant and nondominant hand. But our results have demonstrated that, when measuring the actual time taken to complete the Sollerman tasks, I were able to identify smaller differences in hand function between volunteers, when the original technique of the 5-point scale demonstrated a ceiling effect at 80 points.

The Sollerman test is based on seven of the eight handgrips used during the activities of daily living. Each of the 20 tasks requires a different type of handgrip and some tasks require more than one type of grip (Table 3.31). Four handgrips are used for tasks requiring precision (pulp pinch, lateral pinch, tripod pinch, five-finger pinch) and three are used for tasks needing power (diagonal volar grip, transverse volar grip, spherical volar grip). I calculated the percentage of time spent on each of the handgrips in the video assessment of the volunteers performing these tasks (Table 3.6). Our volunteers took less time to perform tasks requiring both precision and power with the dominant hand than with the nondominant hand (Table 3.9).

4.2 Application to Normal Volunteers

I applied these three techniques of assessment of range of motion, grip strength and Sollerman hand function test to normal volunteers. Firstly, the range of motion assessment with electrogoniometers was assessed in Normal volunteers. The aim was to describe the measurement of range of
active circumduction of the wrist in normal volunteers with the use of a flexible electrogoniometer, develop summary descriptors of the data, and to quantify the velocity and smoothness of circumduction. I also wished to explore the oblique functional plane of wrist circumduction and establish the reproducibility and reliability of these measures of circumduction. Normal values for wrist arc of motion vary widely in the literature, ranging from 100° to 151° in flexion-extension (Rawes et al., 1996, Palmer et al., 1985, Leonard et al., 2005), and from 40° to 88° in radio-ulnar deviation (Palmer et al., 1985). This variation may be due to the differences in finger posture in different studies, or due to differences in the populations studied. In this study, the calculation of the range of motion with the biometric electrogoniometer was carried out with the patient’s forearm in full pronation and the hand gently clenched. Hence, the range is slightly less than measurements with fingers held straight (Gehrmann et al., 2008).

The mean area of circumduction curve was around 4700°, and it was similar in both hands. This is comparable to a previous study (Rawes et al., 1996). Our method also allowed calculation of the skew and obliquity of the plane of the circumduction curve in normal volunteers. This oblique plane of circumduction lies at an angle of 28° to the vertical flexion and extension axis, although it has a large variability (SD 16°). This axis inclines slightly from dorsal and radial to palmar and ulnar and represents the physiological axis of wrist activity (Taleisnik, 1985). This could correspond to the dart thrower’s arc of motion that was postulated to represent an important functional plane of motion (Wolfe et al., 2006, Crisco et al., 2005). This technique could allow measurement of the effect of different surgeries, like the radioscpapholunate arthrodesis on the dart-throwing movement (Calfee et al., 2008) before and after surgery.

The velocity and the time measurements presented in this study reflect the natural motion of wrist circumduction and enable a dynamic analysis. This method graphically represents the area of circumduction of the wrist, and
velocity can be overlaid onto the curve to represent the changes in velocity of circumduction. Volunteers were asked to circumduct the wrist at a comfortable speed, rather than a maximum speed, to allow maximum range. I wanted to develop the method of data analysis to measure velocity and acceleration during circumduction and to compare speed in the quadrants. Velocity in circumduction had been partly analysed in the past, but emphasis in the previous study (Ojima et al., 1991) was on the range of motion. It also showed that the speed becomes slower in maximum flexion and maximum extension. Smoothness assessment presents additional practical information on wrist movement. Another study (Hansson et al., 1996) on smoothness assessment involved the calculation of ‘pauses’, as occasions where angular velocity was below 1°/s for a continuous period of at least 0.5 s. I looked at changes in direction of acceleration signal and identified the zeros where acceleration changed from negative to positive, or vice versa. I wished to understand the velocity and smoothness of one activity in normal volunteers that was used to compare with patients. During circumduction, there were more zeros in flexion and extension than in radio-ulnar deviation quadrants due to the change in direction of motion. The visual representation with green and red overlay circles indicating acceleration and deceleration could allow easier comparison between patients and enable a better understanding of the quadrant where the impact of any pathology is noteworthy. I speculate that patients with ulnar-sided pain would have reduced range in the ulnar deviation quadrant, with associated reduction in velocity and smoothness.

Further, I assessed the sustainability of grip strength with digital dynamometer using force-time curves and applied it to normal volunteers. In the study I performed on patients with rheumatoid hand deformities, I had found that peak force alone might not give a complete assessment of the mechanical capacity of the diseased hand. The area under the curve may be a better measure of assessing sustainability of grip and can
differentiate between hands with weak peak force but greater sustainability and hands with greater peak force but shorter duration of grip. It correlated well with the peak and average grip strength and reveals the same trend of decreasing area with worsening finger deformity (Figure 3.22). The small area under the curves confirms the marked weakness caused by swan neck and combined deformities (Table 3.25). Overlaying the curves gives the best visual impression of the differences between the deformity groups. In clinic, the peak force still remains the easier summary assessment of the hand, if correct equipment is available; however, when conducting research, force-time curves give a better understanding of capacity.

In Normal Volunteers, the peak grip strength was greater in the dominant hand than nondominant hand by 10% and similarly the area under the force-time curve was also greater in the dominant hand (13144 Ns) compared to the nondominant hand (11097Ns). Dominant hands showed a greater drop in strength over 60 seconds as the slope was steeper. The variability of force (SD of slope) was similar in both hands. Area under the Force Time curve was also found to be a better predictor of hand function.

Finally I applied the timed Sollerman Hand function test to the normal volunteers. Our assessments have shown that using the actual time taken to perform the Sollerman hand function test can identify differences between the dominant and the nondominant hand. The original authors mention that volunteers with normal hand function achieve a score of 80 with the dominant hand, and from 77 to 79 with the nondominant hand. Other hand function tests (Jebsen et al., 1969, Michimata et al., 2008) also indicate that volunteers with normal hand function perform better with the dominant hand. However, using the timed Sollerman test shows that the dominant hand performs grip and pinch tasks quicker than the nondominant hands.
The change in the total time taken to complete all 20 tasks with age was similar to the observations made for other assessments. Klum et al. (Klum et al., 2012) found that the grip strength and pinch strength reached a maximum for volunteers between 30 and 49 years of age and then decreased with age. Werle et al. (Werle et al., 2009) also found a similar curvilinear relationship with grip strength increasing with age, peaking between 35 and 39 years in men, and between 40 and 44 in women and then declining in both sexes. I found that this effect was more marked in the dominant hand in women. Wrist movement has not shown a similar pattern and it was best in volunteers between 18 and 29 years (Klum et al., 2012, Gunal et al., 1996). Data are not available regarding change in function with age for the Sollerman hand function test. However, other hand function tests have found a decline in function with age in both men and women (Michimata et al., 2008, Agnew and Maas, 1982).

The timed Sollerman hand function test can identify differences based on gender. If all ages and both hands were analysed together, there would be no difference between men and women for the total time taken to complete all the Sollerman tasks. However, with the nondominant hand, women took longer to lift the iron and the wooden blocks over the 5 cm edge. In the Australian version of Jebsen's Test of Hand Function, a similar pattern was seen when men performed better at "moving large heavy objects" and "large light objects", while women were better at "writing" and were generally better in "manipulating small objects" (Agnew and Maas, 1982). Using the time taken to perform each individual task, gender differences between tasks requiring precision and power could be identified, showing that men could perform the power tasks faster than women (Werle et al., 2009).

I found that the time taken to perform the test reflected the volunteer’s handedness. Handedness is defined as a volunteer’s preference to use one hand predominantly for tasks, and reflects the ability to perform these
tasks more efficiently with that hand (Corey et al., 2001). Handedness can be measured using a questionnaire. In ambidextrous volunteers, the time taken to complete the tasks with the dominant and nondominant hands was similar. However, individuals who are right-handed took less time to complete tasks with their dominant hand compared to the nondominant hand. In this study, the presented centile curves could allow investigators to check if any observation of change in hand function is due to expected age-related changes, or due to a true change caused by the disease or its treatment (Figure 3.10 & 3.11).

4.3 Application to Patients with Wrist Osteoarthritis

Finally, I applied the techniques of assessment to patients of wrist osteoarthritis (SLAC and SNAC wrist) before surgery and after four-corner fusion, proximal row carpectomy, three-corner fusion, and total wrist fusion to identify the impact of these procedures on the range of motion, grip strength and hand function compared to the normal volunteers.

Four-corner fusion (4CF) for patients with SLAC and SNAC wrists has been reported to consistently lead to good function after fusion with satisfactory pain relief. (Bain and Watts, 2010) However this study indicates that surgery may not improve range of motion or grip strength. In this project, I found that the patients with wrist osteoarthritis (SLAC and SNAC wrist) had identical range of motion variables (area of circumduction, 1992°°) to patients with 4CF (area of circumduction curve, 1233°°). The range of motion for patients with wrist osteoarthritis was nearly 50% of normal volunteers (4613°°). The flexion-extension, radio-ulnar deviation was similar for patients with wrist osteoarthritis and 4CF. There was no difference in grip strength variables after 4CF (Area under the force time curve, 8777N) but peak strength for SLAC/SNAC cohort (7128N) was nearly half of normal volunteers (15709N). Similarly there was no difference in grip strength between patients after wrist arthrodesis (total radiocarpal fusion) and four-corner fusion (4CF). The grip strengths
were similar between groups with four-corner fusion, wrist osteoarthritis and wrist arthrodesis (total radiocarpal fusion). This could be due to small number of patients of wrist osteoarthritis (12 patients) but the number of patients undergoing fusion for wrist osteoarthritis is small and this procedure is reserved for only late stages of disease. But this finding could help counsel patients of improvement in outcome after 4CF but grip strength and range of motion may not change after surgery.

In this study, the flexion-extension arc of the operated wrist was greater after a PRC than after a 4CF, however, the radio-ulnar deviation arc was reduced after a PRC compared to a 4CF. This conforms to the findings of biomechanical studies (Sobczak et al., 2011), where the difference in the arcs of curvature of the lunate facet and head of capitiate limits the radiocapitate motion to mainly translation in the flexion and extension plane. Assessment of patients who underwent 3CF showed that they significantly better range of radioulnar deviation compared to 4CF but it was similar to patients with PRC (p=0.45). Similarly, the area and circumference of circumduction was similar in patients after a 4CF, a 3CF or a PRC. If only the extremes of flexion extension and radio-ulnar deviation are considered, a PRC would show a greater range of motion, but the total capacity of circumduction is similar after either a 3CF, a 4CF or PRC.

Representation of wrist motion as circumduction also allowed calculation of the skew and obliquity of the plane of the circumduction ellipse (Singh et al., 2011). This ellipse lies at an angle to the vertical flexion and extension plane. It inclines from dorsal and radial to palmar and ulnar and could represent the physiological axis of wrist motion (Taleisnik, 1985). This corresponds to the dart thrower’s arc of motion, which is postulated to represent an important functional plane of motion (Wolfe et al., 2006, Crisco et al., 2005). The orientation of the oblique plane of the circumduction ellipse was 22° for patients with a PRC, which is identical to the plane in normal volunteers (Singh et al., 2011). The axis of
circumduction in the 3CF group was 19° versus 9° in the 4CF group (p=0.03), which is also closer to the normal wrist axis (23°) and represents the dart thrower’s axis of motion. However, the ellipse was closer to the vertical flexion extension plane for patients with a 4CF (9°), suggesting that these patients lack motion in the oblique dart-throwing functional plane (Singh et al., 2011) (Figure 3.17). The midcarpal joint allows most of the dart thrower’s motion, and it is fused in a 4CF.

The centre of the circumduction ellipse for a patient with a 3CF was 6° of extension and 4° of radial deviation, compared to the 4CF of 12° flexion and 8° of radial deviation and for PRC was 8° extension and 11° of ulnar deviation. The centre of the circumduction ellipse of the PRC was closer to that of the normal wrist (10° extension, 8° ulnar deviation). Previous studies indicate that wrist disease or pain may affect a specific quadrant of wrist circumduction (Nagy and Buchler, 1997), and most activities of daily living are performed in specific arcs of wrist motion (Ryu et al., 1991). The change in locations of the circumduction ellipses after the three operations (Figure 3.14) could have an impact on activities of daily living.

Measurement of the velocity of circumduction of the wrist indicates that the dynamic capacity of the wrist is better after a PRC compared to 4CF and 3CF. The time taken to complete one cycle of circumduction and smoothness of movement was also significantly better after a PRC, indicating that it is better at retaining the rate and rhythm of movement than a 4CF. The dynamic measurements of wrist circumduction demonstrate that the 3CF wrist moves faster and smoother than the 4CF but were identical to PRC.

I found that peak grip strength is similar in the different surgical groups; however, when the patients were asked to perform a maximum grip for 60 seconds, the sustainability, as indicated by the area under force curve, was greater after a PRC (Table 3.19). The dorsal impingement from the plate in patients with a 4CF could be responsible for the reduced grip
strength, as these patients had limited extension compared to patients with a PRC. The 3CF restored more grip strength compared to the contralateral side (82% vs 59%). However the area under the curve was higher in the group after a PRC compared to other two groups. Bain reported that volunteers had greater grip strength in extension, and that the mean position to achieve maximal strength was 28 degrees of extension. (Bain and McGuire, 2012) The PRC provides greater wrist extension, which would utilise this biomechanical advantage of wrist extension.

The Michigan hand questionnaire allows assessment of both right and left hands individually and it has previously been used after 4CF surgery (Chung et al., 2006). In our groups, the MHQ score for the operated hand was higher after a PRC than a 4CF, with higher scores in activities of daily living and satisfaction but similar pain scores in the two groups. The 3CF had significantly better outcome using the MHQ, including the sub-scores for activities of daily living (P=0.05), pain (P=0.001), and satisfaction (P=0.03) compared to 4CF. The difference between PRC and 3CF was not significant. No differences were observed in MHQ score for the nonoperated sides of the three groups. The mean PEM score was different for 3CF compared to 4CF however, the difference did not reach significance (P=0.38). The mean PEM score was lower after a PRC, while the patients with a 4CF have particular difficulty with fiddly activities. PEM score after PRC was slightly higher after 3CF but did not reach significance.

I used Sollerman hand function test to objectively assess wrist and hand function in patients with 4CF and PRC. I could not perform the test on the patients with 3CF as I was unable to take the Sollerman equipment to Australia due to restriction on transporting wood items to Australia from other countries. Assessment of the ADL was previously carried out by questionnaires, but this may result in the wrong conclusions. Adams et al.
found that measured function loss, with both physical test and questionnaires, may be less than the perceived disabilities (Adams et al., 2003). The Sollerman hand function test was originally developed for tetraplegic patients. Using the original test in our patient group would have given a limited view on the ability to complete activities in daily living, because the patients in these groups are much quicker than tetraplegic patients. If the original test was used in the PRC and 4CF group, the Sollerman score would have been the same. The modified timed Sollerman hand function test gives much more information about the ability to perform tasks in ADL.

Different studies showed that the ability to perform ADL is related to specific arcs of wrist motion (Ryu et al., 1991, Brumfield and Champoux, 1984, Murgia et al., 2004). 4CF provide a larger radio-ulnar deviation arc compared to the PRC who, instead, have a better flexion-extension arc and the position of the ellipse of circumduction is more similar to an unaffected hand. Nichols et al. (Nichols et al., 2013) examined the torque needed to maintain functional postures by comparing kinematic computer models of PRC and 4CF wrists. They found that PRC wrists required less torque than 4CF wrists, even compared to normal wrists. PRC patients are, therefore, expected to be less limited in performing most activities of daily living than 4CF patients.

In our study, most activities of daily living were performed quicker by the PRC patients compared to 4CF patients. An exception was the “opening jars” task, which was performed quicker by the 4CF patients compared to the PRC patients. For this task, a large wrist torque is required. The Michigan hand questionnaire (MHQ) and the patient evaluation measure (PEM) confirmed our findings by showing that patients experienced less disabilities during activities of daily living and more satisfaction after a PRC compared to an 4CF.
The findings in this dissertation indicate that patients with PRC have better range of flexion extension, grip strength and function compared to 4CF and are similar to patients with 3CF. However long-term clinical outcomes after PRC are not well-characterized. Radiographic follow-up reveal joint narrowing and arthritic changes within the radiocapitate joint (Ali et al., 2012) but PRC could continue to provide a high level of satisfaction and function in long term. (Wall et al., 2013) In the recent studies, Lunocapitate fusion has been identified to give better range of motion compared to four-corner fusion in the long term (Ferreres et al., 2009) as the triquetrum is not fused and during ulnar deviation, it rotates into extension and translates distally and medially along the helicoidally shaped articular surface of the hamate. In addition, as lunate is preserved and it articulates with radius in lunocapitate fusion, compared to proximal row carpectomy, this procedure is expected to preserve the cartilage in the radiocarpal joint over long term. (Ferreres et al., 2009) However, the results have not been compared to proximal row carpectomy. I plan to conduct a future randomised controlled trial between lunocapitate fusion and proximal row carpectomy with the outcome variables presented in this dissertation with results compared over the long term.
The key highlights of this dissertation are:

1. In Normal Volunteers, the mean area of circumduction (4729°°) and circumference (265°) of the circumduction curve indicates the total range of circumduction. The velocity of circumduction (mean 179°/s) and the time (1.6s) taken to complete one cycle of circumduction were similar in both dominant and non-dominant hands. The four quadrants for the velocity of circumduction showed that the velocity was faster in the radio-ulnar deviation quadrants compared to flexion and extension. Quadrant analysis also showed that the smoothness was greater in the radio-ulnar deviation quadrants compared to the flexion and extension quadrants. The oblique planes of the circumduction curves of all the normal wrists lie in an ulno-palmar and radio-dorsal direction, with a mean angle of 28° to the vertical flexion and extension plane.

2. Volunteers completed the tasks 20 seconds quicker with the dominant hand than with the nondominant hand. Women took less time to complete all the tasks in the 30-40 years age group than women in the 20-30 years age group and beyond 40 years using the dominant hand. Men also showed worsening with age. Individuals who were right-handed took less time with the dominant hand. The timed Sollerman hand function test can identify differences in hand function, which worsens with age in the dominant hand.

3. Patients with wrist osteoarthritis (SLAC and SNAC wrist) had identical range of motion variables (area of circumduction, 1992°°) to patients with after surgery (area of circumduction curve, 1233°°). The range of motion for patients with wrist osteoarthritis was nearly 50% of normal volunteers (4613°°). Peak strength for SLAC/SNAC cohort (7128N) was nearly half of normal volunteers (15709N).
4. The mean area of circumduction of the operated wrist was similar after a PRC (1302°), a 3CF (1276°) and a 4CF (1233°). The mean area under the force time curve of the operated wrist was slightly higher after a PRC (12835N), similar a 4CF (7769N), a 3CF (9030N). The center of the ellipse for a patient with a 3CF was closer to the center of the circumduction ellipse of the opposite normal wrist. The mean velocity of wrist circumduction was faster after a 3CF than a 4CF. In addition, after a 3CF, the velocity of wrist motion was greater in all the quadrants of the circumduction ellipse, especially in flexion and ulnar deviation quadrants. The smoothness of movement of the wrist during circumduction (measured by the number of zero points per second) was greater after a 3CF compared to a 4CF in the flexion and ulnar deviation quadrants. PRC patients completed the timed Sollerman hand function test significantly quicker than the 4CF patients (221sec. vs. 241sec., p=0.007). PRC patients performed most tasks (8 of the 16) significantly quicker than 4CF patients. PRC patients reported better function during ADL compared to 4CF patients (P <0.001).

5. The center of the circumduction ellipse for a patient with a PRC was closer to that of the opposite nonoperated wrist. The orientation of the plane of circumduction was 22° to the vertical flexion extension plane after a PRC but after a 4CF, the plane was more vertical (9°). The peak grip strength and the area under the force-time curve were greater after a PRC than after a 4CF. The MHQ was higher after a PRC than after a 4CF.
There are limitations in this study. I looked at only the circumduction of the wrist in a standardised position of the wrist in normal volunteers and not during daily activities. The crosstalk error between fixed and flexible electrogoniometers is worse when forearm rotation is allowed. The premise in the study was to allow an analysis of the data in one standard position and to minimise errors. Although the crosstalk was limited during the manufacturing process, the specification for crosstalk is +/- 3 degrees measured over a range of 60 degrees. This has to be identified as an insignificant source of error, as measurements were taken in a standard position where minimal rotation was allowed between goniometers. It can be argued that the volunteers were not asked to move their wrists at a maximum velocity; however, at this stage, the study aim was to allow analysis of the data for velocity and smoothness and gauge reliability of these assessments.

Differences between the groups could be due to their small numbers. Many patients were unable to attend research clinics. I were limited by the conditions of the ethics approval that prevented us from approaching patients unless they agreed to participate in the study. Preoperative range of movement could have an effect on the postoperative range after surgery (Lizaur et al., 1997), but complete information was not available in our cases for inclusion in this work. Moreover, the research aim for this study was to perform a comparison of outcomes after either of the procedures. The difference in range of motion could be explained by the longer immobilisation in a plaster cast required after a partial wrist fusion. The study populations were from different institutions, so the differences could be due to surgeon factors or differences in study populations. Nonetheless, there were no differences in grip strength or range of motion in contralateral nonoperated wrists and the patients in the study populations were similar in demographic variables. The time since surgery was significantly greater after four-corner fusion (72 months) compared to
proximal row carpectomy (24 months). The function results could deteriorate with time after surgery. Previous studies have indicated that the outcome of four-corner fusion (Bain and Watts, 2010) and proximal row carpectomy (DiDonna et al., 2004) may not deteriorate significantly up to 10 years after surgery.

The Normal volunteers were drawn from only one region of the country. The number of left-handed individuals in our group, reflecting the general population, is small; therefore, the difference based on dominance for left-handed individuals may not be representative. I have not assessed the repeatability of the timed Sollerman hand function test. However, the original Sollerman test is reliable and I have only omitted the categorisation of time data into ordinal scale, thus losing information.
6 Future Directions

This thesis assessed wrist function and disability in patients with wrist osteoarthritis before and after surgery. I assessed the range of motion and grip strength in normal volunteers and patients with wrist osteoarthritis with innovative techniques. It has potential for further applications based on clinical need and further biomechanical advancements. The potential applications are outlined in this chapter.

6.1 Clinical Interfaces

These techniques can be developed for clinical settings. At present, these are more adopted to laboratory work due to the time required to apply the equipment and unfamiliar output format. This can be modified to visually display the output of both range of motion and grip strength in a figure that presents the total capacity of the wrist, and allows it to be overlaid with results from previous visits to the clinics over time at the touch of a button. This could show changes in a patient’s capacity over time before and after surgery.

The use of newer techniques of three-dimensional visualisation of the wrist in space with two cameras with Microsoft Kinect, or other similar equipment, could make it adaptable to clinical settings. This, however, requires further collaboration between engineers and medical practitioners to encourage the adoption of motion measurement techniques.

6.2 Motion display

The development of range, rate and rhythm measurement of wrist motion with an electrogoniometer can be adopted to other patient groups, such as wrist arthroplasty and lunocapitate fusion, to discern differences from these groups. This could also be used to develop the wrist arthroplasty
design to capture real time motion and improve longevity of the artificial joint.

These techniques can allow the capture of data during real time activities of daily living, like the Sollerman hand function test, when electrogoniometry can be used to study the movements of the wrist during day-to-day tasks. The aim could be to measure the functional range of the dart-throwing movement of the wrist during daily activities using directional analysis. Dart throwing is a coupled motion that moves through an arc from radial deviation and extension to ulnar deviation and flexion. However, quantification of this movement has been difficult and requires complex cross-sectional radiological techniques.

6.3 Analysis of the acquired data

I have presented the grip strength, range of motion and Sollerman hand function data for 100 normal volunteers that can be used as a reference work for future studies. Further data analysis could be considered to discern if, from our data, a shorter version of the timed Sollerman hand function test can be developed that would reflect the score for 20 tasks. The question could be whether fewer tasks would produce an equally effective objective assessment of hand function, as this will make the test less cumbersome to administer. The Sollerman test can be adapted further to reduce tasks by including the best task for each of the seven grips to assess precision, strength and forearm rotation from within the 20 key tasks in the Sollerman test.

6.4 Diverse adaptations

These motion sensors and measurement techniques could be extended to other joints, such as the shoulder joint, where circumduction movement could provide a similar setting to measure an individual’s shoulder motion...
envelope. This can be adapted to other clinical scenarios, like rotator cuff tears, provided that a suitable method for generating a relevant motion envelope for the joint in question is available. Two high-frequency cameras placed perpendicular to each other can capture motion in space and the data generated can be analysed to measure the rate and rhythm of motion, in addition to the range. This could help generate frequency plots of data to identify how patients adapt to a disability after rotator cuff tears and still adjust the other upper limb joints to achieve a similar range of motion.
7 Appendices
7.1 Appendix One: Specification Details of instruments

Goniometer
- Equipment supplied by Biometrics Ltd, Gwent, Wales
- SG65 wrist sensor used with Biometrics Data link unit and ADU301 angle display unit
- Biometrics software DL1001, Version 3.2

Dynamometer
- Digital pinch/ Grip analyser supplied by MIE Medical Research Ltd, Leeds, UK
- Multinanalyser Digital display unit
- WinCAS software supplied by MIE Medical research limited

Programming software
- MATLAB (version 10) supplied by The Math Works Inc.

Sollerman Hand function kit
- Locally manufactured based on specifications of original Sollerman Hand function test
7.2 Appendix Two: Data Collection Proforma

Validated Questionnaire
**Instructions:** This survey asks for your views about your hands and your health. This information will help keep track of how you feel and how well you are able to do your usual activities.

Answer **every** question by marking the answer as indicated. If you are unsure about how to answer a question, please give the best answer you can.

1. The following questions refer to the function of your hand(s) during the past week. (Please circle one answer for each question). Please answer **every** question, even if you do not experience any problems with the hand/other wrist.

   A. The following questions refer to your **right** hand/wrist.

<table>
<thead>
<tr>
<th></th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Very Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overall, how well did your right hand work?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. How well did your right fingers move?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. How well did your right wrist move?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. How was the strength in your right hand?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5. How was the sensation (feeling) in your right hand?</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B. The following questions refer to your **left** hand/wrist.

<table>
<thead>
<tr>
<th></th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Very Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overall, how well did your left hand work?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. How well did your left fingers move?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. How well did your left wrist move?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. How was the strength in your left hand?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5. How was the sensation (feeling) in your left hand?</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Version no. 2

Dated 11/01/2009
II. The following questions refer to the ability of your hands to do certain tasks during the past week. (Please circle one answer for each question.) If you do not use a certain hand, please estimate the difficulty with which you would have in performing it.

A. How difficult was it for you to perform the following activities using your right hand?

<table>
<thead>
<tr>
<th>Activity</th>
<th>Not at All Difficult</th>
<th>A Little Difficult</th>
<th>Somewhat Difficult</th>
<th>Moderately Difficult</th>
<th>Very Difficult</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Turn a door knob</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. Pick up coins</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. Hold a glass of water</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. Turn a key in a lock</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5. Hold a writing pen</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

B. How difficult was it for you to perform the following activities using your left hand?

<table>
<thead>
<tr>
<th>Activity</th>
<th>Not at All Difficult</th>
<th>A Little Difficult</th>
<th>Somewhat Difficult</th>
<th>Moderately Difficult</th>
<th>Very Difficult</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Turn a door knob</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. Pick up soap</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. Hold a glass of water</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. Turn a key in a lock</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5. Hold a writing pen</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

C. How difficult was it for you to perform the following activities using both of your hands?

<table>
<thead>
<tr>
<th>Activity</th>
<th>Not at All Difficult</th>
<th>A Little Difficult</th>
<th>Somewhat Difficult</th>
<th>Moderately Difficult</th>
<th>Very Difficult</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Open a jar</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. Button a shirt/socks</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. Easy to write in cursive</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. Carry a grocery bag</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5. Wash dishes</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>6. Wash your hair</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>7. Type on a computer</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Version no. 2
Dated 11/01/2000
III. The following questions refer to how you did in your normal work (including both housework and school work) during the past four weeks. (Please circle one answer for each question)

<table>
<thead>
<tr>
<th></th>
<th>Always</th>
<th>Often</th>
<th>Sometimes</th>
<th>Rarely</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IV. The following questions refer to how much pain you had in your hands/wrist(s) during the past week. (Please circle one answer for each question)

A. The following questions refer to pain in your right hand/wrist.

1. How often did you have pain in your right hand/wrist?
   1. Always
   2. Often
   3. Sometimes
   4. Rarely
   5. Never

If you answered Never to question IV-A.1 above, please skip the following questions and go to the next page.

2. Please describe the pain you had in your right hand/wrist.
   1. Very mild
   2. Mild
   3. Moderate
   4. Severe
   5. Very severe

Version no. 2
Dated 11/01/2009
V. A. The following questions refer to the appearance (look) of your right hand during the past week.
(Place circle one answer for each question)

<table>
<thead>
<tr>
<th>Question</th>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree nor Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I am satisfied with the appearance (look) of my right hand.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. The appearance (look) of my right hand sometimes made me uncomfortable in public.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. The appearance (look) of my right hand made me depressed</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. The appearance (look) of my right hand interfered with my social activities.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

B. The following questions refer to the appearance (look) of your left hand during the past week.
(Place circle one answer for each question)

<table>
<thead>
<tr>
<th>Question</th>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree nor Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I am satisfied with the appearance (look) of my left hand.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. The appearance (look) of my left hand sometimes made me uncomfortable in public.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. The appearance (look) of my left hand made me depressed</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
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<td>4. The appearance (look) of my left hand interfered with my social activities.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Version no. 2
Dated 11/01/2009
B. The following questions refer to pain in your left hand/wrist.

1. How often did you have pain in your left hand/wrist?
   1. Always
   2. Often
   3. Sometimes
   4. Rarely
   5. Never

If you answered Never to question 1 above, please skip the following questions and go to the next page.

3. How often did the pain in your left hand/wrist interfere with your sleep?
   1. Always
   2. Often
   3. Sometimes
   4. Rarely
   5. Never

4. How often did the pain in your left hand/wrist interfere with your daily activities such as eating or holding?
   1. Always
   2. Often
   3. Sometimes
   4. Rarely
   5. Never

5. How often did the pain in your left hand/wrist make you unhappy?
   1. Always
   2. Often
   3. Sometimes
   4. Rarely
   5. Never

Version no. 2
Dated 11/01/2009
VI. A. The following questions refer to your satisfaction with your right hand/wrist \textit{during the past week}.

<table>
<thead>
<tr>
<th>Question</th>
<th>Very Satisfied</th>
<th>Somewhat Satisfied</th>
<th>Neither Satisfied nor Dissatisfied</th>
<th>Somewhat Dissatisfied</th>
<th>Very Dissatisfied</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overall function of your right hand</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. Motion of the fingers in your right hand</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. Motion of your right wrist</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. Strength of your right hand</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5. Pain level of your right hand</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>6. Sensation (feeling) of your right hand</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

B. The following questions refer to your satisfaction with your left hand/wrist \textit{during the past week}.

<table>
<thead>
<tr>
<th>Question</th>
<th>Very Satisfied</th>
<th>Somewhat Satisfied</th>
<th>Neither Satisfied nor Dissatisfied</th>
<th>Somewhat Dissatisfied</th>
<th>Very Dissatisfied</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overall function of your left hand</td>
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<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. Motion of the fingers in your left hand</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. Motion of your left wrist</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. Strength of your left hand</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5. Pain level of your left hand</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>6. Sensation (feeling) of your left hand</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Version no. 2

Dated 11/01/2009
Please provide the following information about yourself. (Please circle one answer for each question.)

1. Are you right-handed or left-handed?
   a. Right handed
   b. Left handed
   c. Both

2. Which hand gives you the most problem?
   a. Right hand
   b. Left hand
   c. Both

3. Have you changed your job since you had problems with your hand(s)?
   a. Yes
   b. No

   Please describe the type of job you did before you had problems with your hand(s).

   Please describe the type of job you are doing now.

4. What is your gender?
   a. Male
   b. Female

5. What is your ethnic background?
   a. White
   b. Black
   c. Chinese
   d. Asian
   e. Mixed
   f. Other (Please specify):__________

6. What is the highest level of education you received?
   a. Less than high school graduate
   b. High school graduate
   c. Some college
   d. College graduate
   e. Professional or graduate school

Version no. 2          Dated 11/01/2009
7. What is your approximate family income including wages, disability payment, retirement income and welfare?
   a. Less than €10,000
   b. €10,000 - €19,999
   c. €20,000 - €29,999
   d. €30,000 - €39,999
   e. €40,000 - €49,999
   f. €50,000 - €59,999
   g. €60,000 - €69,999
   h. More than €70,000

8. Is your injury covered by Workers' Compensation?
   a. Yes
   b. No

**PATIENT EVALUATION MEASURE**

**PART ONE: TREATMENT**

Please put a circle around the number that is closest to the way you feel about how things have been for you. There are no right or wrong answers.

1. Throughout my treatment, I have seen the same doctor:
   1  2  3  4  5  6  7
   Very well                                    Not at all

2. When the doctor saw me, he or she knew about my case:
   1  2  3  4  5  6  7
   Very well                                    Not at all

3. When I did talk to the doctor, he or she gave me the chance to talk:
   1  2  3  4  5  6  7
   As much as I wanted                          Not at all

4. When I did talk to the doctor, he or she listened and understood me:
   1  2  3  4  5  6  7
   Very well                                    Not at all

5. I was given information about my treatment and my progress:
   1  2  3  4  5  6  7
   All that I wanted                            Not at all
Part Two: how is your hand now (Hand health Profile)

1. The feeling in my hand is now:
   1 2 3 4 5 6 7
   Normal Absent

2. When my hand is cold and/or damp, the pain is now:
   1 2 3 4 5 6 7
   Very sensitive Unbearable

3. Most of the time, the pain in my hand is now:
   1 2 3 4 5 6 7
   Not-existent Unbearable

4. The duration my pain is present is:
   1 2 3 4 5 6 7
   Never All the time

5. When I try to use my hand for fiddly things, it is now:
   1 2 3 4 5 6 7
   Skillful Clumsy

6. Generally, when I move my hand it is:
   1 2 3 4 5 6 7
   Nimble Stiff

7. The grip in my hand is now:
   1 2 3 4 5 6 7
   Strong Weak

8. For everyday activities, my hand is now:
   1 2 3 4 5 6 7
   No problem Useless

9. For my work, my hand is now:
   1 2 3 4 5 6 7
   Skillful Clumsy

10. When I look at the appearance of my hand now, I feel:
    1 2 3 4 5 6 7
    Unconcerned Embarrassed & self-conscious

11. Generally, when I think about my hand I feel:
    1 2 3 4 5 6 7
    Unconcerned Very-upset
Part three – overall assessment

1. Generally my treatment at the hospital has been:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very satisfactory</td>
<td>Very unsatisfactory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Generally my hand is now:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very satisfactory</td>
<td>Very unsatisfactory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Bearing in mind my original injury or condition, I feel my hand is now:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Better than I expected</td>
<td>Worse than I expected</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Sellotape Test

1. Put key into Yale lock, turn 90°.
2. Pick coins up from flat surface, put into purse, return on wall.
3. Open/close zip.
4. Net up coins from purse.
5. Lift wooden cube: over edge 5 cm in height.
6. Lift iron over edges 5 cm in height.
7. Turn screw with screwdriver.
8. Pick up coins.
10. Do up buttons.
12. Put on Tungrip stocking on other hand.
13. Write with pen.
14. Fold paper, put into envelope.
15. Put paperclip on envelope.
16. Lift telephone receiver, put to ear.
17. Turn door handle 90°.
18. Pour water from "Pam-pak."
19. Pour water from jug.
20. Pour water from cup.

Guidelines for scoring of substes:

| Task completed within 20 s and with prescribed hand grip at normal quality | 4 |
| Task completed, but with slight difficulty, or the task is not completed within 60 s but within 90 s, or the task is completed with the prescribed hand grip at slight divergence from normal | 3 |
| Task completed, but with great difficulty, or the task is not completed within 60 s, but within 60 s, or the task is not performed with the prescribed hand grip | 2 |
| Task is only partially performed within 60 s | 1 |
| Task cannot be performed at all | 0 |

Version no. 2
Dated 11/01/2009
7.3 Appendix Three: Handedness questionnaire
HANDEDNESS QUESTIONNAIRE

We would like you to answer a few questions about your handedness and that of your family, by ringing the best answer, or by ticking in the box. If you are not certain then please leave an item blank, rather than guess.

Which hand would you use:

<table>
<thead>
<tr>
<th></th>
<th>Always right</th>
<th>Usually right</th>
<th>Either</th>
<th>Usually left</th>
<th>Always left</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>To hold a pen while writing a letter?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>To throw a ball at a target?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>To hold a pencil while drawing a picture?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>To hold a dish while drying it?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>To turn the winder on a clock?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>To hold a jar while unscrewing its lid?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>To hold a thread while guiding it through the eye of a needle?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>To hold a knife when eating with a knife and fork?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>To hold a potato while peeling it?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>At the top of a broom when sweeping the floor?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>To pick up a glass of water?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Which foot would you use to kick a ball at a goal?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>With which eye would you look through a keyhole?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

14. Which of the following diagrams most closely corresponds to the position of your hand when writing?

15. Has injury, damage or disease ever meant you were unable to use your normally dominant hand? No / Yes
   If Yes: How old were you? ______ years Which hand/arm was injured or damaged? Right / Left
   Was the effect temporary or permanent? Temporary / Permanent If Temporary, how long? ______
   Please describe the problem briefly: ____________________________________________

16. Has any person ever tried to change your handedness? No / Yes
   If Yes: Was it? From using the right hand to using the left hand / From using the left hand to using the right hand.
   How old were you when the attempt was made? ______ years
   Who was the person who tried to change your handedness? __________________________________
   How successful was the attempt? Very successful / Moderately / Not very / Not at all successful

Please tell us about the handedness of your family. Only describe natural (that is, blood) relatives, not step-parents, or persons adopted or fostered. If you are not certain about someone's handedness, do not guess, but say 'Not sure'.

17. Is (or was) your mother right- or left-handed? Right-handed / Left-handed / Not sure.
18. Is (or was) your father right- or left-handed? Right-handed / Left-handed / Not sure.
19. Is (or was) your mother's mother right- or left-handed? Right-handed / Left-handed / Not sure.
20. Is (or was) your mother's father right- or left-handed? Right-handed / Left-handed / Not sure.
21. Is (or was) your father's mother right- or left-handed? Right-handed / Left-handed / Not sure.
22. Is (or was) your father's father right- or left-handed? Right-handed / Left-handed / Not sure.
23. How many sisters do you have? ___ How many are right-handed? ___ How many are left-handed? ___
24. How many brothers do you have? ___ How many are right-handed? ___ How many are left-handed? ___
25. How old are you? ______ years
26. Are you male or female? Male / Female

THANK YOU FOR YOUR HELP WITH THIS RESEARCH PROJECT
7.4 Appendix Four: Ethics approval Forms

Consent Form

DEPARTMENT OF ORTHOPAEDIC SURGERY
Professor J J Dias, Consultant Orthopaedic Surgeon
Direct Dial: 0116 256 3088 (Secretary)
0116 256 3873 (Appointments)
Fax: 0116 256 2476

Patient Identification Number for this trial:

Consent form

Wrist arthrodesis versus motion preserving surgery for degenerative wrist disease: Comparative assessment of range of motion, grip strength and disability.

Name of Researcher: Harvinder pal Singh

Please initial box

1. I confirm that I have read and understand the information sheet dated 11/01/2009 version 2 for the above study and have had the opportunity to ask questions.

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected.

3. I understand that sections of any of my medical notes may be looked at by researchers involved in the present study at Glenfield hospital where it is relevant to my taking part in research. I give permission for these individuals to have access to my records.

4. I understand that the hand videos may be used in the future for other research or training purposes.

5. I understand that my GP will be informed of participation in the study.

6. I agree to take part in the above study.

Name of Patient          Date          Signature

Researcher              Date          Signature

Version 2
11/01/2009
Letter to Participate

DEPARTMENT OF ORTHOPAEDIC SURGERY

Professor J J Dias, Consultant Orthopaedic Surgeon

Direct Dial: 9116 256 3049 (Secretary)
3116 256 3173 (Appointments)

Fax: 9116 250 2676

Wrist arthrodesis versus motion preserving surgery for degenerative wrist disease:
Comparative assessment of range of motion, grip strength and disability.

Dear Sir/Madam,

You are invited to participate in the above-mentioned study being conducted at Glenfield hospital. The purpose of this study is to help orthopaedic surgeons treating patients with various wrist diseases. At present we do not know how the muscle strength changes with various deformities of wrists and how it affects the hand function after surgery.

You have been chosen as you underwent surgery on your wrist some time ago. I have enclosed a participant information sheet which will tell you more about this research project. It is up to you to decide whether or not to participate. If you decide to participate you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time without giving a reason. This will not affect the standard of care you receive.

You are invited to make a single visit to Glenfield Hospital for a 50 minute assessment. A surgeon with an interest in these types of wrist problems will see you. He will ask you to complete a questionnaire about how you find your wrist now. He will then examine your wrist and assess the wrist movements with an electronic device. We will take a video of both the hands during the performance of the activities of daily living for assessment of range of motion.

If you have any further questions or wish to know more you may contact me, Mr Harvinder pal Singh, in the Department of Orthopaedics at the address above. If you agree to take part, please contact us on the above mentioned telephone number when we could arrange for an appropriate date for your visit to the department.

Thank you very much for reading all of this and for considering taking part.

Mr Harvinder Pal Singh
Speciality registrar in trauma and orthopaedics.
DEPARTMENT OF ORTHOPAEDIC SURGERY
Professor J J Dias, Consultant Orthopaedic Surgeon
Direct Dial: 0116 256 3010 (Secretary)
316 256 3873 (Appointments)
Fax: 0116 250 4676

PARTICIPANT INFORMATION
For a study on
Wrist arthrodesis versus motion preserving surgery for degenerative wrist disease:
Comparative assessment of range of motion, grip strength and disability.

You have been asked to participate in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with friends, relatives and your GP if you wish. Ask us if there is anything that is not clear or if you would like further information. Take time to decide whether or not you wish to take part.

What is the purpose of this study?
The purpose of this study is to help orthopaedic surgeons treating patients with various wrist problems. At present we do not know how the muscle strength changes with various deformities of wrist and how it affects the hand function. We wish to assess the function of your hand and correlate it with the disability and range of motion.

Why have I been chosen?
Because you had had a surgical procedure on your wrist some time ago. / Because you have osteoarthritis of wrist.

Do I have to take part?
It is up to you to decide whether or not to participate. If you decide to participate you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time without giving a reason. This will not affect the standard of care you receive.

What type of study is it?
It is a prospective observational study in which you would be part of a large group of people with similar sort of wrist problems. We would like to study the strength and range of motion in the hands with osteoarthritis of wrist and study the effect of surgery.

What do I have to do?
You are invited to make a single visit to Glenfield hospital for a 50-minute assessment. This visit will be additional to your routine follow-up. A surgeon with an interest in these types of wrist problems will see you. He will ask you to complete a questionnaire about how you use your wrist now. He will then examine your wrists and assess the wrist movements with electronic device. Both your wrists will be studied so the data from the normal wrist can be used for comparison. He will take a video of your hands during the performance of the activities of daily living. These videos will be used to assess range of motion with computer software and may be used in the future for the research and training purposes.

Version 2
11/01/2009
What is the drug or procedure being tested?
The study does not involve taking any medications or further x-rays.

What are the possible disadvantages or risks of taking part?
Only the time taken to visit the hospital. (Study time is 30 minutes)
We are unable to provide the travel expenses incurred on the visit.

What are the possible benefits of taking part?
You will not benefit directly from taking part in this study unless you have any questions about your wrist, in which case we will be able to answer these. However, what we hope to achieve is to be able to treat patients better in the future who find themselves in the similar position as you are in.

What if something goes wrong?
As there are normal risks involved, there are no anticipated risks. Regardless of this, if you wish to complain, or have any concerns about any aspect of the way you have been approached or treated during the course of this study, the normal National Health Service complaints mechanisms would be available to you.

Will my taking part in this study be kept confidential?
If you decide to take part it will remain confidential. All information which is collected about you during the research will be kept confidential. Any information about you, which leaves the hospital, will have your name and address removed so that you cannot be recognised from it. Your GP will be informed of the participation in the study.

What will happen to the results of the research study?
If you are interested in the outcome of the study we will happily let you have a copy of the finished work and its conclusions. We aim to publish these when the work is complete in surgical journals.

Who has reviewed the study?
The study has been considered by the Leicestershire, Northamptonshire and Rutland research ethics committee. To ensure that it is appropriate to be making such a request of you.

If you have any further questions or wish to know more you may contact me, Mr Harvinderpal Singh, in the department of orthopaedics at the address above. You may keep this information sheet and if you agree to take part, a copy of the form you will be given you will be asked to sign confirming your consent to take part.

Thank you very much for reading all of this and for considering taking part.

Mr Harvinderpal Singh
Speciality registrar in trauma and orthopaedics.
Appendix Five: Timed Sollerman Hand function test
(Visual Basic code)

Private Declare Function timeGetTime Lib "winmm.dll" () As Long
Public bStart As Boolean
Public iStartTime As Long
Public iEndTime As Long
Public iTotalTime As Long
Public Sub MyTimer()
    bStart = Not (bStart)
    If bStart Then
        iStartTime = timeGetTime
        Application.Speech.Speak "Start!"
    Else
        iEndTime = timeGetTime
        Application.Speech.Speak "Stop!"
        iTotalTime = iEndTime - iStartTime
        With Sheets("Sheet1!").Range("c65536").End(xlUp).Offset(1, 0)
            .Value = iTotalTime / 1000
            .Offset(0, 1).Value = "seconds"
        End With
    End If
End Sub
7.6 Appendix Six: Publications and presentations from the dissertation

Assessment of velocity, range, and smoothness of wrist circumduction using flexible electrogoniometry.
HP Singh, JJ Dias, H Slijper, S Hovius
Contribution: My contribution was towards recruitment, set-up of this study, assessment of volunteers, analysis, write up and presentation of this article. Harm Slijper wrote the Matlab code and Prof S Hovius provided guidance and helped in patient recruitment in proximal row carpectomy group. Prof Joseph J Dias provided guidance and contributed towards set-up and writing of this article.

Grip strength characteristics using Force-time curves in Rheumatoid Hands
JJ Dias, H Singh, N Taub, J Thompson
Contribution: I was involved with analysis, write up and presentation of this article. Prof Joseph J Dias provided guidance and helped in set-up and writing of the article. Dr Ashok Kumar collected the data. Mr. Mike Barnes helped set up the grip strength measurement system. Mr. N Taub and Prof J Thompson provided statistical support.

Dynamic assessment of wrist after proximal row carpectomy and 4-corner fusion
H Singh, M Brinkhorst, J J Dias, T Moojein, S Hovius, B Bhowal
Contribution: Mr. Harvinder Singh designed each study and agreed methods, conducted data collection, recruitment of patients in the
UK, Netherlands and Australia, managed the data sheets and CRFs, assisted in generation of Matlab Codes, data summary and analysis, co-authored the paper and helped interpretation. Prof Joseph J Dias designed the study, supervised all aspects of study definition, development of method, data collection, data processing, data analysis, interpretation, provided guidance and departmental support and jointly authored the article. Michelle brinkhorst collected data for the proximal row carpectomy group in Netherlands and helped in translation during data collection. I was involved in the set of the study in Netherlands making sure the same protocols were followed and was present during the data collection of the first nine proximal row carpectomy patients. Mr. T Moojen, Prof. S Hovius, Mr. B Bhowal were the clinicians who treated these patients and provided guidance and support for smooth running of this project.

*Timed Sollerman hand function test for analysis of Hand function in Normal volunteers*

HP Singh, JJ Dias, JR Thompson
Contribution: I was involved with recruitment, data collection, analysis, write up and presentation of the whole article. Prof Joseph J Dias contributed towards guidance, set-up and write-up of the study. Prof J R Thompson helped in the statistical analysis and power calculation for this study.

*Comparison of the Clinical and Functional Outcomes following Three- and Four-Corner Fusions*

Journal of Hand Surgery (American) 2015 Apr 3
HP Singh, JJ Dias, J Phadnis, G Bain
Contribution: I was involved with recruitment, data collection of three corner fusion patients, analysis, and presentation of the article. Prof G Bain and Mr. J Phadnis were the clinicians who treated these patients and provided guidance and support for smooth running of this project. Prof Joseph J Dias contributed towards guidance, set-up and write-up of the study.

*Sollerman test in four-corner fusion and proximal row carpectomy.*

Submitted to Bone and Joint Journal (BJJ) for publication.

M Brinkhorst, HP Singh, JJ Dias, B Bhowal, R Selles, S Hovius

Contribution: I was involved with recruitment, data collection of four corner fusion patients, analysis, and presentation of the article. Michelle brinkhorst collected data for the proximal row carpectomy group in Netherlands and helped in translation during data collection. I was involved in the set of the study in Netherlands making sure the same protocols were followed and was present during the data collection of the first nine proximal row carpectomy patients. Mr. T Moojen, Prof. S Hovius, Mr. B Bhowal were the clinicians who treated these patients and provided guidance and support for smooth running of this project. Prof Joseph J Dias contributed towards guidance, set-up and write-up of the study.

Abstracts


Presentations


2. Salvage surgery for Wrist OA: Which is better: Proximal row carpectomy or Four corner fusion. Leicester Orthopaedic Research (LORA) meeting 2012 Regional Meeting (First prize).


8 Bibliography


Indianapoils: American Society of Hand therapists


