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Measurement of Functional Wrist Motion

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Measurement of Functional Wrist Motion

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Abstract

Little is known, from a clinical perspective, about the use of wrist motion during daily living activities. This work aimed to identify an informative list of physical tasks that could be measured practically in a clinical setting.

Measurement methods including data gloves were investigated, but these were not used for reasons of practicality and accuracy. A commercial electrogoniometer system was chosen and used to measure wrist motion in flexion/extension and radial/ulnar deviation planes while eighteen right-handed, healthy, volunteer subjects (twelve male and six female, aged 23 to 56 years, mean 29.9 years) carried out mock-ups of the twelve everyday tasks listed in the Michigan Hand Questionnaire.

The 2-plane data from each task-measurement test were displayed on an angle-angle scatter plot, overlaid with an elliptical, estimated maximum-motion envelope.

The mean ranges of motion, averaged over all eighteen subjects, varied widely between tasks: 1.3° of flexion/extension (S.D. 1.49°) and 1.4° of radial/ulnar deviation (S.D. 2.10°) were seen while holding a glass of water, and corresponding values of 61.4° (S.D. 12.1°) and 24.3° (S.D. 7.79°) while buttoning a shirt. Frequency plots were also generated to show which wrist positions were most commonly used during the tasks.

Qualitative and quantitative methods were used to reduce the original task list to just four tasks which represented a wide range of aspects of wrist motion, including large mean ranges of motion and mean locations that were displaced away from the neutral wrist position.

These four short-listed tasks (holding a frying pan, turning a key in a lock, holding a glass of water and buttoning a shirt) could all be carried out whilst seated, with little reliance on other physiological joints and with low-cost props.

The overall approach described in this thesis could be refined into a useful clinical tool, either for identifying motion impairments tracking individual patients’ progress. In particular, the use of the elliptical estimated motion envelopes gave immediate and useful context to the task data.
1 Introduction and Background

The human wrist is a complex joint that contributes to many physical activities. From a simple wave, greeting another person at a distance, to the strong, practised hit of a squash racket against a moving ball, the range of actions performed by the wrist every day is vast. Many performing arts, such as playing a musical instrument, or everyday tasks like writing, require fine, dextrous movements of the hand and wrist; in many sporting situations, such as performing handstands in gymnastics, the wrists are relied on heavily to provide a strong, stable, high-load bearing base. These and many other demands are put on the wrist time and time again every day, for leisure activities or in occupational settings, and the impact of any loss of wrist function on a person’s quality of life should not be underestimated.

The successful function of the wrist relies on several factors, including pain-free movement and adequate strength. The strength of the wrist can easily be measured clinically, and this gives a good overall impression of the function of the wrist, but it does not tell the whole story about what the wrist can achieve. The range of motion of the wrist, which is also easy to measure in clinic, does not in itself indicate how much a person can achieve with that range of motion; there is currently no simple answer to the question, “Will I still be able to do x, y and z after my wrist operation?” even if a surgeon can make a good estimate of the expected range of motion after surgery. The small number of previous studies that have attempted to link wrist function to wrist motion justifies further study in the area of functional wrist motion.

This thesis describes the evaluation of the functional wrist motion of healthy subjects during a set of specified tasks, in order to provide clinicians with clinically useful methods. In particular, individual subjects’ measured data are set in the context of their own maximum range of motion data, providing an extra level of information to clinicians. The data gathered also shed light on each of the measured tasks, and the study goes on to indicate a short-list of tasks that could be used in clinics to gather data rapidly and create a “snapshot” of a patient’s functional wrist motion.
This chapter describes the key areas that motivate and inform the work in this thesis:

1.1 *The structure of the wrist* describes the bony anatomy of the wrist.

1.2 *Wrist function* describes the interaction between wrist motion and wrist loading.

1.3 *Wrist motion* describes briefly the relevant anatomy of the wrist and the ways that it can move simultaneously in two planes.

1.4 *Wrist disease and surgical treatment* describes the ways in which the wrist can be compromised, and discusses two types of surgical treatment that can potentially be informed by the work described in this thesis.

1.5 *Functional wrist motion* is a key concept in this work, and is introduced here in the context of previous studies.

1.6 *Outcome measures* introduces ways of measuring the success of clinical and surgical treatments using questionnaires. A set of twelve tasks is drawn from these outcome measures, for use in motion measurement experiments.

The aims and objectives of this work are then drawn from these areas.
1.1 The structure of the wrist

The wrist joint itself is the articulation of the carpal bones with the radius bone in the forearm (shown in Figure 1.1 as viewed from the palm). The bones are bound together by many strong ligaments, which attach the bones to each other and prevent excessive joint motion.

![Figure 1.1: Palmar view of bones of the hand and wrist: 1=Pisiform, 2=Triquetrum, 3=Hamate, 4=Capitate, 5=Trapezium, 6=Trapezoid, 7=Scaphoid, 8=Lunate](image)

1.2 Wrist function

The function of the wrist is complex, and requires several systems, such as the musculoskeletal system and the nervous system, to work well together. In biomechanical terms, wrist function can be considered in terms of forces and motion, which are closely interlinked. The combination of both strength (the ability to transmit loads across the wrist joint) and flexibility is sought after when treating wrist problems. Neither a strong wrist with little motion, nor a flexible yet weak wrist is ideal, but a surgeon will aim to achieve the best possible wrist function when treating a wrist injury or disease.

While force and motion are both integral to wrist function, to study these simultaneously usually requires complex or multiple measurement methods, which is restrictive both in circumstances where time is short (e.g. in clinics) and where there is an attempt to capture normal motion unhindered by measurement equipment. Force measurement and motion measurement tend to be more straightforward when each is considered separately.
Previous studies undertaken by the author have measured forces applied to the wrist during two high-load activities: the sit-to-stand task (standing up from a seated position) and walking using crutches. In the case of the sit-to-stand task, the vertical load transmitted through one wrist when normal subjects used their hands for support on the chair arms was typically found to be 20 to 30% of bodyweight [1]. Subjects with lower limb injury or weakness could be expected to rely even more heavily on the hands, thus potentially putting even greater forces across the wrist joint. A pilot study carried out by a final year undergraduate student [2] used a pair of instrumented elbow crutches developed by the author to measure the loads seen by the crutches during walking. When subjects walked with two crutches, the force applied by each upper limb (and hence transmitted across the wrist joint) to the crutch was seen to be up to 50% of bodyweight, demonstrating the high demand placed on the wrist during crutch walking. Both of these systems measured the external loading applied to or by the wrist; they did not measure the distribution of the loading within the wrist joint, or any internal loads placed on the wrist joint by the muscles and tendons of the wrist.

While the custom-built measurement systems used to assess the above activities could both be adapted to measure wrist motion as well as forces, this would be cumbersome and would greatly increase the time taken to set up each experiment and the time taken to compile the resulting data.

So, while recognising the importance of the interplay between motion and loading of the wrist, this work focussed on measuring wrist motion alone, and on doing this in a clinically practical way that would not hinder “normal” function.

1.3 Wrist motion

1.3.1 How does wrist motion occur?

The two main planes of motion of the wrist are flexion/extension and radial/ulnar deviation. The motion of the wrist in both of these planes is driven by muscles in the forearm, which pull on the ten tendons that run across the wrist joint from the forearm to the hand. These wrist-operating muscles are known as the extrinsic muscles of the hand as they are located outside the hand, in contrast to the intrinsic muscles in the hand which act more locally to enable the hand to change shape, e.g. moving the base of the thumb and little finger towards each other.
In simple terms, extension of the wrist is caused by the wrist extensor muscles (extensor carpi radialis longus and brevis, and extensor carpi ulnaris) in the back of the forearm (dorsal side) pulling on the wrist extensor tendons, and muscles on the front (palmar side) of the forearm (flexor carpi ulnaris and flexor carpi radialis) pull on the wrist flexor tendons, causing the wrist to flex as shown schematically in Figure 1.2.

![Figure 1.2: (a) Wrist flexion and (b) extension caused by forearm muscles acting on wrist tendons](image)

Motion occurs in the second plane, as the hand moves in radial deviation (towards the thumb) and ulnar deviation (away from the thumb) as shown in Figure 1.3. All of the wrist flexor and extensor muscles, including those that drive flexion and extension, are involved in performing radial and ulnar deviation [3].

![Figure 1.3: Radial deviation and ulnar deviation](image)

While the many bones, tendons and the other soft tissue structures afford the wrist a wide range of functions, it is clear that any compromise of any of these structures can drastically affect the use of the wrist and, consequently, the hand.
1.3.2 Where do the centres of rotation lie?
The two primary planes of motion (flexion/extension and radial/ulnar deviation) are approximately perpendicular to each other. Leonard et al [4] described the “two-hinge axis” model of the wrist, which uses the idea that the axes of rotation of these two planes of motion do not coincide, as shown in Figure 1.4.

![Figure 1.4: Two planes of motion with non-coincident rotation axes](image)

Studies disagree about the amount and even the direction of displacement between the two axes, as this is not consistent between individuals. The displacement can either be positive or negative, i.e. the flexion/extension axis can either be proximal to the radial/ulnar deviation axis as in Figure 1.4 or distal to it. Leonard’s study found that the mean position of the radial/ulnar deviation axis was 6.8 mm distal to the flexion/extension axis, but with a range from 21.0 mm proximal to 28.2 mm distal. While the idea of non-coincident axes can have significant implications in some areas of study, such as the design of wrist replacements whose aim is to allow “normal” wrist motion, the two-hinge axis idea was not studied during this work because the types of motion required and methods of measurement used could not realistically measure or account for these differences.

1.3.3 Is there a third plane of motion at the wrist?
A third, lesser plane of motion is thought to occur at the wrist joint: that of axial rotation. While the rotation of the hand and wrist relative to the elbow is known to occur because of rotation of the forearm bones around each other (pronation and supination), some studies have demonstrated that some rotational movement also occurs within the wrist joint itself. This distinction between pronation/supination and axial rotation within the wrist joint is described in Figure 1.5.
Palmer et al in 1985 [5] conducted a test which indicated that measuring wrist rotation by attaching a goniometer to the skin gave significantly different values compared with similar tests where the goniometer was attached directly to the bones using metal pins. They reported wrist rotations ranging from $2.2^\circ$ to $11.8^\circ$ with an average of $6.9^\circ$, which they felt confirmed that the wrist joint had not two but three degrees of freedom. Another study carried out in 2004 by Gupta and Moosawi [6] found that up about $17^\circ$ each of pronation and supination could be achieved within the wrist joint itself as relative motion between the radius and the metacarpal bones. Measurement of this axial motion at the wrist joint is not straightforward as it requires accurate measurement of the relative movement of the bones themselves, for example by affixing markers directly onto the wrist bones as in Palmer’s study, so is not an appropriate type of motion to attempt to capture when aiming to study a subject’s natural functional wrist motion.

The axial wrist rotation values within the wrist joint found in these studies are also small enough to be considered negligible in the context of this work, whereas pronation and supination can cause particular skin movement issues during measurement of the two primary planes of motion. The two planes of motion chosen for study in this work were therefore flexion/extension and radial/ulnar deviation, with consideration given to the effects of pronation and supination where these could interfere with measurement of the two primary planes of motion.
1.3.4 What shape is the region of physically possible wrist motion?

While the two primary planes of motion of the wrist have so far been identified for study in this work, each one is rarely seen in isolation, as described by Ryu [7]; any movement or posture of the wrist tends to include some flexion/extension and some radial/ulnar deviation. Conversely, it is not possible to obtain extremes positions simultaneously in two different planes of motion (e.g. maximum flexion and maximum radial deviation) because of the local anatomy of the wrist.

This concept is illustrated in Figure 1.6, where any combined wrist position that falls within the shaded area can be achieved physically, but any combined position that falls outside the shaded region cannot be achieved.

![Figure 1.6: Combined planes of motion](image)

Leonard’s study [4] measured the three-dimensional wrist motion of 108 healthy volunteers. The position of the third metacarpal head (the distal end of the middle metacarpal) was measured relative to the forearm, while the pronation/supination of the arm was minimised by securing the forearm in a jig. Each subject carried out a prescribed wrist movement pattern to determine the extremes of motion in two planes and to capture positions throughout the region of active motion (active motion being motion carried out actively by the subjects, rather than being moved passively by a clinician). While Leonard’s study was particularly interested in the two-axis hinge model of the wrist in the context of designs for wrist replacement, the three-dimensional cloud of points generated for individual subjects’ motion in two planes indicated an approximately elliptical
shape in space when viewed from proximal to distal, as shown in Figure 1.7, although the overall shape of the point-cloud was curved in three planes.

By “flattening out” this physical 3D dataset onto an angle-angle plot, an elliptical shape would form a boundary around the edge of the data.

This indicates that it would be reasonable to use an ellipse to approximate the region of physically possible combined motion of the wrist in two planes. It is noted however that this elliptical shape was obtained during tests that prohibited any pronation/supination, so any effect of this extra rotation on the two-plane motion region is not known from Leonard’s work.

Other studies have focussed on the interaction between the two planes of motion, as it is known that wrist motions in the two main planes are coupled together. Palmer’s study [5] recorded flexion/extension and radial/ulnar deviation motions during separate tests, and found that, over the range of flexion/extension measurements, extension was coupled with some radial deviation and flexion was coupled with a small amount of ulnar deviation. Similarly, the radial/ulnar deviation range test included elements of extension towards the extreme of radial deviation, and very little extension or even some flexion during ulnar deviation.

Li et al/s study [8] on this coupling effect between the two primary planes of motion measured the motion of surface markers on the hand and forearm of healthy male volunteers using a motion analysis system. Elbow movement was
restricted, and the subjects each lightly grasped a cylinder that was held vertically to give a consistent hand posture. Three motions were studied: flexion/extension, radial/ulnar deviation, and circumduction (described below).

During the single-plane motions, the subjects were encouraged to perform comfortable movements, rather than movements in a strictly vertical or horizontal plane as might be expected intuitively. These unconstrained “single-plane” motions actually resulted in oblique movements, from radial deviation plus extension to ulnar deviation plus extension, said to be similar to a dart-throwing motion, in agreement with the results seen by Palmer et al. The shape of unconstrained maximal active motion in each of the two planes was shown to be a shallow s-shaped curve rather than the straight lines that might be expected intuitively. These unconstrained, movements are shown schematically in Figure 1.8.

![Figure 1.8: (a) Unconstrained "radial/ulnar deviation" (b) Unconstrained "flexion/extension"](image)

Li’s study also indicated that, as in Figure 1.6, movement in one plane of motion limits the possible range of motion in the other primary plane, with the greatest range of motion occurring when movement in the other plane of motion was near the neutral position. Motion in the flexion-extension direction was found to have a greater influence on radial/ulnar deviation than vice versa, i.e. a large amount of flexion or extension prevented radial/ulnar deviation, whereas considerable flexion and extension were still possible at the extremes of radial/ulnar deviation. This implied an elliptical, rather than circular, region of motion.
The circumduction motion, which measured the subjects’ trace of their outer limits of motion similar to the idea shown in Figure 1.6, was found by Li to be egg-shaped rather than elliptical. The authors attribute this shape to the fact that the flexion-extension direction of motion was, in practice, a horizontal direction and therefore gravitational effects on the muscle activity of the radial-ulnar deviation, rather than physiological effects, were thought to have caused the non-elliptical shape. The circumduction shape was also slightly asymmetric, with the asymmetry being consistent with the oblique dart-throwing motions.

Marshall et al [9] also studied the interplay between the two planes of wrist motion, and like other studies found that flexion-extension positions away from the neutral position reduced the amount of possible radial-ulnar deviation, and vice versa, although the study looked at some specific non-maximal wrist positions, such as 15 degrees of radial deviation combined with 40 degrees of flexion. These relatively low angular values were chosen because they were thought to be values which all subjects would be able to reach, and therefore do not indicate maximum values for individuals in the study.

Moore et al’s paper [10] describes a database of carpal bone anatomy and kinematics of a large number of healthy volunteers built up from previous studies by the authors using detailed CT scans. A range of positions encompassing the full range of motion was recorded for each subject, defined by the angular position of the capitate (one of the carpal bones) with respect to the radius. In this study the shape of the combined flexion-extension and radial-ulnar deviation, equivalent to the shaded region in Figure 1.6, given as a single combined scatter plot for all of the subjects, showed an overall elliptical shape.

Given the results of the studies discussed here, the use of a simple ellipse to describe the physically possible combined motion of the wrist in two planes was believed to be a reasonable assumption. It was also recognised that further subtleties, such as a rotation of the axes of the ellipse, could be incorporated into the assumption if a more detailed model were needed.

1.4 Wrist disease and surgical treatment
Because of the complexity of the wrist joint and the number of bony and soft tissue structures around it, there is significant scope for the wrist to be compromised by injury or disease (pathology) that can affect the function of the wrist and have a significant impact on the quality of life of an individual.
Injury or disease of the wrist can cause varying degrees of loss of function, and these can be assessed clinically to make suitable diagnoses and to assess changes over time. The five key needs of a healthy wrist in clinical assessment have been described by Mr G Giddins (consultant orthopaedic and hand surgeon at the Royal United Hospital, Bath) as:

1. Grip: how strongly the patient can grip
2. Stability: the absence of any “clicks” or “clunks” during motion
3. Absence of pain
4. Sensibility: ability to feel
5. Mobility: how well/how much the hand and wrist can move

While all of these aspects are relevant to clinical care and often overlap, e.g. reduced motion may be attributed to either stiffness or pain, or both, the aspect particularly considered in this work is motion.

Loss of wrist motion can be caused by injury or disease, and the effects may be temporary or permanent, and may change over time. Injuries such as simple sprains may not cause long-term loss of motion, whereas fractures may cause longer-term pain and impairment. Many surgical and non-surgical procedures exist to reduce and repair the effects of wrist injury and disease.

Arthritis is a term used to describe a number of diseases, and overall it affects 1 in 5 of the adult population of the UK [11]. It is the most common type of disease affecting the wrist, and is commonly seen in the form of osteoarthritis (OA), or rheumatoid arthritis (RA).

1.4.1 Osteoarthritis

Osteoarthritis is the most common form of non-inflammatory arthritis [12] and is sometimes known as “wear and tear” arthritis because it tends to occur as a result of long term use of the joints and the process of ageing [13].

OA is characterised by the deterioration of the surface articular cartilage which usually allows bones to glide against each other during motion, leaving exposed bone ends to rub painfully against one another as shown in Figure 1.9.

OA can also be a secondary effect following injury, so while the large, load-bearing joints tend to be affected, the smaller joints such as the wrist are also susceptible to OA caused by injury or repetitive stress. An OA joint is usually stiff and painful, and an illustration of hands affected by OA is given in Figure 1.10.
1.4.2 Rheumatoid arthritis

The other main type of arthritis that affects the wrist is rheumatoid arthritis, which is a chronic inflammatory disease affecting the tissues surrounding joints as illustrated in Figure 1.11. Around 1.16% of men and 0.44% of women in the UK are thought to suffer from RA [14], equating to just under a million people.

The inflammation is associated with swelling and pain, and causes permanent damage and hence progressive disability. According to Apley [15], the wrist is the second most common site of RA, after the metacarpophalangeal (knuckle) joints. A large degree of deformation can occur at the joints, with the metacarpophalangeal joints typically causing the fingers to drift ulnarwards as seen in Figure 1.12.
The exact cause of RA remains unknown, but it is generally considered to be an autoimmune response in which T-cells (normally part of the body’s immune system) are triggered by some means and attack the joints [16].

![Figure 1.11: (a) Healthy joint (b) Joint affected by rheumatoid arthritis](image1)

![Figure 1.12: Ulnar drift at the MCP (knuckle) joints caused by rheumatoid arthritis](image2)

Adams [17] describes the choice of treatment for the arthritic wrist as not being clear-cut, as the patient’s activities and the surgeon’s preferences have an influence, and patients’ priorities regarding grip strength, motion, duration of recovery and durability vary between individuals. Any studies that contribute to the information available to surgeons in this position are therefore potentially useful.

Two types of major surgical intervention particularly associated with the treatment of arthritic joints are arthroplasty (joint reconstruction, typically using a joint replacement) and arthrodesis (surgical fusion of the wrist joint). The success of these treatments depends in part on the potential wrist positions and movements that result from the procedures, and are discussed below.
1.4.3 Wrist arthroplasty

As with the more commonly replaced joints of the body, such as the hip, wrist arthroplasty typically involves replacing the damaged wrist joint with two articulating components, with the aim of relieving pain and restoring function. As the physiological wrist is not a simple ball and socket joint, the overall shape of the design is not straightforward as it needs at least to allow rotation about two (possibly displaced) axes as described in the Wrist Motion part of this chapter, and potentially allow for some axial rotation within the joint to prevent torsion effects causing loosening of the implant and subsequent failure of the whole joint replacement. Shepherd and Johnson [18] suggest that a “sloppy hinge” design may be of benefit, by allowing for variation between patients’ centres of rotation and letting a wrist implant design find its own centre, particularly in a Rheumatoid patient. There has hence been a tendency towards designing wrist joints which act as mobile bearings, to allow for some axial rotation.

Currently available wrist joint replacement designs typically replace the carpal bones with two or more articulating components [19], as shown schematically in Figure 1.13.

![Figure 1.13: Schematic diagram of a wrist replacement design](image)

The carpal and radial components are fixed into the metacarpal bones and the radial bone respectively using screws and stems. An example of a current wrist joint replacement is the Universal II wrist joint from KMI, shown in Figure 1.14. The shape of the articulating surface is critical to the potential success of the arthroplasty procedure, as it must allow enough movement to restore adequate...
function to the wrist, but crucially must not dislocate under physically possible movement conditions.

In addition to the detailed understanding of wrist kinematics and careful design of the individual components’ geometry, research questions such as “how much wrist motion is really used by people?” are relevant to the successful design of wrist replacements, as the replacement joints must be able to withstand normal motion patterns which may be imposed by a patient post-operatively.

Figure 1.14: KMI’s Universal II wrist joint prosthesis [20]

Data showing how much wrist motion is used during certain tasks can be particularly useful in the prototype stages of a wrist replacement design, as prototypes can be subjected to known motion patterns, gathered from real subjects, and their behaviour assessed. One example of this is the custom built wrist simulator developed at the University of Bath [21] which allows controlled movement of a simulated hand and forearm, with a prototype wrist replacement design seated between the two as shown in Figure 1.15.

Figure 1.15: Wrist simulator developed at the University of Bath
Movement of the hand is enabled by applying loads to cables that simulate tendons. In order to subject the artificial wrist joint to realistic motion patterns and assess its performance and likelihood of dislocation in a valid way, wrist motion data must be acquired from real subjects. This is one illustration of the ways in which motion data can be used in a biomechanics research laboratory as well as in direct clinical settings; wrist motion data can contribute to answering the question, "What motions might a wrist replacement be subjected to after surgery, and will these cause wrist dislocation?".

1.4.4 Wrist arthrodesis

Arthrodesis (deliberate surgical fusion of the wrist joint) is used both as a procedure in its own right and as a “salvage procedure”, that is a procedure following a previous unsuccessful surgical intervention such as arthroplasty. During arthrodesis, the carpal bones are fused together using screws and/or plates to eliminate flexion/extension and radial/ulnar deviation of the wrist. It is simple to imagine this as an internal splint placed inside the wrist. Although various types of partial fusion (fusion of some, not all, of the carpal bones) can be performed, a total wrist fusion eliminates all motion within the wrist joint itself. While this sounds like a drastic procedure, a successful total wrist fusion can give the patient a strong, pain-free wrist joint and the rest of the upper limb allows a high degree of flexibility if the other joints are healthy. Pronation and supination still occur unaffected outside the wrist joint, so the hand is still able to rotate with respect to the elbow. This means that, in comparison with other joints, the wrist joint can be fused with fewer disadvantages than other, larger joints in the body such as the knee.

A key question considered by the surgeon when performing a wrist arthrodesis is the position in which to fuse the wrist, as this should be appropriate to the patient and must maximise the useful function of the wrist while minimising any inconvenience caused by a fixed position. Factors to be maximised in the chosen position can include positions that facilitate good grip strength, and positions that allow a wide range, or a key selection, of tasks to be carried out. Factors to be minimised can include fixing the wrist in a position that prevents particular tasks from being carried out, or which might allow or encourage further damage or discomfort of the wrist.

Barbier et al’s study of wrist arthrodesis [22] compared the long-term functional results of fused and non-fused wrists of patients with rheumatoid arthritis. The average position of the fused wrists was found to be 8 degrees of extension and
9 degrees of ulnar deviation, although these varied widely, with 25 degrees of extension to 10 degrees of flexion, and 2 degrees of radial deviation to 25 degrees of ulnar deviation. The Wheeless’ Textbook of Orthopaedics [23] suggests using 5 to 10 degrees of ulnar deviation in patients with rheumatoid arthritis, to counter the natural radial distortion of the rheumatoid wrist, and a neutral or flexed position in the flexion/extension plane. It does also note however that some patients may prefer more flexion or extension, and suggests, where possible, casting the wrist prior to surgery in order to find a suitable and comfortable position for the patient. Moran and Berger’s study on hand trauma [24] indicates the importance of wrist extension in performing power gripping and rising from a chair, and indicates again that the suitable position for a wrist fusion must be carefully considered.

So, while the choice of fusion position of the wrist will always be a compromise, there are clearly benefits to carrying out studies that identify the important features of functional motions and positions of the wrist. Extending this to accommodate an individual patient’s movements prior to surgery could potentially provide even more valuable information to a surgeon when considering a position for wrist arthrodesis.

Measured wrist motion and position data can therefore be used to inform the answer to the question, “What position should I use when performing a wrist arthrodesis on this patient?”.

1.5 Functional wrist motion
When considering the motion of the wrist in a clinical context, it is clearly important to consider not only how much wrist motion a person has in total, but how much motion they need or use in practice in order to carry out their normal activities. Any data that contributes to knowledge of functional wrist activity can potentially inform clinical practice, particularly where the idea of desirable post-treatment wrist positions is concerned. The idea of functional wrist motion, as opposed to simply maximum ranges of wrist motion, is therefore discussed here.

The maximum ranges of motion in the two primary planes of motion vary between individuals and over time as injury, disease or treatment occur. Barr et al describe typical values of 65 to 80 degrees of flexion, 55 to 75 degrees of extension with flexion being approximately 10 degrees greater than extension, and 15 to 25 degrees of radial deviation and 30 to 45 degrees of ulnar deviation, based on published studies. However, the amount of function afforded by these
ranges of motion is not always clear, as the other aspects such as pain and the mobility of other upper limb joints can have a significant effect on the functional usefulness of that amount of wrist motion.

Functional wrist motion can be measured in terms of ranges of motion from a defined neutral position; as total arcs of motion; or in terms of mean positions. The neutral position of the wrist is defined clinically as the alignment of the middle metacarpal and the radius, usually with the fingers extended.

A number of papers have been published on the subject of functional wrist motion, varying in method and purpose. All of the studies discussed here were conducted using normal, healthy subjects, rather than patients with wrist injury or pathology, and were typically carried out using a small number of subjects.

Brumfeld and Champoux’s study [25] measured wrist flexion and extension arcs for fourteen activities. Their paper discusses possible wrist positions for arthrodesis, noting that positions from 15 degrees of flexion to 20 degrees of extension have been recommended by various previous studies of wrist arthrodesis. The authors suggest from their own results that 10 degrees of extension is “probably the most versatile position for wrist fusion”, apparently based on the wide range of activities in which this position occurs. There is however no discussion of the significance of whether 10 degrees of extension is actually a critical point within the motion and whether it is of use in isolation. There is also the potential for an individual to require one part of the measured range of motion more than another, based on their individual needs. Wrist prosthesis designs are also discussed in the paper, and the authors indicate that the range of motion afforded by existing prosthesis designs would be adequate to allow most of the studied activities to be performed.

Palmer et al published a paper [5] in which they measured three degrees of freedom in 52 “miscellaneous” activities using a triaxial goniometer. They classified the activities by task (e.g. personal hygiene) or occupation (e.g. secretary). The motions associated with all of the functional tasks were presented as centroids of motion, grouped by occupation. The centroids, although giving no indication of the ROM involved, did give a simple and clear means of comparison between the different tasks and categories of tasks. In summary, the authors state that all of the measured tasks required about 35° of flexion/extension and 25° of radial/ulnar deviation, and that most of the tasks were performed with the wrist in extension. Only the occupational activities in
the surgeon category typically involved simultaneous flexion and ulnar deviation; in contrast, the housekeeper tasks used almost exclusively extension and radial deviation. No mention is made in the paper of how the “miscellaneous” tasks were selected for the study; it is not therefore known whether the tasks were intended to be representative of a given occupation or to demonstrate the extremes of typical activities. The authors drew the conclusion from their data that the functional range of wrist motion was between 5° of flexion, 30° of extension, 10° of radial deviation, and 15° of ulnar deviation.

Like Brumfield et al, Palmer et al also raise the idea that, “…operative procedures that limit wrist motion are not necessarily functionally detrimental” but go on to say, “however, an attempt should be made to place this limited wrist motion within the…determined functional range of wrist motion.” This is a more valid claim than that made by Brumfield et al, as no direct link is assumed between a single position appearing in many tasks and a useful wrist position for arthrodesis. As with Brumfield’s study, the results cannot be used directly to indicate appropriate wrist positions for arthrodesis and other motion-limiting surgical procedures; this study does however provide a useful demonstration of the positions of the wrist used during a range of tasks. The data also implies the importance of considering the occupation of the individual patient when planning a motion-limiting surgical procedure of the wrist.

A study of flexion/extension was carried out by Ryu et al in 1991 [26] which studied the motion used by 40 unrestricted normal subjects to perform 31 tasks, some of which were occupational and some daily living activities such as personal hygiene and food preparation. As with the study by Brumfield et al, measurements were taken of the range of motion used by subjects during tasks, although these are referred to as the range of motion required by subjects to perform the tasks, a subtle but important difference. The results are therefore useful but not in quite the way stated by the authors. The activities studied included hammer and screwdriver activities, holding a telephone, turning a steering wheel and writing, as well as the more commonly studied activities such as food preparation, key turning and buttoning a shirt. The daily living activities measured were not necessarily representative of all daily living activities, although the authors felt that the range of tasks provided a reasonable representation of the arcs of motion required for most daily living activities.
They found that the minimum range of motion “required” for subjects to perform all tasks was $60^\circ$ extension, $54^\circ$ flexion, $17^\circ$ radial deviation and $40^\circ$ ulnar deviation. Overall, the tasks studied by Ryu et al tended to involve primarily extension and ulnar deviation, and the authors concluded that the wrist should generally be positioned in extension and ulnar deviation during arthrodesis or prolonged immobilisation. They do however also acknowledge that consideration should be given to a patient’s occupation and vocational activities before choosing a fixed position for the wrist.

An interesting value described by the authors is the comparison between measured total ranges of motion and ranges used during the tasks: “Seventy percent of this extreme range (40 degrees each of extension and flexion, 10 degrees of radial deviation, 30 degrees of ulnar deviation) assured completion of a majority of the 24 functional tasks studied.” This statement must be read in the context of the rest of the paper, not simply that 70% of maximal wrist motion is required to carry out daily living activities, both in terms of the relevance of the activities studied and the assumption that range of motion used is an indicator of the required range of motion.

In 1997 a paper by Nelson [27] used a different approach to examining functional wrist motion by limiting the range of motion of healthy subjects using splints and determining how difficult certain tasks were to perform under restricted conditions. The primary point was that the amount of available wrist motion and the amount of wrist function were not related in a simple way, and were certainly not related linearly: “Which…relationships best describe wrist motion and function needs to be established by experiment, not taken as a premise.” One part of Nelson’s work aimed to identify a range of activities which could be considered to be representative of daily living in general. Daily living activities were chosen over occupational or recreational studies on the grounds that these were more likely to be consistent between individuals. A list of activities identified from previous studies was refined by using volunteers wearing completely restrictive wrist splints to identify which activities were the most difficult, and adding activities to the list where appropriate. The conclusion was that very little wrist motion was required to perform daily living activities, contrary to the claims made by the previous authors who in fact measured the motion used when free motion was allowed.

Four splints, each with a fixed range of allowed motion in two planes, were also used to carry out the range of activities, again concluding that little motion was
required. The difficulty of the tasks was generally reduced in the splints with the greatest range of motion, and with practice. The main part of the study concluded that the list of 123 daily living activities could be considered as representative of all daily living activities for future work, and that the functional range of motion (i.e. that needed to perform a task) was much smaller than that previously reported by other authors and was not linearly related to wrist function. A more useful shortlist was identified of twelve activities which caused the greatest difficulty when wrist ROM was limited, and it was therefore considered that if subjects could perform these twelve tasks then they would be able to perform all DLAs:

- Fastening a brassiere
- Writing one’s name
- Turning doorknob
- Dusting low surfaces
- Handling sharp knife
- Washing pots and pans
- Washing one’s back
- Using manual egg beater
- Turning faucet
- Using manual can opener
- Turning steering wheel
- Wringing out dishcloth

These tasks are however not equally critical in daily living, for example the need to use a manual egg beater can be overcome by using a different method, whereas writing one’s name is used frequently on many essential documents. This shortlist may therefore not be useful as a definitive list of tasks, but simply a list of those tasks which suffer particularly when wrist motion is restricted. Some of the tasks may also have had artificial difficulty built into them by the nature of the wrist splint extending onto the palm of the hand, perhaps affecting tasks such as handling a knife or a pen. Nelson’s work benefits from more rigorous reasoning and clarity of the distinctions required in this field, despite making no physical measurements. His discussion and further work suggestions are therefore valuable, as is the identification of particularly demanding daily living activities.

A study by Adams et al [17] also used splints to compare the disability caused by reduced or absent wrist motion, using splints on 21 normal subjects, with unrestricted motion. The effects of the reduced motion (30 degrees each of flexion and extension) and minimised motion were compared using physical tests and clinical patient questionnaires similar to those described later in this chapter. The tasks performed were taken from the Jebson Hand Function Test and thirteen daily living activities obtained from the Patient Rated Wrist Evaluation (PRWE) and from previous studies, chosen for their difficulty or wide range of required motion. The time taken to complete the tasks and the difficulty
in performing them was measured. Both the partially restricted and highly restricted conditions resulted in a longer time to complete tasks, although the difference was not statistically significant. The individuals’ perceptions of disability appeared to be influenced by their amount of available wrist motion, but the perceptions varied widely, as did the compensatory motions of other joints.

The authors acknowledge the limitations in applying their results to patients with wrist arthritis, on the basis of patient factors which were not measured in the study, such as pain, grip strength and possible reduced ability to compensate for limited wrist motion. The possibility of artificial restriction caused by the palmar part of the brace was also mentioned, as noted in Nelson’s paper.

1.5.1 Conclusions on functional wrist motion measurements

Based on this review, studies on functional wrist motion seem to be particularly prone to misinterpretation, so care must be taken when reading quoted or interpreted conclusions or statements from other authors’ studies. The reasons for the choice of measured tasks are not discussed in some papers, and the author believes that this can prevent clear interpretation of the validity of the results and how widely the results can be extrapolated.

As with any biological data measurements, and particularly where normal subjects are being measured during normal behaviour, variability should be expected in task measurements. However, consistency in tasks should be introduced into testing as far as reasonably possible, and key information such as sex and occupation should be gathered from the subjects to provide potential explanations for any outlying data.

In addition, the chosen tasks should be well defined, as the tasks used are not described in detail in some papers, or are simply stated as being carried out “in a consistent way”. While some tasks are well-defined by their nature, such as those taken from physical tests including the Jebsen Hand Function Test which consists of physical set of objects with clear instructions about their use, some studies use tasks that are defined only by a brief title in their original context, such as those derived from experiments which search for difficult tasks or which are reported by patients. These tasks need to be clearly defined and described to avoid any potential misunderstanding of what was actually measured.
1.6 Outcome measures

The performance of physical tasks can be studied in a biomechanical setting for various reasons, such as measuring a range of physiological data or simply finding out how easy a task is to perform. However, in a clinical setting, there is a need to demonstrate the “before and after” effects of medical treatment on a patient’s health or condition. There is increasing pressure on medical professionals to demonstrate the effectiveness of the treatments that they carry out, and the development of instruments known as outcome measures has provided a way of quantifying a person’s overall health, or a specific condition.

Outcome measures are not physical instruments, but questionnaires and scoring systems that can be applied on different occasions to measure changes in a person’s health primarily as a result of treatment [28]. A large number of these measures exist, covering general or specific aspects of health, and outcome measures are used increasingly in orthopaedics so that surgeons can document the outcome of their procedures.

The two main types of outcome measure are (i) those that measure the doctor’s assessment, and (ii) those that measure the patient’s own assessment of their condition. In their textbook on outcome measures in orthopaedics, Pynsent et al say that they have become increasingly convinced of the value of patient-based measures after investigating the field in detail.

Examples of patient questionnaires which focus on specific aspects of health include the Harris Hip Score [29] which scores on pain, function, range of motion and lack of deformity to give an overall score on the condition of a patient’s hip, or the Oxford Knee Score [30] which asks the patient to describe their knee in terms of pain and how well various activities can be performed.

More general measures also exist, which assess the overall impact on the patient’s health rather than just the impact on, say, the limb which has undergone treatment. These include the SF-36 (“Short-Form 36”) [31], which according to Fitzpatrick [32] is the most widely-used generic instrument and has been extensively tested for use in orthopaedic surgical outcome assessment. The SF-36 includes a wide range of questions relating to, for example, physical functioning, social functioning, mental health and pain, and can be applied to measure the outcome of treatment to many different joints, with varying degrees of usefulness. In particular, in Dias’s chapter on outcome measures relating to the wrist [33], he indicates that the SF-36 is not specific enough to evaluate
some aspects of hand conditions because most of its functional assessment concerns activities involving the legs rather than the arms.

Since there exists a large number of outcome measures relating to the wrist, the author chose just three patient-completed questionnaires relating to the wrist and hand to be considered for this work. All of these questionnaires included a range of tasks and all were found by previous studies, including a study which compared all three measures against each other, to be valid and reliable [34]. They were therefore considered to be a useful starting point from which to identify clinically relevant tasks for measurement. The three outcome measures, all currently used in the UK, were:

1. Disabilities of the Arm Shoulder and Hand (DASH)
2. Patient Evaluation Measure (PEM)
3. Michigan Hand Questionnaire (MHQ)

Each of these questionnaires measures disability by asking the patient a range of questions on topics including pain, strength, and ability to perform named tasks, and the patient records a numerical score on a scale.

The three outcome measures were considered in terms of the tasks that they included, in order to identify relevant tasks to be studied. While patient questionnaires do not include any physical measurement, the activities are considered by patients, to allow them to indicate which tasks cause them problems in normal daily activities and are therefore relevant to this work. The plan to use all of the tasks from a single outcome measure, taken as a complete set, was considered to be a sensible approach, provided that the number of tasks was not excessive in terms of practical measurement.

The PEM questionnaire described by Macey and Burke [35] contains three sections: Treatment, How Your Hand is Now, and Overall Assessment. While it covers a range of questions on areas including the feeling in the hand and the pain in the hand, it does not use any specific tasks; instead a general question regarding “everyday activities” is used. This was therefore not chosen for experimental work.

The DASH was developed by Hudak et al [36] and covers a range of topics including difficulty in carrying out general recreational activities, the effects of the problem on regular activities, and the severity of pain. The questionnaire applies not only to the wrist but to the whole of the upper limb. The difficulty in
performing seventeen specified tasks, such as preparing a meal and making a bed, is also rated. While a list of specific tasks is included, it includes tasks that could not reasonably be reproduced or simulated in a laboratory setting. For this reason, and because this questionnaire applies to the whole upper limb and can be considered to be too wide-ranging, the tasks in the DASH were not chosen for use in this work.

The MHQ developed by Chung et al [37] is a relatively long questionnaire used to score aspects such as motion, strength, pain and appearance of the hands, as well as the ability to perform twelve specified tasks. The tasks include picking up a coin, holding a glass of water, and carrying a grocery bag, and all of the tasks were considered to be suitable for simulating in the laboratory. While the title indicates that the questionnaire applies to the hand, Dias points out that outcome measures for the wrist overlap with those for the hand; this is not surprising, as the hand and wrist are so clearly linked, and poor function of one is likely to affect the other. The MHQ was therefore chosen for its tasks.

The tasks listed in the MHQ are grouped by the use of one or both hands. The question, “How difficult was it for you to perform the following activities using your right hand?” is asked in relation to the following five tasks:

- Turn a doorknob
- Pick up a coin
- Hold a glass of water
- Turn a key in a lock
- Hold a frying pan

The same question is asked regarding the left hand. The further question, “How difficult was it for you to perform the following activities both hands?” was asked of the following seven tasks:

- Button a shirt/blouse
- Eat with a knife/fork
- Open a jar
- Wash dishes;
- Wash your hair
- Carry a grocery bag;
- Tie shoelaces/knots.

While these twelve tasks may not be the most critical tasks for daily living, the designers of the MHQ assessed this outcome measure rigorously for reliability and validity and concluded that the chosen tasks were useful. Important tasks such as personal hygiene are not included, and although this may seem to be counterintuitive, the outcome measures are designed to be useful in a clinical outcomes context; some of the more critical tasks are considered by surgeons to be ones which cannot realistically ever be improved by surgery and are therefore not useful in such outcome measures. The experimental set up of
each of the twelve tasks listed in the MHQ is described in the Materials and Methods chapter.

1.7 Aims and objectives
Based on the areas described in this chapter, the aim of this work was to develop and use a useful method of evaluating functional wrist motion, with a view to developing a clinically useful tool.

The objectives of the work were:

- To design experimental set-ups to enable specific tasks to be studied in a laboratory setting
- To choose and validate appropriate measurement equipment to carry out the measurement experiments
- To measure the functional wrist motion of a group of normal subjects during the chosen tasks
- To develop programs to analyse this task measurement data in the context of individual subject’s total wrist motion
- To identify, qualitatively and quantitatively, characteristics of the wrist motions used during each task
- To produce a clinically useful shortlist of tasks from the original task list
2 Materials and Methods

This chapter describes the equipment and experiments used to gather two-plane wrist motion data for this study, in order to fulfil the aims and objectives set out in the first chapter of this thesis.

2.1 Measurement equipment not only describes the equipment used, but also considers other types of measurement method and justifies the use of the chosen equipment

2.2 Subjects describes the volunteer subjects who underwent the wrist measurements

2.3 Tasks defines in detail and justifies the set-up of the physical tasks measured during the experiments

2.4 Experimental protocol defines the equipment checks and the data gathered from each subject during the experiments

2.5 Data handling and analysis describes the uploading and manipulation of the raw data, and the custom MATLAB programs used to handle the data
2.1 Measurement equipment

The choice of measurement equipment used in this study was based on the practical requirements that would be encountered when taking wrist motion measurements in a laboratory setting, and also the potential for transferring the study to a clinic. These requirements are laid out in the following requirement specification.

2.1.1 Requirement specification for measurement equipment

It was decided that the equipment should:

- Have a minimal set-up time for the investigator
- Have an appropriate level of measurement accuracy (of the order of 1 degree)
- Be easily portable and require little storage space
- Be appropriate for use in laboratory and clinical settings
- Allow subjects to walk around while wrist measurements are taken
- Not interfere with subjects’ natural movements or task props

2.1.2 Selecting the measurement equipment

Four types of equipment were potentially available for use during this work, and were considered in relation to the criteria laid out in the requirement specification:

1. Video-based measurement equipment
2. Electromagnetic position-based measurements
3. Data gloves
4. Electrogoniometers

Of these, the first two types of equipment were considered briefly but discounted for practical reasons from this work, whereas the two remaining types of equipment were considered in more detail.

Optoelectronic measurement systems, such as those made by Vicon Motion Systems, are used extensively in the field of sports and exercise science, and for clinical gait studies. These typically use reflective markers attached to the relevant parts of the body, which are tracked by video cameras as the body moves as shown in Figure 2.1.
Figure 2.1: Motion capture of a dancer using reflective markers and multiple cameras

The motion of the markers can then be reconstructed from the frames of the video recordings. This type of system is particularly effective for recording motions that occur largely in two dimensions, such as gait cycles viewed from one direction.

Three-dimensional video capture systems can extend the applications of this type of measurement to include more complex, three-dimensional motions by viewing from several angles simultaneously. While this can capture a large amount of three-dimensional data, the reflective markers can “disappear” from view behind parts of the body during recording. This can be resolved to an extent by the data processing software, but this can require significant processing power and some manual intervention to track all of the markers correctly.

The physical scale of the measurements that can be taken using this type of equipment is wide-ranging; it is large enough to allow for whole-body data capture from human gait studies and sporting activities, and the availability of increasingly small reflective markers (of the order of 1 millimetre diameter) suitable for finger joints or even facial details means that it is becoming more and more suitable for detailed applications.

However, while this equipment can be ideal for some measurement applications, the main barrier to its effective use in both a laboratory and clinical setting is its size and lack of portability. The tasks being considered here would need to be carried out in a specified location with cameras and other equipment set up
specifically for that set of experiments. This would realistically require a dedicated, permanent space for the equipment, which is considered to be impractical under normal clinical conditions where clinicians often move from room to room for consultations and space is at a premium. A smaller, more portable form of equipment than camera-based measurement systems was therefore needed.

The available electromagnetic position-based measurement system was the Fastrak system by Polhemus (see Appendix A) which was used by Leonard et al. [38,4] in their wrist measurement study. The equipment records the location of a chosen marker point relative to a fixed origin, as shown in Figure 2.2.

![Figure 2.2: FastTrak system (a) marker attached to third metacarpal and (b) fixed origin block, from Leonard's study](image)

The chosen point can be identified using either a “pen”, which can be used to select individual points on the body by pointing to them, or by attaching a physical marker onto the point. Leonard et al used this when measuring wrist motions while the forearm was held stationary in a rig to prevent unwanted forearm motion. While this system can be very effective for taking measurements, with its resolution of 0.75mm, it has some potential drawbacks in particular circumstances.

The physical range of the system is restricted, as the marker has to be kept within range of the fixed origin; this range is of the order of a metre, and so is ideal for many laboratory applications, like Leonard’s study, but not necessarily those which involve large or unpredictable movements. The presence of metal within the electromagnetic field can also cause distortion of the recorded data, so metallic objects must be kept away from the measurement area. This type of equipment could easily provide the required level of accuracy for the measurement of wrist tasks, but the need to avoid metallic objects and the need
to be close to a fixed origin would be too restrictive for use with multiple tasks and props. The portability of the equipment was a priority for this work, so the suitability of the two remaining types of equipment was considered: data gloves and electrogoniometers.

Data gloves are instrumented gloves used to capture the motion of parts of the hand, and can incorporate force or pressure sensors. These are typically used in Virtual Reality applications to control 3D computer models or environments, for example moving a joystick while wearing a movement-sensing data glove to drive corresponding movements in a flight simulator.

This type of equipment has the potential to be used in a wide range of fields, and its use has been explored in a number of alternative applications, including the automatic recognition of specific hand gestures such as those in sign language [39,40] and a novel way of verifying online signatures [41]. The literature does not show many medical applications for this type of equipment, although research has been carried out into the use of data gloves in neurology [42], virtual reality to aid surgery [43], and studies of myoelectric control of computerised hands for amputees [44].

While not typically used directly for measurement purposes, the perceived potential for using this type of equipment to measure wrist and hand motions was considered to be a worthwhile area of investigation for several reasons. These included the familiarity of the glove as perceived by the test subjects, the lightweight and portable nature of the equipment, and the scope for using the gloves in a wide range of applications. These applications could include using a data glove as a simple assessment tool in a hand clinic, by recording the detailed movements of a patient from one visit to the next; and as a visual tool controlling an animated image of a hand on a computer screen to describe whole-hand postures easily.

The investigation into the use of this type of equipment is described below.

A data glove was acquired by the Department of Mechanical Engineering with funding from the David and Frederick Barclay Foundation (London). Currently available commercial data gloves tend to incorporate finger bending sensors but no wrist angle sensors, so one was custom-made by noDNA GmbH and supplied via Inition (see Appendix A) to include both finger and wrist sensors. The glove in this case fitted a right hand (see Figure 2.3).
Figure 2.3: Custom Data glove

The glove comprised two layers of flexible fabric, with sensors sewn in between the layers. Each finger and thumb of the glove contained a single flexible strip to measure the overall bending of the digit. The bending measurement of the fingers was achieved by a patented method of conductive ink on a flexible ground plate, using changes in electrical resistance to indicate changes in bending of the plate. The motion at the wrist was measured in two respects: flexion/extension, and pronation/supination.

The glove was connected to a “GloveBox” conditioning box which allowed up to two data gloves to be connected simultaneously, e.g. a right glove and a left glove, and which was connected to a computer via a standard USB port. The data glove was supplied with “JGlove” software by the manufacturer (see Appendix A), which allowed live viewing, calibration and logging of the data on each of the channels.

The software interface displayed the channel outputs both in bar format and graphical format as seen in Figure 2.4.
The finger and thumb bending channels were labelled by name, from (“Glove Thumb” through to “Glove Little”, and the pronation/supination channel and flexion/extension channel were labelled as Sensor 21” and “Boot x”, and the sample rate was fixed at approximately 50Hz.

The software allowed calibration of individual channels so that the extremes of movement likely to be seen during hand motion could be used to define the total measurement range of each sensor.

The data glove also allowed a useful feature called “gesture recognition”, which enabled the user to identify whenever a pre-determined gesture was made by the glove. The tolerance, that is how closely the gesture had to match the pre-recorded gesture before being recognised, could be adjusted. Figure 2.5 shows the gesture defined as “thumbs up”, formed by the combination of channel settings shown on the left (thumb in extension and the fingers in small amounts of flexion). The success or failure of the system to recognise the gesture is shown by the field on the right either as (a) full recognition or by (b) no recognition.
This gesture recognition application is commonly used in data gloves, and can be used to capture words formed in sign language, allowing rapid translation. These data gloves can also use MIDI or other interfaces to control 3D animations on screen as shown in Figure 2.6, which could potentially provide useful visual aids for clinicians.

While this glove certainly had potential for capturing wrist and finger data, the wrist measurement channels were not accurate enough to take useful measurements, and the finger sensors only provided a single bend angle measurement for each digit. In particular, the pronation/supination channel exaggerated the known issue of skin movement by having two layers of fabric moving over each other. The flexion/extension channel suffered the same issue but to a lesser extent, as expected. This glove was therefore felt to be a useful tool, more suited to gesture recognition and animation applications than for accurate measurement purposes.
A second, commercially available data glove was also obtained, using funding from the Dunhill Medical Trust: a 14-sensor by 5DT (see Appendix A). While this did not allow wrist motion to be measured, it did have more sophisticated finger motion measurement than the other glove. Each digit had two bend sensors, so that the flexion/extension of each digit could be measured separately at the first and second knuckle joints (MCP and PIP joints respectively), and between each pair of digits was an abduction sensor. This allowed more complex gesture recognition and hand posture, as it was able to differentiate between postures where the fingers were together and those where the fingers were spread apart. The glove was also fingertip-less, and therefore did not hinder fine fingertip motion and allowed a good fit on a range of finger lengths.

This glove is shown in Figure 2.7; this model of glove has the option of being operated wirelessly, providing a significant practical benefit for laboratory or clinical use.

![Figure 2.7: 5DT 14 sensor data glove (see Appendix A)](image)

The channels of this glove could be automatically calibrated in a similar way to the previous data glove, by capturing the maximum and minimum positions encountered by each sensor during a short trial period and adjusting the rest of the recorded data to fit within these limits. This would be appropriate for animation and gesture recognition, but not for accurate measurements. In order to obtain absolute, rather than relative finger sensor positions, it was possible to obtain the raw data recorded by the sensors and to manipulate that data in the most appropriate way for a given application. In response to this, a custom MatLab program was written to gather the raw data from the sensors (see Appendix D). This could then be used in conjunction with calibration values obtained by physically measuring the position of the sensors while the glove was being worn on a hand, in order to output angular values as shown in Figure 2.8.
While this manual calibration setup would allow a more accurate means of measurement, the method of taking physical measurements used to calibrate every sensor would ideally be improved as this was quite time consuming. The manipulation of the data into data in degrees is in itself a useful outcome of the investigation of this type of equipment, as it enables real movement data to be used to inform clinical or biomechanical studies that need real finger joint movement data.

The gloves inevitably cannot cater for all hand shapes and sizes, although the elasticity of the fabric does enable this to a large extent. As with any equipment, care must be taken to ensure that the equipment is used appropriately, but there is certainly potential for using data gloves in simple measurement scenarios and particularly for rapid gesture recognition for marking a patient’s progress over time. Further extension of this could lead to physiotherapy tools to encourage increased movement with reference to a patient’s previous motion data. Data gloves were not, however, appropriate for measuring wrist motion in the current study.

The fourth type of equipment considered for use in this study was electrogoniometers, which are widely used in sports and biomechanics measurements. Angle measurement sensors are available for a range of joints, from the large hip and knee joints to small finger joints. An electrogoniometer kit including a wrist-specific sensor is available in the Mechanical Engineering
Department (see Appendix A). The wrist sensors are attached to the skin as shown in Figure 2.9 and the relative angular motion of the two parts of the sensor is recorded.

![A Biometrics goniometer sensor attached across the wrist joint (see Appendix A)](image)

The available wrist-specific sensor had a resolution in the order of two degrees, which was considered to be appropriate for the purposes of this study. These sensors have the benefit of being lightweight and portable, do not interfere with the motion of the wrist, and can be used in as small or large a working area as required.

Based on previous experience of using this type of equipment, the system was known to be portable, and although not wireless, the data logger was sufficiently small to be carried easily by a subject during measurement. This therefore allowed portability between and during tests. The overall size of the equipment, in terms of both use and storage, was known to be small, with the whole system (aside from a laptop) fitting in a briefcase-sized case. The known drawbacks include some cross-talk between channels during use, which is discussed in the following section, however this did not outweigh the potential benefits of using the equipment.

Using the broad specification needed for this work, it was therefore decided that the electrogoniometer was the most suitable type of equipment that would take appropriate measurements while being suitable for use in both the laboratory and in clinics.

### 2.1.3 Details of chosen measurement equipment

The electrogoniometer used was supplied by Biometrics Ltd (see Appendix A for specification details). The kit comprised a range of sensors that could be attached to the skin either side of a joint, and a portable datalogger. An angle display unit was also provided, allowing real-time viewing of one channel at a
time, and software was provided to allow data to be uploaded to a computer and processed. While the analogue resolution of the sensor was infinite, the output data from the datalogger had a resolution of 1.8 degrees.

Each sensor comprised two plastic blocks joined by a strain-gauged wire, allowing the relative angular position of the two blocks to be recorded. The SG65 sensor shown in Figure 2.10 was intended by the manufacturer for two-channel angular measurement at the wrist, corresponding to flexion/extension on one channel and radial/ulnar deviation on the other. These two channels could be recorded simultaneously at a chosen sampling rate.

![Figure 2.10: SG65 sensor for measuring wrist motion](image)

2.1.4 Setting up the electrogoniometer

The equipment allowed up to four channels to be sampled using the data logger. Two of the available channels were chosen for use:

- Channel A: Flexion/extension
- Channel B: Radial/ulnar deviation

The sensor was zeroed using the following standard procedure. (The choice of zero position and other datum positions is described later in the Experimental Protocol section of this chapter.) The sensor was positioned so that the two blocks were axially aligned with each other. The readings from each channel were then recorded in the datalogger as ACal1 and BCal1 to be offset from any further measurement readings. The positive direction for each channel was then set by moving the sensor towards the desired positive direction for each channel and capturing it on the datalogger, in this case:

- Channel A positive direction = Extension
- Channel B positive direction = Radial deviation

These conventions were used throughout the experiments and data handling.
For the purposes of taking measurements using the electrogoniometer, the wrist was assumed to have two coincident axes of rotation.

2.1.5 Calibration
The electrogoniometer was checked against a protractor to determine that it met the characteristics set out in the manufacturer’s manual, which stated an accuracy of ±2 degrees measured over 90 degrees from the neutral position. A range of up to 90 degrees in the extension/flexion direction and 60 degrees in the radial/ulnar deviation direction was used, as these were considered to be worst-case maximum achievable angles during testing. The goniometer output values were taken from the Angle Display Unit (ADU) provided with the goniometer kit, which gave real-time display of the angle output of one channel at a time.

The results shown in Figure 2.11 agree with the manufacturer’s stated accuracy over the measured range.
Figure 2.11: Simple calibration graphs for (a) Extension, (b) Flexion, (c) Radial Deviation and (d) Ulnar Deviation
2.1.6 Zero-drift
The sensor was checked to see whether the zero position was likely to drift during the course of each 30 minutes experiment. Initial checks made by moving the sensor during a thirty-minute period indicated that the zero was stable. A check was also incorporated into the beginning and end of each subject’s testing, as mentioned in the Experimental Protocol section of this chapter.

2.1.7 Cross-talk between two channels
Cross-talk between channels is known to occur with the type of electrogoniometer used in this work, with movement of one channel affecting readings on another channel because of the physical nature of the strain gauging in the sensors. While papers by Marshall et al [9] and Hansson et al [45] describe methods for evaluating and compensating for cross-talk in electrogoniometers, it was decided that a simple method of gathering test data should be used, in order to make the method appropriate for clinical use, and the cross-talk simply evaluated to give an awareness of its potential impact in the data.

The cross-talk was evaluated simply using the rig shown in Figure 2.12. The sensor was attached to the two sensor-block holders using double-sided adhesive tape. The central hinged plate allowed flexion and extension of the sensor, and the movable sensor-block holder allowed the distal (hand) sensor-block to move in radial/ulnar deviation.

![Calibration rig](image)

*Figure 2.12: Calibration rig*

The sensor was moved through a range of values in one plane of motion, with each of these experiencing a range of angular positions in the other plane of motion. The effect of each channel on each other was checked, i.e. the effect of flexion/extension on radial/ulnar deviation and vice versa.
The instruction manual indicated that the cross-talk should be $< \pm 5\%$. The results from the cross-talk tests carried out in the laboratory, an example of which is shown in Figure 2.13, agreed with this value.

However, as the cross-talk only occurred significantly when physiologically extreme (and therefore difficult or unobtainable) combinations of wrist motion occurred, the readings within the physically possible region of combined motion were therefore less affected by cross-talk than those at the extremes or outside the region and the cross-talk between the two channels was limited by the physical situation being measured.

### 2.1.8 Cross-talk caused by axial rotation of the sensor

A further issue was that of cross-talk effects caused by rotation, which was again known to skew data on the other channels.

Although little axial rotation is thought to occur across the wrist joint as discussed in the Wrist Motion section of the Introduction chapter, the skin of the forearm can be seen to rotate around the bones significantly during pronation and supination, possibly introducing skin movement artefacts into the measured data in the two measured planes of motion by causing relative axial rotation between the sensor blocks. Johnson *et al* [46] compared two wrist goniometer systems in terms of accuracy, and suggested that goniometers be calibrated in the pronation/supination position that was most likely to occur during data collection, an idea which was considered when attaching the sensor. The manual for the goniometer suggests mounting the two sensor blocks as close...
together as is practical, minimising the overall length of the sensor and hence minimising the potential for rotational skin movement errors.

Unlike studies such as that by Leonard et al, where forearm rotation could be deliberately eliminated as far as possible during measurements, the purpose of the experiments in this work was to measure free motion during tasks, and as such the forearm rotation could not be eliminated if realistic data were to be gathered.

The obvious way to measure the axial rotations seen at the skin would be to use a sensor similar to the SG65 two-channel sensor but which could make torsional measurements. Unfortunately such a sensor was not available from the manufacturer; only longer torsional sensors were available, which would not have measured the same skin rotation as that experienced by the shorter SG65 sensor. The alternative option was then to measure the change caused to channels A and B when then sensor was moved to known positions of axial rotation, to indicate the effect that various levels of skin rotation might cause.

The effect of axial rotation of the sensor on channels A and B was measured in a similar way to the two-channel cross-talk described above, but with the addition of a wedge placed under the distal block of the sensor to rotate that block axially by the desired amount. Wedges giving rotation of $0^\circ$ (no wedge), $30^\circ$ and $45^\circ$ were used. An example of the results is shown in Figure 2.14.

![Figure 2.14: Rotational cross-talk results: the effect of using wedges to add axial rotation to the sensor while in extension](image)

$0^\circ$ 10 20 30 40 50 60 70
ADU extension angle

$0 10 20 30 40 50 60 70$
Physical extension angle (degrees)

- No wedge
- 30 degree wedge
- 45 degree wedge
The effect of even large imposed axial rotations of 45 degrees was considered to be relatively small in the context of the measurements, being only up to 5 degrees for what was thought to be an unrealistically large axial rotation.

As forearm rotation could not be eliminated from functional motion tests without limiting the tasks physically, its effects were instead reduced as far as possible by careful choice of sensor attachment position on the subject, as discussed in the experimental protocol section.

2.2 Subjects

The subjects chosen for this study were healthy volunteers with no recent or current upper limb pain or injuries. The age, height, occupation and main hobby were recorded for each subject in order to provide potentially useful additional information about the results.

Because the subjects were healthy volunteers, full ethical approval from the Local Research Ethics Committee, as required for more invasive clinical studies, was found to be unnecessary. A means for checking that ethical issues had been considered was devised by the author for use in this type of non-invasive work throughout the Department of Mechanical Engineering, and was approved by the University of Bath’s Ethics Committee. The ethical checks consisted of an information sheet for the subjects, outlining the testing to be carried out and allowing them the opportunity to ask questions; a consent form to allow the subjects to give informed consent to participate in the study; and an ethical approval form to be checked by the project supervisor to confirm that all relevant ethical issues had been considered. Templates for these are given in Appendix C. This process was used for all of the volunteer subjects tested during this work.

As with any testing of human volunteers, experimental issues relating to their participation had to be considered. For example, subjects can try to “do well” at a particular test, which is counter-productive to a researcher who is keen to measure “natural” or “normal” data. This can be overcome to an extent by concealing the goals of the testing, for example by concealing a computer screen from the subjects during testing in order to conceal and live data. This technique was found to be useful by the author during previous work, where subjects had a tendency to turn towards the computer monitor that displayed their results in real time during a sit-to-stand activity, potentially skewing the
data. No visual data was available during the testing, so this temptation was avoided during the task testing in this work.

The author deliberately avoided putting any time pressure on the subjects as they were being tested, in order to minimise any artificially rushed activity. Each subject was given the information sheet associated with the ethical approval form at the time that they were recruited, so that they knew what the experiments involved and how long they were asked to volunteer for in advance of arriving for testing. This not only meant that they had clear expectations about the experiments, but also that they had realistic expectations of the length of time that they were asked to volunteer for and did not attempt to rush the testing.

This idea of “reactivity”, i.e. altering behaviour in response to being measured, was minimised as far as possible particularly as the measurement of normal or natural behaviour was the main purpose of the experiments in this work. This was also considered in the design of the experimental protocol and the use of comfortable and unobtrusive measurement equipment. These are described, where relevant, in the description of the experimental protocol.
2.3 Tasks
As explained in the Introduction chapter, the tasks to be measured in these experiments were the twelve tasks taken from the Michigan Hand Questionnaire:

- Turn a doorknob
- Pick up a coin
- Hold a glass of water
- Turn a key in a lock
- Hold a frying pan
- Button a shirt/blouse
- Eat with a knife/fork
- Open a jar
- Wash dishes
- Wash your hair
- Carry a grocery bag
- Tie shoelaces/knots

These descriptions had to be expanded to produce practical, useful experimental tests. Details of this process are given below.

2.3.1 Repetition of tasks
The amount of repetition included in the design of each task emerged as an important idea during the design of the tasks. Some tasks, by their nature, incorporate a certain amount of repetition of a motion, such as that used when washing the hair, whereas other motions are only likely to be performed once on each occasion that the task is carried out, such as turning a key in a lock.

This idea is important to gaining useful measurement information because any artificially included repetition could skew the data and give a false impression of the movements used during a task, particularly when looking at the data in terms of how frequently each part of the motion was encountered. Adding extra cycles of the motion back-to-back could introduce pauses into the data at the start and end of each cycle, rather than a single pause at the start and end of the data. Any artificiality introduced by the start and finish would therefore be magnified unnecessarily when using extra cycles that did not mimic real task repetition, and imply that the end points of the cycle were more important than they really were.

The separate issue of taking multiple measurements of each task was addressed in part by choosing one task at random, per subject, and repeating this task three times on separate occasions throughout the subject’s testing. This gave a useful snapshot of the repeatability of each of the repeated tasks for that subject, while limiting the total test time required of each subject (which would have been up to 1.5 hours if all task were repeated three times). While this meant that some tasks were not performed several times for each subject, each task measurement was still a natural incidence of the task being carried
out. Any changes to the task performance due to unfamiliarity were eliminated as far as possible by describing each task before it was carried out, and allowing the subject the opportunity to practice it, without taking measurements, if they wished to do so. So, while each task was not rigorously repeated for every subject, it was felt that the measurements taken were reasonably representative of the tasks and the reduced overall measurement time afforded by this allowed every task to be measured for each subject.

2.3.2 Hand dominance

Throughout this study, only the dominant wrist of right-handed subjects was measured. This was done in order to introduce consistency into the data, so that the tasks themselves could be studied more closely. The right hand, rather than the left, was chosen in order to recruit enough volunteer subjects for the study.

Only one hand was measured, to reduce the complexity of the experimental set-up. The use of two hands would have increased substantially both the experimental set-up and the length of time required from each volunteer.

The dominant hand was considered to be important as it could reasonably be assumed that the majority of one-handed tasks would be accomplished by the dominant hand, and that tasks requiring both hands would need the dominant hand to play an important role. Where the tasks used both hands, the part of the tasks carried out by the dominant hand was noted, and all of the one-handed tasks were checked to see that they were to be carried out by the dominant hand, in order to check that the subjects were essentially carrying out the same activity with the dominant hand.

The consistent use of the right hand also allowed conventions to be established and used throughout the testing. As each of the two channels was allocated a plane of movement and a positive direction, the use of the right hand introduced a further consistent element, so that the relationship between the physiological direction (e.g. radial deviation) and the sensor direction (e.g. to the right when viewed from above) was always fixed. The additional use of the left hand would have introduced other factors; for example the doorknob task, which was always a clockwise motion, could have potentially being a very different physiological activity when carried out by the left hand compared with being carried out by the right hand. The use of one hand only was therefore considered to be a more useful means of collecting data in this work.
2.3.3 Definitions of tasks

The tasks listed in the Michigan Hand Questionnaire are not defined in detail in their original form, because they were originally identified for use in an outcome measure, rather than for detailed measurement. A reasonable description of each task therefore had to be defined in order to take consistent enough measurements to study, while at the same time avoiding introducing artificial behaviour by over-restricting the tasks. The reproducibility of each task in the laboratory setting also had to be considered, as did health and safety concerns and the appropriateness of carrying out each task in laboratory and clinical settings.

The Michigan Hand Questionnaire was chosen as the source of the tasks as described in the Outcome Measures section of the Introduction chapter, so the use of each task per se was not under question at this point. After initial trials in the laboratory, the task definitions described below were chosen and used throughout the study.

Turn a doorknob

A doorknob and was attached to a vertical board as shown in Figure 2.15 so that it required clockwise rotation to “open” the lock and was sprung so that it returned to its original position when released.

![Figure 2.15: Doorknob mounted on vertical board](image)

The total travel of the doorknob was approximately 90 degrees. The board was positioned so that the centre of the doorknob itself was approximately 1.2m above the floor level. The nearest edge of the doorknob was placed approximately 200mm from the front edge of the laboratory work-bench and each subject stood directly facing the board in order to carry out this task. The distance between the subject and the doorknob was allowed to be chosen by
the subject during the tasks and was not mentioned to the subject, in order to encourage a natural posture during the task.

The subject started the task with the hand on the doorknob as shown in Figure 2.16, rotated it clockwise and allowed it to return to its original position while keeping the hand on the doorknob.

![Hand on doorknob at start and end of test](image)

Figure 2.16: Hand on doorknob at start and end of test

A practice was given to allow the subject to use a comfortable starting position for the recorded test.

A doorknob, rather than a door handle, was chosen for this test because of the original task title. The author considered that a doorknob would be more difficult to turn than a door handle because of the required simultaneous grip and rotation.

**Pick up a coin**

A 2 pence coin was placed about 150 mm from the front edge of the laboratory workbench and the subject stood in front of the bench facing the coin. The subject started with the hand in a relaxed position with the hand near to the coin. The subject then picked the coin up from the bench as shown in Figure 2.17, without sliding it along the bench, and held it a small distance above the bench.

![Picking up a coin](image)

Figure 2.17: Picking up a coin
**Hold a glass of water**

For safety reasons, a standard disposable plastic cup was used in the laboratory and this was filled to approximately 10 mm below the rim with tap water. As the task title was simply the holding of a glass of water, no lifting or drinking action was included and a static test was instead recorded.

![Figure 2.18: Holding a cup of water](image)

While standing, each subject was asked to lift the cup from the workbench in front of them, and to hold it in a relaxed position at a comfortable height. This typically resulted in elbow flexion of about 90 degrees, with the elbow held close to the body as shown in Figure 2.18. This test posture was recorded for approximately five seconds once the subject was holding a steady position. The water was used to ensure that the cup was held upright.

It was noted that the level of fine control needed to grip a plastic cup rather than a glass would have been greater than the firmer grip that could be applied to a glass, but it was judged that the overall wrist posture was likely to be similar for the two cases.

**Turn a key in a lock**

The lock was of the type shown in Figure 2.19 and was attached to the same vertical board as the doorknob.
The rotation of the key was sprung only in the middle part of its total travel, corresponding to the region that moved the lock mechanism, and could rotate approximately 150 degrees during the sprung region. At the start of each test, the key was positioned with the held part of the key at approximately –70 degrees from vertical. The subject then started the test with the fingers holding the key as shown in Figure 2.20, rotated the key clockwise through approximately 150 degrees in a single movement, and finished with the fingers still holding the key.

Hold a frying pan

This task was carried out as a static test using a lightweight frying pan of approximately 250 mm diameter. In order to simulate the effect of containing hot oil and encourage the subjects to hold the pan horizontally, the pan was filled.
with water to a depth of several millimetres. This meant that the task had to be carried out with the frying pan being held in a controlled way.

The subject was asked to lift the pan, while standing, from the workbench in front of them, and hold it steady a small distance above the bench as shown in Figure 2.21. This posture was recorded for approximately five seconds, once a steady posture was attained.

![Figure 2.21: Holding frying pan containing water](image)

**Open a jar**

In this task, the subject was asked to open a glass jar. The jar used was a small food jar of approximately 65 mm diameter.

![Figure 2.22: Hands opening a jar](image)

The subject held the jar in the hand that they would naturally use when opening a jar, as determined during the experimental protocol (described below) and placed the other hand on the lid as if ready to open it as shown in Figure 2.22.

The jar was then opened using a single twisting motion and the hands remained touching the jar and the lid at the end of the task. The jar was empty, so there was no specific incentive for the subject to hold the jar in a particular orientation to prevent the contents falling out; this was considered to be reasonable,
because some jars contain contents which do not spill easily, although this did allow a range of possible grip postures.

**Button a shirt/blouse**

The shirt used for this task was provided by the subject and was worn over the subject’s clothing throughout the testing, with the sleeves rolled up if it had long sleeves, to avoid having to put the shirt on after the sensor had been attached to the subject.

Three buttons were fastened during the test as shown in Figure 2.23. At the start, all of the buttons on the shirt were undone. The subject started with the fingers at the highest button, excluding any collar button. The subject then fastened the top three buttons in order, starting with the top one, and finished with the fingers on the third button.

![Figure 2.23: Buttoning a shirt](image)

**Eat with a knife/fork**

Standard metal cutlery and a plate were used for this task. The plate was placed on the workbench with the knife and fork on either side of it, with the knife to the right.

The subject started by holding the cutlery as if to cut a piece of food, as shown in Figure 2.24 while sitting on a laboratory stool at the workbench. No food was provided, however the subjects were asked to imagine they were cutting a piece of food on the plate. The task consisted of a cutting action followed by lifting the fork to the mouth as if to eat, carried out three times, followed by returning the cutlery to the cutting position.
The test measured only the knife action, because the subjects used the right (dominant) hand to hold the knife, rather than the fork. This was accepted as a limitation of the overall decision to measure the dominant hand during all tasks.

**Carry a grocery bag**

A standard disposable plastic carrier bag (containing lightweight contents) was used for this task as it is widely used. The bag was placed on the floor next to the right side of the subject, who began by standing with the arms relaxed by the sides. At the start of the test, the subject picked up the bag with the right hand, carried it forward approximately 4 metres as shown in Figure 2.25, and placed it back on the ground to their right side. The final posture was the same as the starting posture.

The start and finish postures were considered to be an important part of the carrying task as the carrying task must, in practice, include a means of picking up and putting down the bag.
Wash dishes

This task was simulated by using a plate and scouring sponge in an empty washing-up bowl as shown in Figure 2.26. The subject stood facing the bowl, which was placed on the workbench in front of them, and picked up the sponge in the hand that they would usually use to hold it. The hand used to hold the plate was noted.

The subject then “washed” the front of the plate, in a circular motion, using the sponge then turned the plate over and washed the back of it.

![Figure 2.26: Washing dishes](image)

The task ended with the subject still holding the sponge and the plate in the washing-up bowl.

Wash your hair

The subject placed both hands on the head as shown in Figure 2.27, as if to start washing the hair. The subject was asked to move the hands repeatedly over the scalp as if washing the hair. This was recorded for approximately five seconds and the subject finished with the hands still on the head as in the starting position.

![Figure 2.27: Washing hair](image)
Tie shoelaces/knots

This task was chosen to be tying shoelaces rather than tying knots, as this was believed to be a more relevant and commonly performed task. The test was carried out with the subject wearing a pair of their own lace-up shoes, for familiarity. No other specification was made about the type of shoes. The subject started in a crouching position as shown in Figure 2.28, with the hands on the untied shoelaces. No preference for the right or left shoe was suggested to the subjects, and most subjects chose the shoelaces on the right shoe.

![Figure 2.28: Starting the shoelace-tying task](image)

The method used by the subject to tie the laces was not specified, as it was considered that any detailed requirements put on the subjects might artificially alter their behaviour. The subject was asked to tie their shoelaces in their normal way, and the task ended with the subjects' hands still holding the tied shoelaces.

Once these twelve tasks had been defined, they were incorporated into an experimental protocol, the details of which are described below.
2.4 **Experimental protocol**

The experimental protocol was designed to incorporate the necessary equipment checks and subject information as well as the tasks measurements. Informed consent was obtained from all subjects before testing began.

2.4.1 **Health-related questions**

In addition to the straightforward questions about age, height etc, the subjects were asked about their general health and whether they had had any current or past pain, injury or disease in their fingers, hands, wrist, elbows or shoulders (each part of the upper limb being given as a separate question on the advice of Mr G Giddins). Any problems were noted. Subjects were also asked whether they were allergic to plasters, to give an indication of whether they might react to the adhesive tape used to attach the sensor to the skin. This was however simply a precaution, as the tape used was double-sided medical tape provided by the goniometer supplier for use with the sensor.

2.4.2 **Dominance checks**

Two initial checks were carried out to verify the hand-dominance of the subject. In the first, the subject was asked whether they were able remove the lid from the jar which was on the bench in front of them. At this stage, no mention was made of dominance, and the subjects were given the impression that they were testing the tightness of the jar lid. This test gave a clear impression of which hand the subject used on the jar during this task, as subjects had hesitated, when asked which way they would normally hold a jar, during trials of the experiments. This was followed up with a direct question asking each subject to confirm whether they were right- or left-handed.

2.4.3 **Equipment checks**

Before any data was gathered for each test, the equipment was checked to verify that it was working. The sensor was moved through approximately 90 degrees in the positive and negative directions of both planes of movement while viewing the real-time display of the angle display unit.

2.4.4 **Sample rate**

An appropriate sample rate had to be chosen for the study, to avoid issues such as aliasing caused by low sample rates or high data-processing and storage requirements associated with high sample rates. Previous handling of the goniometer indicated that a sample rate of 20 or 50Hz might be appropriate for many physiological measurements. In order to confirm this, a test was
performed with the sensor attached to the back of the hand and wrist. The sensor was actively moved rapidly through a series of flexion and extension motions as shown in Figure 2.29, as this was considered to simulate the worst case (most rapid) motion requirements that might be required of the sensor during task tests. The motions were carried out at approximately 4Hz. This allowed not only for apparently more active tasks, but also for brief, one-off motions during the slower tasks.

![Rapid Flexion/Extension](image)

**Figure 2.29: Rapid flexion and extension motion**

The sample rate for this test was set to the maximum available value of 1000 Hz so that the data points could subsequently be removed to indicate the accuracy of the slower sample rates in relation to 1000 Hz. The available sample rates afforded by the equipment were 1000 Hz, 500 Hz, 200 Hz, 50 Hz and 20 Hz. Slower sample rates were available but not considered relevant to this study. When the data was reduced by removing data points from the 1000 Hz data, where the peak extension angle was measured as 25.2 degrees, the following results were obtained: at 500 Hz and 200 Hz the peak value still appeared to be 25.2 degrees; at 100 Hz and at 50 Hz it dropped to 23.4 degrees (a fall of 7.1%) and at 20 Hz it had dropped to 19.8 degrees (a fall of 21.4%). On this basis, the sample rate of 50 Hz was chosen.

A higher sampler rate than 50 Hz could be considered if rapid movements were expected to form a large part of any other wrist motion measurement experiments.
2.4.5 Capturing the “zero” position

The zero position of the sensor, as opposed to a neutral position, was defined by resting both of the sensor blocks on the laboratory bench with one side of each block positioned against the base of a vertical surface to ensure that the sensor blocks were axially aligned as shown in Figure 2.30.

![Figure 2.30: Zero position of sensor](image)

A recording of this position was made so that this could be used as a baseline value during data processing if required. The two values of this position could be used in place of the calibration values ACal1 and BCal1. Taking measurement of this position over time, rather than as a single snapshot in time, also confirmed that the zero position was not drifting in the short term, which was seen in early tests when the battery connectors were not making full contact.

A further recording of this zero position was taken at the end of each subject’s testing, to check that the zero position had remained constant.

2.4.6 Attachment of sensor

Johnson et al. [46] compared two wrist goniometer systems in terms of accuracy, and suggested that goniometers be calibrated in the pronation/supination position which is likely to occur during data collection. The sensor was therefore attached to each subject’s right hand and forearm while the arm was raised on a horizontal rest ready to capture the neutral position as described below, with the fingers straight and the subject resting their forearm, wrist and hand comfortably on the rest.

The 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 using marked points on the skin for guidance as shown in Figure 2.31.
Figure 2.31: Marked points for sensor placement (top view)

The three marked points were positioned at the midpoint across the wrist, at the head of the third metacarpal, and at the midpoint of the forearm near to the elbow as viewed from above, based on positions suggested in the sensor manual.

The axial location of the sensor blocks was chosen from experience of using the sensors. The two blocks were placed so that they spanned the wrist joint with one block on either side of the wrist. Minimising the distance between the two sensor blocks was known to reduce errors introduced by rotational skin movement (simply by spanning a shortest distance of the rotating skin) and a minimal practical distance was therefore built into the sensor. The axial position of the sensor blocks during testing was chosen such both flexion and extension were uninhibited as far as possible, although in some cases the sensor blocks were not quite far enough apart to allow the very extremes of motion of the subjects’ wrists, particularly on taller subjects.

The sensor blocks were attached to the skin using medical double-sided adhesive tape, and the forearm sensor was held onto the arm using an adjustable hook-and-loop strap. A similar strap was used to hold the cables onto the arm, to prevent the forearm sensor block from being pulled out of alignment by the cables. Once the sensor was attached to the subject, it remained in place for the duration of the testing.

2.4.7 Capturing the “neutral” position

A neutral position was captured for each subject at the start of their testing. This was done in order to have a means of comparing the measured data with a datum relevant to that subject. This neutral position could also be compared between subjects, by relating an individual’s neutral position with the zero position of the sensor.
The choice of the neutral position was guided mainly by the need to minimise possible skin rotation effects on the two measured channels of data, and was the position in which the wrist was placed while the sensor was attached to the skin. While the manufacturer’s manual for the electrogoniometer stated that the sensor should be attached when the wrist was in a neutral position in terms of flexion/extension and radial/ulnar deviation, no mention was made of pronation/supination. Following suggestions from Mr Giddins, a position of neutral pronation/supination was chosen so that any activity demanding full pronation or full supination would experience, in the worst case, only part of the potential rotational error. The use of a fully pronated position, for example, would potentially allow a large excursion from there to full supination, with the skin moving a substantial distance over the forearm bones.

This position of neutral pronation/supination was combined with neutral flexion/extension and neutral radial/ulnar deviation as shown in Figure 2.32 by resting the forearm and hand on a simple horizontal armrest at approximately shoulder height at the side of the subject, with the elbow bent to approximately 90 degrees and the fingers pointing forwards.

![Figure 2.32: Measuring the neutral position](image)

Where a subject was too short for the armrest to be at shoulder height, they were asked to stand on a block so that they were in the correct position relative to the armrest. A height difference of several centimetres was believed to have little effect on the neutral position of the arm between subjects, as the angle of the shoulder did not vary substantially over the height range of most of the subjects.
Once the subjects were in a comfortable position, they were asked to hold still for a few seconds while the neutral position was recorded. A similar recording was taken at the end of each subject’s testing, to allow comparison between the initial and final neutral positions.

2.4.8 Capturing “maximum ranges of motion”

Following the discussion in the Introduction chapter, there was a need to generate an ellipse to approximate the maximum range of motion in two planes for each subject. A simple test was carried out before the task tests to capture each subject’s range of flexion/extension and of radial/ulnar deviation.

This test was carried out while the subject still had their arm resting on the armrest following the measurement of the neutral position. The subject was asked to keep their fingers straight, and then to move from a neutral position to comfortable extremes of extension and flexion three times at their own speed (as shown in Figure 2.33), and then to return to the neutral position and move to comfortable extremes of radial and ulnar deviation three times before returning to the neutral position (as shown in Figure 2.34). This was intended to capture the natural extremes of motion in both planes.

![Figure 2.33: Capturing extremes of (a) flexion and (b) extension](image1)

![Figure 2.34: Capturing extremes of (a) ulnar deviation and (b) radial deviation](image2)
2.4.9 Capturing “hanging arm” position
A further position was measured on each subject, for interest, to give an indication of consistency of this position between subjects. This position comprised the subject allowing the arms to hang in a relaxed way by the sides in a natural, comfortable position. Once this position was believed to be a steady, static posture, it was recorded for a few seconds.

2.4.10 Measuring tasks
The tasks were measured in a randomised order to minimise any training or fatigue effects. Each task was described to the subject immediately before it was carried out, with the opportunity for the subject to practice the tasks before it was measured and ask any relevant questions.

In order to begin recording of static tasks, the datalogger was started once the subject’s position had become static. For tasks which involved more motion from the start, the researcher counted down “three, two, one, go” at a steady pace and began recording on “one”. This was based on experience from a previous study [1] during which subjects had a tendency to anticipate the start of an activity, leading to recordings of data that did not capture the very beginning of the activity.
2.5 Data handling and analysis

Once the data had been collected, it was uploaded and converted to text file format for ease of data handling in MATLAB, which allowed simple processing of data and handling of multiple files.

2.5.1 Uploading and converting data files

At the end of each test, the test data was uploaded from the datalogger using the Biometrics software supplied with the electrogoniometer (see Appendix A).

Each uploaded test was converted to an ASCII file using the Biometrics software, and then converted to a text (.txt) file in Microsoft Excel. The first seven lines of the file contained information about the test and the following lines contained the sampled data. An example of an output data file in text file format is given in Figure 2.25.

![Figure 2.35: Example of an output file in Excel](image)

As the key values in the text file, such as the calibration values ACal1 and ACal2, were embedded within other information in the text file, they needed to be extracted as part of the data conversion program described below.

The angular values stored in the datalogger were not recorded in degrees, and the following formula was required by the manufacturer to convert the raw data from each channel to angular values in degrees and account for the calibration values ACal1 and BCal1, as shown in (1).

\[ \text{Angle in degrees} = (\text{Raw value} - \text{Calibration value}) \times 1.8 \]  

This was done for each channel, using the relevant calibration value (ACal1 or BCal1). The raw data from the two channels was extracted and stored in a matrix called RawAngles. This matrix was obtained by using a MATLAB
program (gather_raw_angles, see Appendix D) to gather data from the text files containing the original data. The key aspects of this code were:

- Gather non-data lines from the data file, using fgets
- Extract calibration values for both channels and convert from string to number format, using the str2num command
- Count the number of characters in the (non-data) rows and start counting data after that many characters, using fseek
- Define and fill the matrix RawAngles with data and transpose this into a many x 2 matrix containing simply two channels of data, with Channel A in column 1 and Channel B in column 2
- Convert the data in RawAngles to angles in degrees, using the conversion given in (1), and store in a similar matrix called TrueAngles

This TrueAngles matrix of angular data was extracted from each test file using gather_raw_angles and manipulated as required, with the first column containing data from Channel A (Flexion/Extension) and the second column Channel B (Radial/Ulnar Deviation).

The approach illustrated above used the calibration values captured by the zeroing process to convert the matrix RawAngles to the matrix TrueAngles, in degrees. However, it was felt that using the initial neutral position gathered for each subject was a more useful datum for comparison of the task data between subjects, as the calibration values did not account for each subject’s neutral positions. Alternative code was therefore produced, using the following approach:

```
FENeutralDatum = mean(RawAngles(:,1));
RUNeutralDatum = mean(RawAngles(:,2));
```

The above code was simply applied to the file containing the initial measured neutral position for any given subject to gain a single averaged position in each of the two directions, which were then considered as a single pair of coordinates.

### 2.5.2 Elliptical motion boundary

The extreme values in each of the two primary planes of motion were captured and the peak values in each direction were identified and used to generate an ellipse.
The approach to creating the ellipse was to use simply the maximum upper and lower limits in both directions as the peak values for the ellipse, as if creating a simple rectangular frame.

The program generated the elliptical boundary either relative to the initial sensor zero value for both channels, or relative to the initial neutral position value for both channels, based on a choice by the program user when defining the manipulation of TrueAngles. This allowed a corresponding ellipse to be generated for a given subject, when their data was displayed in terms of a zero or a neutral position. The maximum (Max) and minimum (Min) values were defined for both channels (FE and RU) from the relevant TrueAngles matrices.

```matlab
MaxActiveFE = max(TrueAngles(:,1));
MinActiveFE = min(TrueAngles(:,1));
MaxActiveRU = max(TrueAngles(:,2));
MinActiveRU = min(TrueAngles(:,2));
```

The ranges of the data in both directions was found using the following:

```matlab
FEActiveRange = MaxActiveFE-MinActiveFE
RUActiveRange = MaxActiveRU-MinActiveRU
```

The MATLAB command `rectangle` was used to generate the ellipse. The syntax required coordinates \( x \) and \( y \) to define the starting point of the rectangle, and \( w \) and \( h \) to define the width and height of the rectangle. The elliptical shape was produced by providing a curvature to the rectangle, in this case using a curvature of \([1,1]\).

The input values used in the `rectangle` command were:

\[
\begin{align*}
x &= \text{MinActiveRU}, \\
y &= \text{MinActiveFE}, \\
w &= \text{RUActiveRange}, \\
h &= \text{FEActiveRange}
\end{align*}
\]

The effect of this was to create an ellipse as shown in Figure 2.36.
This simple approach does not account for some of the subtleties raised in the Combined Planes of Motion section of the Introduction Chapter, and the implications of this are discussed in the Results section.

2.5.3 Standard data display

The standard way of displaying the data from the tests was a simple x-y plot of the two planes of motion. Flexion and extension were placed on the vertical axis, with extension positive, and radial and ulnar deviation were placed on the horizontal axis with radial deviation positive. This not only allowed consistency with the sign conventions established during the experiments, but also allowed some intuitive understanding of the data, with the positive extension direction occurring vertically in both physical and graphic terms as shown in Figure 2.37.

Figure 2.36: Ellipse generation using \( x, y, w \) and \( h \)
After being converted to values in degrees, the task data was displayed as simple scatter plots using the `plot` function in MATLAB to plot the converted data values (TrueAngles) from the two channels as follows:

```matlab
%define and plot data
a = TrueAngles(:,1);
b = TrueAngles(:,2);
plot(b,a,'.k');
```

This plotted Channel A data as “a” on the vertical axis and Channel B as “b” on the horizontal axis, with points being marked in this example as black dots.

A simple superimposition of the elliptical approximated boundary of motion onto the task data gave a clear indication of where that tasks data fitted into that person's estimated overall motion space, as shown in the example in Figure 2.38.
Figure 2.38: Task data and elliptical boundary on a standard set of axes

A program called Plot_task (see Appendix D) was used to generate and plot the task data and the corresponding estimated boundary ellipse for any given subject and test. This program also allowed the data to be produced in relation to the measured “neutral” position for that subject.

2.5.4 Displaying in terms of data frequency

While the standard data display described above allowed the data to be viewed in a clear format, some data sets did not reveal much about the motions carried out. Whereas some tasks involved either a static posture (such as holding a glass of water) or a single sweeping motion (such as turning a doorknob), the tasks which create a less-well-defined “cloud” of data, such as tying shoelaces, could benefit from showing extra information when viewing the data.

This concept grew from the idea that a simple scatter plot did not show clearly which points occurred only once and which occurred several times during the test. This difference could arguably indicate the relative usefulness or importance of two points in a way that could not be distinguished on a simple scatter plot. Displaying the frequency of the wrist positions experienced during a task has not been done in this type of work before, and is potentially a useful new approach to studying patient data and deriving useful conclusions quickly and easily.

By displaying the data on a version of the simple scatter-plot axes, the frequency plot of the data could be compared easily with the simple scatter plot. While separate, individual frequency plots could have been generated for the
flexion/extension direction and for the radial/ulnar deviation direction, this would have eliminated the valuable information relating the two directions to each other.

Both the scatter plots and the frequency plots disregarded the length of time taken by the subject to complete each test, and this was felt to be a useful approach, although it was acknowledged that some tests used in clinics, such as the Jebson Hand Function Test, do include the length of time taken to complete activities as a measure of patients’ ability.

The frequency data was plotted using the MATLAB command `pcolor`, which simply plots the contents of a matrix on a grid using different colours to indicate different values, as described below. Other approaches to displaying the frequency data were considered, but were found not to be as visually useful as the results obtained using `pcolor`. A relevant matrix, containing the frequency with which each measured data value occurred, therefore had to be derived for the two-channel data, as follows:

- Convert the two channels of angle data (in the matrix `TrueAngles`) to integers, by dividing all values by 1.8, the resolution of the angular values, to allow values to be used as matrix coordinates

- Find the maximum and minimum values occurring in each channel

- Use the minimum values to shift the data by an amount `ADegShift` for Channel A and `BDegShift` for Channel B, so that all data is positive and can therefore be used as matrix coordinates

- Define the size of the frequency matrix as `TMax` in the radial/ulnar deviation direction and `SMax` in the flexion/extension direction, and set all values in that matrix to zero as shown in the sample frequency matrix in Figure 2.39.
Figure 2.39: Empty frequency matrix of dimensions SMax, Tmax

- Scan the pairs of values from the two channels and add 1 to the matrix entry corresponding to the relevant coordinate each time it appears in the data, in effect counting how many times each coordinate appeared during a test. The example in Figure 2.40 shows that the matrix coordinate (5,5), i.e. the value corresponding to a position of 5 units in both Channel A and Channel B, has occurred once, and the value corresponding to a position (8,8) in the matrix has occurred twice in the data.

Figure 2.40: Filling the entries of the frequency matrix

- Once all of the pairs of coordinates in the data had been scanned, the frequency matrix Freq was complete, but still contained scaled (integer and positive), rather than true, values of the coordinates.

- The command `pcolor` was used to plot the frequency matrix Freq and to shift and scale the data back to its original non-integer, positive and negative values as follows:
%find shift values S and matrix size values X,Y
    Sx = BDegShift;
    Sy = ADegShift;
    X = 1:size(Freq,2);
    Y = 1:size(Freq,1);
%plot colour plot using scaled grid values
    pcolor((X-Sx)*1.8, (Y-Sy)*1.8, Freq)

By using the command `pcolor`, each matrix co-ordinate was allocated a coloured pixel according to how often that co-ordinate point occurred in the data, where the colour of the pixel was based on the grid position of its bottom left corner. In this case, the pixel resolution was the same as that of the goniometer, at 1.8 degrees.

As the resulting plot was a visualisation of a matrix, rather than a plot on a set of axes, an origin and a set of axes could not be shown for clear comparison with the simple scatter plots. However, the matrix plots could be labelled numerically, giving a simple indication of what was, in effect, an equivalent plot to the scatter plot. For some tasks, even simply plotting the patch of data from the frequency plot, without axes, was found to be a useful addition to a scatter plot.

A sample `pcolor` plot is given in Figure 2.41, shown with and without the grid that defines the edges of the pixels.
Figure 2.41: Sample frequency plot of task data

The colour bar showing the colours corresponding to the frequency of occurrence was added to the plot by using the MATLAB command `colorbar`. The range of colours was set up using `colormap` as follows:

```matlab
%define colormap for colour plot
a = [0:.22:1.0]';
a = flipud(a);
b = a;
c = a;
cm = [a b c];
```
The colour map consisted of a three-column matrix, [cm], with each column containing a value for the three colours, red green and blue. All rows contained equal values between 0 and 1 in the three columns, and therefore gave a three-digit code for a shade of grey from white (1,1,1) to black (0,0,0). The column matrix used to generate each column consisted of an upper and lower limit, from 0 to 1, and an interval value, in this example 0.22 giving 6 boundaries and hence 5 shades of grey: from 0.00 to 0.22, from .22 to .44 etc through to 0.88 to 1.00.

The maximum frequency value C1, which corresponded to the black end of the scale, was defined in the code by setting the colour limits CLim as shown below:

\[ CLim = [0,C1] \]

Any values greater than C1 were also assigned the colour black.

The scaling of the frequency values on the colour bar could be calculated in two ways: firstly as absolute values, e.g. if a coordinate value occurred ten times during the data, it was assigned a frequency value of 10; or alternatively as normalised values, where a coordinate was assigned a value corresponding to its relative frequency, e.g. a value occurring ten times out of a total of 1000 data samples was assigned a value of 1 per cent. The upper limit of C1 in this case was set to be the highest normalised frequency value occurring in normalised frequency matrix, e.g. five percent.

The results obtained using the approaches described above are presented and discussed in the following chapter, together with suggested applications of the data.
3 Results and Discussion

This chapter presents the results of the experimental work, and uses examples to illustrate the key findings. Both qualitative and quantitative results are discussed.

The following sections are covered:

3.1 Subject information describes the information gathered about the volunteer subjects

3.2 Datum values presents and discusses the datum values obtained from the subjects prior to taking task measurements

3.3 Extremes of motion describes and discusses the use of estimated elliptical motion boundaries

3.4 Task data presents examples of angle-angle plots of the measured data and discusses the results

3.5 Quantifying task characteristics defines the quantitative parameters used to compare the tasks and presents the calculated values for all of the tasks

3.6 Reducing the task list describes a reduced list of tasks that could be used as effectively as the full list of tasks, in a clinical setting

3.7 Summary of the results gives an overview of the methods developed and the data produced in this work
3.1 Subject information
Eighteen subjects were tested successfully, ranging in age from 23 to 56 years old (mean 29.9 years). Six subjects were female and 12 were male. The subjects' reported heights ranged from 1.57 to 1.85 m (mean 1.76 m).

The subjects’ occupations were generally office or laboratory based, including web design, marketing management and, most commonly, academic research. Their hobbies were wide ranging, but included a high number of active pursuits such as running, cycling and climbing. While this information was unlikely to be useful on a small number of subjects, it was considered to be appropriate to collect it in order to have a consistent protocol that could be used clinically over a large number of patients.

All subjects stated that they were in general good health at the time of the experiments, and none responded that they were allergic to plasters, indicating a low likelihood of allergy to the medical adhesive tape. Some subjects had past upper limb injuries (but not current or recent ones), which they felt did not affect their performance at the time of the experiments, and no subjects reported any current or recent pain in any joints of their upper limbs.

All subjects confirmed at the time of testing that they were right handed.

3.2 Datum values
Using the same convention as in the preceding chapters, “zero” positions refer to the two blocks of the sensor being axially aligned with each other while not attached to the subject, and “neutral” positions are those where a physically neutral position was obtained while the sensor was attached to a subject with the forearm aligned on the armrest.

These zero and neutral values were each averaged over a period of 5 seconds, in order to produce a single value for each, both at the start and at the end of each subject’s testing, to give four values per subject: initial zero, final zero, initial neutral and final neutral. Where necessary, these values were rounded to the nearest integer, to allow ease of programming when calculating frequency data.

The final values for the zero and neutral positions were used simply to gauge how much the datum values moved over the course of each subject’s experiments; only the initial zero and initial neutral value were used to calculate data output.
3.2.1 Zero-drift

Figure 3.1 shows how much zero-drift was experienced by the sensor during the course of the testing, with the final zero values for all subjects being plotted as individual points relative to the initial neutral position (at the origin of the graph) for the corresponding subject.

Figure 3.1: Final zero position, relative to initial zero position, for all subjects

Less than 5 degrees of zero-drift was seen during all of the tests, which was considered to be acceptable for the study as this occurred over a duration of approximately 30 minutes. The drift occurring during a single task could be reasonably assumed to be small, as each task took only a few seconds. The randomisation of the task order minimised any possible zero-drift biasing of particular tasks between subjects.

3.2.2 Drift of neutral position during testing

The results of the initial and final measurements of the neutral position are given in Figure 3.2. In this case, the initial neutral position from each subject is positioned at the origin so that the difference between the initial and final position, both in magnitude and direction, can be seen.
Two outlying points can be seen, one of which shifted by thirty degrees into flexion, and the other into almost twenty degrees of both ulnar deviation and extension. These outliers could have been caused by twisting of the sensor blocks relative to one another, or by the sliding of the sensor positions on the skin over the course of the thirty-minute test. As these two outliers moved in different directions, and the other data points moved in a range of directions, it is reasonable to assume that there was no single underlying drift direction of the neutral position during testing. The other final neutral positions all stayed within fifteen degrees of the corresponding initial neutral positions.
3.2.3 Consistency of initial neutral position

The initial neutral positions used by subjects are compared in Figure 3.3, with the corresponding initial zero value for each subject at the origin.

Most subjects showed an initial neutral position which was up to fifteen degrees in one or two directions from the initial sensor zero position, with only two subjects having initial neutral positions of between fifteen and twenty degrees from the initial zero in one or more directions.

Most subjects had a neutral position that had some radial deviation and/or extension, perhaps indicating either that this was a comfortable position within the given constraints of the experimental neutral position, or that the constraints themselves caused this position to occur, despite the intention for the neutral position to include minimal excursion from the sensor zero position. While this experimental position could be constrained further to potentially make the neutral position more consistent between subjects, the priority of minimising the time and complexity taken to set up experiments in a clinical setting could not be ignored and hence the simple set-up was considered to be appropriate. One possible means of eliminating some of the variability of the neutral positions could be to specify the position of the palm, as some subjects appeared to press the palm flat to the top of the arm rest, while others had the palm slightly raised and the hand more relaxed.

Figure 3.3: Initial neutral relative to initial zero

Most subjects showed an initial neutral position which was up to fifteen degrees in one or two directions from the initial sensor zero position, with only two subjects having initial neutral positions of between fifteen and twenty degrees from the initial zero in one or more directions.

Most subjects had a neutral position that had some radial deviation and/or extension, perhaps indicating either that this was a comfortable position within the given constraints of the experimental neutral position, or that the constraints themselves caused this position to occur, despite the intention for the neutral position to include minimal excursion from the sensor zero position. While this experimental position could be constrained further to potentially make the neutral position more consistent between subjects, the priority of minimising the time and complexity taken to set up experiments in a clinical setting could not be ignored and hence the simple set-up was considered to be appropriate. One possible means of eliminating some of the variability of the neutral positions could be to specify the position of the palm, as some subjects appeared to press the palm flat to the top of the arm rest, while others had the palm slightly raised and the hand more relaxed.
Because of the variation between subjects, the use of each subject’s own initial neutral position was seen to be a more valid datum than the sensor’s zero position for comparing tasks within and between subjects. Since the neutral position was used as the datum to present both the extremes of motion ellipses and the task data, the positions of these two types of data were fixed relative to each other and hence the position of the data within an individual’s ellipse would remain consistent, regardless of where they were positioned on the axes. The only results to be directly influenced by the location of the datum would be whether the data was shifted in and out of flexion and extension (and similarly for radial and ulnar deviation).

### 3.2.4 Hanging arm position

The measurement of the “hanging arm” position was an additional part of the experimental set-up, intended to indicate its potential as a practical and straightforward means of gathering a consistent “relaxed” position in a clinical setting. Figure 3.4 shows the results of the hanging arm measurement taken at the start of each subject’s test. One subject’s result did not record successfully, so only seventeen points are shown.

*Figure 3.4: Hanging-arm position relative to neutral position*

The range of the data is similar to that of the initial neutral position, although the data is more widely distributed, so while the proximity to a physiological neutral position was not confirmed, it could be inferred that the position might be comparable to the neutral position used throughout the experiments.
It is interesting to note that the data is broadly distributed along a diagonal from extension-plus-radial deviation to flexion-plus-ulnar deviation, corresponding to the known natural tendency of free wrist motion discussed in the Introduction. The maximum deviation in any direction was just over fifteen degrees for any subject, indicating that further investigation into this position could be worthwhile as a potential relaxed neutral position although the consistency of the hanging arm position within and between subjects would need to be verified.

3.3 Extremes of motion
The measurement of extremes of free motion in both planes of interest was taken, to allow an estimated range-of-motion ellipse to be generated for each subject.

3.3.1 Extremes of motion in two planes
The measured flexion/extension range varied from 121 degrees to 209 degrees (mean 144.0 degrees) and the total radial/ulnar deviation range ranged from 54 to 83 degrees (mean 64.0 degrees).

The mean range values fall within the typical ranges described by Barr et al [3] from several sources, indicating a good correspondence between the experimental values and published ranges of motion.

The mean measured extension value for any subject was 70 degrees, and the mean flexion was 74 degrees; the mean radial deviation was 26 degrees and mean ulnar deviation was 38 degrees. These values also agree with the typical values stated by Barr et al [3] in both magnitude and in the relative amounts of flexion to extension, and of radial to ulnar deviation.

3.3.2 Estimated motion boundaries
Examples of the motion boundary ellipse, estimated from the recorded extremes of motion, are given in Figure 3.5. The origin of each graph is the initial neutral position measured for the corresponding subject.

The size and shape of the ellipse varied between each subject, although the example in Figure 3.5 (b) is not typical, in that the generated ellipse is offset significantly from the neutral position so that most of the enclosed region is in ulnar deviation.

The flexion/extension range for (a) and (b) is very similar at approximately 140 degrees, but the radial/ulnar deviation range differs by about 20 degrees between the two examples.
The proportions of the ellipse also varied between subjects, although all subjects had a greater overall range in the flexion/extension direction than in the radial/ulnar deviation range, as expected from the literature.

Plotting the ellipse on axes with the initial neutral position at the origin allowed the location of the ellipse, as well as its size, to be seen at a glance on a single plot, which was felt to be an advantage.

The method of generating the ellipse was based on the maximum free motion range performed by each subject in each of the two planes of motion. The use of this approach was shown to be an effective means of approximating a likely region of motion for most subjects. An example of such an ellipse, together with the data used to generate it, is given in Figure 3.6. Both sets of data were generated relative to the initial neutral position for that subject, with the initial neutral position being at the origin of the graph.
The distinctive “f” shape of the extremes data was seen in all subjects, with slight variations in shape between individuals. The sweeps of motion in both planes of motion tended to be tilted diagonally, from extension plus radial deviation to flexion plus ulnar deviation. This coupled motion during free “single-plane” free motions was encouraging, as it was supported by the findings in the literature by Li et al [8] and Palmer et al [5].

While the generated ellipse fitted the data well in the case shown in Figure 3.6, a small number of subjects’ data showed greater excursions outside the ellipse, typically at the two ends of the “flexion/extension” sweep. Figure 3.7 shows two such graphs.
These graphs are typical of those whose extremes data showed greater excursion outside the ellipse, with those excursions occurring in the same regions for all subjects. The use of a tilted ellipse could improve the match between the extreme data and the ellipse, but the amount of tilt would have to be calculated for each individual and used accordingly. A fixed amount of tilt could not be applied to all subjects, as the amount required varied between the subjects.

Some excursion might be expected outside the boundary during task measurements, particularly in the regions highlighted in Figure 3.7, as the ellipse is an estimated region boundary, and any such excursions should still be examined as potentially critical tasks as the data would be likely to be near, if not outside, the real motion boundary.

The ellipse generation was based on two main assumptions: (i) that the extremes of motion measured during free motion in two planes would give a good indicator of the peak ranges of motion for that subject’s whole range of motion, and (ii) that a simple ellipse would be a valid indicator of the shape of the overall region of motion. Given these assumptions, the simple method employed here gave a reasonable or good approximation to the extremes data in most cases and allowed simple programming to be used to good effect.

While the measurement of the neutral position had some variability, both the estimated boundary ellipse and the measured data were plotted relative to a the same initial neutral position for any given subject, and were therefore fixed relative to each other. The relationship between the location of the measured data and the location of the ellipse was therefore unaffected by any errors in the measurement of the neutral position.

3.4 Task data

This section describes, qualitatively, the main features identified in each of the twelve tasks, giving examples of both typical and unusual aspects of the data and discussing possible reasons for the features.

All of the angle-angle plots show the data relative to the initial neutral position recorded for the subject who performed the given task. Where the angle-angle plots could benefit from further clarity, additional frequency plots are given of task data.
3.4.1 Turn a doorknob

Turning a sprung doorknob resulted, in many cases, in a simple sweeping curved shape as shown in Figure 3.8.

![Figure 3.8: Turning a doorknob](image)

The location of the wrist motion was generally in extension, with some ulnar deviation, although variation was seen between subjects, as shown by the examples in Figure 3.9.

(a) ![Figure 3.9: Turning a doorknob using (a) large motion range and (b) small motion range](image) (b)

The repeatability of the task for a subject is shown in Figure 3.10.
Figure 3.10: Turning a doorknob (3 tests from a single subject)

The variability of the shape and position of the curve between subjects and between repetitions was probably due to the inherent variability in the task: the subjects' hand position on the doorknob was not fixed, and the amount of wrist motion used could vary depending on the posture of the whole arm during the task. Some subjects appeared to use more pronation or supination than wrist motion in the two measured planes, leading to relatively small recorded movements at the wrist itself. The height of the subject could also have influenced the relative posture of each subject's wrist, as the height of the doorknob was fixed.
3.4.2 Pick up a coin

A high degree of variability was expected for this task, as it was a “free form” task with no specific constraints imposed on the subjects and was performed at a fixed height, regardless of the height of the subject.

While this variability was seen in the results, the motions used were, in nearly all cases, well within the ellipse for that subject, indicating that this task, when carried out in a similar manner to the experimental setup, was probably not a critical task in terms of wrist motion.

A graph of this task is shown in Figure 3.11.

Several subjects showed patterns which were similar to the one shown in Figure 3.11, typically with some ulnar deviation, but the range of motion in both directions varied considerably. This was thought to be because the start and end points of the task were not strictly defined, but could also have been because of real variety in the amount of wrist motion used to perform the task. The dexterity of the fingers and flexion of the elbow could also have played a large part in achieving this task.

Three graphs from a single subject are given in Figure 3.12.
Figure 3.12: Picking up a coin (3 tests from a single subject)

The subject whose results are seen in Figure 3.12 showed some variation in range, but there was reasonable consistency. The other subject shown in Figure 3.13 who repeated this task showed more extension than the subject whose results are shown in Figure 3.12, but a similar motion pattern can be seen for the three attempts at the task.
Figure 3.13: Picking up a coin (3 tests from a second subject)

3.4.3 Hold a glass of water

The results for this task were expected to show a high degree of consistency and little range of motion, despite being an unrestricted task. The need to prevent the water spilling was thought to play a large part in determining the posture used by the subjects.

The range, as expected, was small in both directions, as seen in Figure 3.14.
The posture tended to be in extension, but the radial/ulnar deviation position was more variable between subjects than the flexion/extension position. The radial/ulnar deviation position was linked to the height at which the glass was held relative to the body.

No subjects used a posture which was close to their boundary of motion, indicating that holding a glass was not a critical posture in terms of wrist motion.

Figure 3.15 gives three repeated graphs from a single subject, which show good consistency for that subject.

While a plastic cup was used in place of a glass, the posture used to hold the glass was not expected to vary significantly between the two types of container. Different grip control and dexterity would probably have been used between the two types of container, as a glass would have been rigid and breakable, whereas the plastic cup was flexible and not breakable. The shape of the container could also affect the subjects’ hand posture and use.
3.4.4 Turn a key in a lock

This task involved the rotation of a key, so the angular measurements in the two measured two planes were not easy to predict. A higher degree of consistency was expected for this task compared with turning the doorknob, as the fingers needed to be in a specific grip posture in order to grip the key, although the hand and elbow could still be used to help achieve the task and thus reduce the reliance on wrist motion for the task.

An example of turning a key is shown in Figure 3.16.
In many cases, a simple, curved, diagonal profile was seen, typically in some extension. The small ranges of motion seen in some subjects indicated that either very little upper limb motion was used for the task, or that motion at other, unmeasured joints or in other directions was used to achieve the task.

Figure 3.17 shows three graphs from a single subject, showing a similar shape but a widely varying range in both directions.
Different types of key and lock might show different results, however a similar variability might be expected as in the experimental set up, as the option to use other parts of the upper limb would be possible in all cases.

3.4.5 Hold a frying pan

An example of the results from this task is shown in Figure 3.18. Nearly all subjects showed very small ranges of motion in both measured directions during this task.

Subjects typically held the frying pan in some extension and ulnar deviation, although variation was seen between subjects.
In some cases the posture was very close to, or even outside the boundary ellipse, as shown in the example in Figure 3.19.

![Figure 3.19: Example of holding a frying pan, with data close to the boundary ellipse](image)

This proximity to the estimated motion boundary indicated that this task might be a particularly difficult one to achieve if a person’s overall motion boundary were to be limited, particularly in the radial/ulnar deviation direction.

The repeatability of the task for a single subject is shown in Figure 3.20.
While the frying pan used in the study contained water to simulate hot oil, this was thought to provide a reasonable simulation of the control and posture needed to hold the frying pan in a steady manner, so little difference would be expected from a pan containing oil and/or food.

### 3.4.6 Open a jar

At the start of the experimental set up for each subject, the subjects were asked to pick up the jar from the bench and remove the lid, in order to determine which hand they would naturally use to hold the jar. During this check, twelve subjects held the lid in their right hand, and six held the lid in their left hand, indicating that there was not a strong tendency for the subjects, who were all right-handed, to hold the jar in a particular way.

However, after some subjects had been tested, it became apparent that at least one subject changed which hand held the jar between the initial check and the measured test for that task. Subjects tested after this point were therefore also checked to see which hand was used during the recorded task. Some subjects openly said, “I don’t know which hand I would normally use”, without being prompted, during the course of the testing.

Of the nine subjects who were observed both at the start of the testing and during the jar task, only one subject used the hands different ways round on the two occasions. Of those whose hand posture was not noted during the recorded task, reasonable estimates could be made as to whether the task was completed using the right or left hand to hold the jar, as the graphs for the two cases had some clear characteristics, as described below.
The jar-opening task was considered to be a “free form” one, in that the position of the jar in space was not prescribed and the jar could be opened by turning either the lid or the jar relative to the subject. This, combined with the lack of consistency of the lid being held by the same hand, indicated that the results from this task was likely to show a high degree of variability.

An example of a typical graph is shown in Figure 3.21.

![Graph](image)

*Figure 3.21: Typical graph of opening a jar, holding the jar in the right hand*

Figure 3.21 shows a characteristic curved shape seen in most of the subjects’ results, despite a wide variability in the range of motion used. In some subjects, a large excursion was seen which looked like a physical sweep corresponding to a subject moving the lid away from the jar after opening it.

For most subjects, the results fitted a pattern of using either the left or right hand on the lid of the jar. Figure 3.22 gives two examples of opening the jar with the left hand on the lid.
For subjects who used the right hand on the jar lid, the results showed different curves, as shown in the examples in Figure 3.23.

The repeated results from a single subject are shown in Figure 3.24.
While the data was close to the boundary in some cases, this proximity was not in a consistent location between subjects and occurred to different degrees in different subjects. This reinforced the idea that each subject carried out the jar-opening task in an individual way.

Further differences might be seen in the data if the jar was full or heavy; solid or liquid contents might be handled differently depending on the perceived risk of spilling the contents, and a heavier jar might cause a different grip posture. However, the tests carried out in this work indicated that a wide range of results could be expected even when the same, empty jar was used in all tests.

3.4.7 Button a shirt/blouse

Subjects used their own shirts for this task. This introduced some variability in terms of the shirt and the buttons, but this was felt to be representative of the
variability existing naturally between people. While no subjects were asked to include the collar button during the task, some of the women’s shirts (or in some cases blouses) had lower top buttons than the top buttons on the men’s shirts, and there was variation in the tightness of fit of the shirts. Again, these were all felt to be representative of how the task might be carried out in non-laboratory conditions.

Some subjects commented (unprompted) that they would not naturally start with the top button and work downwards, but the reported alternatives were not consistent between subjects, so the use of a standardised technique for all subjects was deemed to be useful.

A typical graph of this task is shown in Figure 3.25.

![Figure 3.25: Typical graph of buttoning a shirt](image)

The results shown in Figure 3.25 show an unexpectedly large range of motion in the flexion/extension direction. The data was also densely distributed in most cases, and in some cases the data was close to, or outside, the elliptical boundary for that subject. However, the data close to or outside the boundary was not consistently found at the same part of the boundary, perhaps suggesting that the large spread of the data in itself was the main cause of the data being close to the boundary.

The large range of the data, combined with the closeness to the estimated boundary in some cases, indicated that this task might be compromised if the available range of motion were reduced.

Repeated graphs of the shirt-buttoning task are shown in Figure 3.26 below.
Only two repeated graphs were available for this subject, because of errors in processing some subjects' data, but the two graphs show a consistent shape and location of the data.

This task is one for which frequency data was expected to add useful additional information to the data display. Using the same data as in Figure 3.25 (a typical result for this task), the corresponding normalised frequency plot is given in Figure 3.27.

Using the data from Figure 3.26, the two graphs from a single subject gave rise to frequency plots as shown in Figure 3.28.
Figure 3.28: Frequency plots of two datasets from one subject

These plots indicate that key parts of the range of motion occurred not only towards the extremes of the total flexion and extension used but also throughout the range.

3.4.8 Eat with a knife/fork

The task of eating with a knife and fork was carried out in most cases with the subject holding the knife in the right hand. Two subjects held the fork in the right hand, despite all subjects being right handed.

Figure 3.29 gives two examples of data from subjects who held the knife in the right hand.
This task involved three repetitions of cutting-lifting-lowering actions of the knife, and in Figure 3.29 (b) these three repetitions can be seen as motions in slightly different locations to each other, in contrast to the data in Figure 3.29 (a) which implies a more consistent action where the three repetitions cannot be distinguished from each other.

The variability of this task was large, but despite this variability, a familiar diagonal motion (from extension plus radial deviation to flexion plus ulnar deviation) was visible in many cases.

Figure 3.30 shows repeated data from a single subject eating with the knife in the right hand.
Figure 3.30: Eating with a knife and fork (3 tests from one subject)

The diagonal pattern and the three repeated motion strokes can be seen to some extent in these graphs, but there is not clear consistency in the shape of the data on the three different occasions where the subject apparently varied the range of motion used for each of the three repetitive actions within the task.

The two subjects who held the fork in the right hand showed different patterns from those who held the knife in the right hand, and these two subjects’ results are given in Figure 3.31.

The graphs in Figure 3.31 show similarities to each other, in that a roughly triangular shape can be seen in the data, although with only two recorded tests only limited information could be drawn from these.
Despite the set up for this experiment involving no physical food or food substitutes, the subjects generally reacted well to performing the task. Using different types of food might show more detailed information about this task, but the task set-up used here was felt to be satisfactory for the purposes of this work.

### 3.4.9 Carry a grocery bag

Carrying a grocery bag was found to be a task involving reasonably large range of motion in both measured directions. A typical example of results from this task is shown in Figure 3.32.
Despite the fairly large range of motion, the data tended not to be located near to the estimated motion boundary, indicating that perhaps this task was not reliant on the more extreme motions available to the subjects.

In some cases, there are clear single motion “sweeps” which seem consistent with either the lifting or lowering phase of the task. An example of this is shown in Figure 3.33, in the upper-left part of the graph.

**Figure 3.33: Carrying a grocery bag: Example of sweeping motion**

Other causes for sweeping motions could be that some subjects tended to swing the bag backwards and forwards while carrying it (see Figure 3.34).

**Figure 3.34: Carrying a grocery bag: possible swinging action**
The graph in Figure 3.34 shows a large motion range in both measured directions and more apparent sweeping motions than in Figure 3.33, which could be attributed to a swinging bag or to large motions during lifting and lowering the bag.

Figure 3.35 shows a normalised frequency plot for the test shown in the angle-angle plot in Figure 3.32, to allow comparison of the two types of data display.

![Figure 3.35: Carrying a grocery bag: normalised frequency plot](image)

### 3.4.10 Wash dishes

All of the subjects used the sponge in the right hand and the plate in the left hand during this task.

![Figure 3.36: Typical graph of washing dishes](image)
The graph in Figure 3.36 shows a typical result for this test, with a wide range of motion in both directions. Some distinct excursions can be seen, which may be accounted for by the subject moving to and from the start and finish position for the task, and while holding the sponge to turn the plate over.

In most cases the data was close to or overlapping the boundary, indicating that subjects used some of their extremes of motion to achieve this task.

Figure 3.37 shows three graphs from a single subject carrying out the washing up task.

---

**Figure 3.37: Washing dishes (3 tests from one subject)**

While this plate only involved washing a plate, the plate was relatively large and heavy, and had to be turned over as part of the task. While the use of other items such as saucepans or glasses could give different results, the task was
originally identified as “washing dishes” so the use of plates was a reasonable experimental task. The large spread of data from just washing a plate indicates that any other form of washing up might be a critical activity, and in practical terms a plate might be the minimum washing-up requirement, considering that it is easy to cook ready-made meals in disposable packaging without using saucepans whereas plates are usually required to serve meals. It could be argued that the task could be eliminated altogether by the use of a dishwasher, but, as with the other tasks from the Michigan Hand Questionnaire, this one was included to complete the full list of tasks.

3.4.11 Wash your hair

Subjects showed some variability during this task, in terms of which parts of the head they touched; some focussed on the side and top of the head, while others appeared to touch most parts of the head.

Figure 3.38 shows a typical graph of a subject performing the hair-washing task.

As expected, a fairly large range of motion in both directions can be seen, although this range did vary between subjects. The location of the centre of the data also varied between subjects, as did the tendency for some data to stray outside the boundary.

Some subjects completed the task entirely in ulnar deviation, and some completely in radial deviation.
3.4.12 Tie shoelaces/knots

The subjects used a varying range of tying methods, including: tying two loops around each other to form the knot; tying a standard shoelace knot; and tying double knots. This variability was deliberately allowed in the testing, as it was a true representation of what the subjects usually did. Some variability between subjects was therefore expected, although the location of the task was quite well defined in space as the subjects all crouched on the floor with the hands on the shoelaces.

A typical graph of data from this task is given in Figure 3.39.

![Graph of tying shoelaces](image)

Figure 3.39: Typical graph of tying shoelaces

A wide spread of data can be seen in both directions, indicating that a large range of motion was used to achieve the task. The data tended to be centred around neutral or in some extension. Because of the large range of the data, there was some proximity to the boundary in most cases.

Three repeated graphs from a single subject are given in Figure 3.40.
Figure 3.40: Tying shoelaces (3 tests from one subject)

These graphs show good consistency in the overall shape and size of the motion range used by one subject to perform the task.

3.4.13 Overview of tasks

A clear indicator of the overall range of motion used during the experiments can be seen by plotting all twelve tasks on the same graph for each of the subjects. Two examples are given in Figure 3.41.
3.5 Quantifying task characteristics

The data from the eighteen subjects were also analysed quantitatively, by considering the important features that had emerged when looking at the data qualitatively. By calculating three different types of parameters for each task, different characteristics of the wrist motion used during the tasks could be seen numerically. These parameters were deemed to provide information that clinicians would want to know about how the tasks were performed.

The following three quantitative parameters were used for analysis: Area Ratio, Mean Location and Range of Motion. These are described below, and the full MATLAB code used to calculate them is given in Appendix D.

3.5.1 Area ratio parameter

This parameter was designed to indicate how much of a subject’s overall envelope of motion, i.e. their extreme motion ellipse, was used during each task. The value of the parameter was a simple ratio of the number of different points seen on an angle-angle plot, divided by the area of the elliptical motion boundary for the corresponding subject. Each location point was only counted once, regardless of the number of times that it occurred during the test.
In order to achieve this, the two key functions of the MATLAB code were (i) to calculate the area of the estimated maximum range of motion ellipse for a subject, and (ii) to calculate the number of different angular data points used during each task.

The ellipse was calculated as before, and its two main dimensions, \texttt{FEActiveRange} and \texttt{RUActiveRange}, were determined.

The frequency matrix used previously was generated for each task, but the frequency of each non-zero value in the matrix was set to 1 to give a “map” of the points used during each task, called \texttt{Freq\_count}. The contents of this matrix were then summed, and divided by the area of the ellipse, to give the ratio \texttt{AREAUSED}:

\begin{verbatim}
%====================================================================
\texttt{AREAUSED} = sum(sum(Freq\_count))/(FEActiveRange*RUActiveRange*pi)
%====================================================================
\end{verbatim}

Figure 3.42 shows the values of the “area ratio” parameter calculated for each task, averaged over all subjects. This plot and subsequent plots also show error bars of ±1 standard deviation about the mean.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{area_ratio_plot.png}
\caption{Area ratio calculated for each task}
\end{figure}
The three tasks with the highest area ratios were:

- buttoning a shirt
- washing dishes
- tying shoelaces.

The knife and fork, carrying a bag and washing the hair activities also used a significant amount of the available range of motion.

3.5.2 Mean location parameter

This parameter was a measure of the “central” position of the motion data in each of the two directions in isolation, defined as the average of the data from each of the two sensor channels.

The MATLAB code to calculate this parameter was very straightforward, and was a simple average value of the angular data (in degrees) from each channel:

```matlab
LOCATIONFE = mean(TrueAngles_task(:,1));
LOCATIONRU = mean(TrueAngles_task(:,2));
```

Figures 3.43 and 3.44 show the averaged value of the “mean locations” of the data for each task, for each of the two directions of motion of the wrist.

![Figure 3.43: Mean location of tasks in the flexion/extension direction](image)
For all of the measured tasks, the mean location of the data was in extension, rather than flexion, and some of these location values were around 20 degrees from the neutral position in that direction.

However, in the other direction of wrist motion, there was a much more even distribution between radial and ulnar deviation, and more of the tasks were located relatively close to the neutral position in that plane.

These findings indicate that, for the measured tasks, the wrist motions tended to favour extension rather than flexion, and that small amounts of both radial and ulnar deviation were used to complete the tasks.

The notable exceptions to this are the frying pan, knife and fork, and key turning activities, which were centred, on average, at over 15 degrees from the neutral position in the radial/ulnar deviation plane.

The tasks which showed the largest mean location in flexion or extension were:

- turning a key
- opening a jar
- washing dishes

These mean locations were all in extension, not flexion.

In the other plane, the tasks with the highest values of ulnar or radial deviation were:
• holding a frying pan
• using a knife and fork
• turning a doorknob

However, it must be considered that this parameter was more susceptible to the effects of any neutral-shift during testing than the area parameter was, as it was based on absolute location data rather than neutral-datum data relative to a neutral-datum ellipse. This means that there is some scope for results close the neutral position to be assigned the wrong direction. For example, a small amount of physical flexion might, after a small neutral shift during the thirty minute test, be recorded as a small amount of extension, or vice versa. However, as this effect is greater on the small values close to the neutral position, and as the physical wrist motions close to the neutral position are considered to be less critical in the scope of this work, the effect can be considered to be small in the context of this study, and the location parameter can be considered to be a useful measure for each plane of motion.

3.5.3 Range of motion parameter

This parameter gave a measure of the range of motion used in each of the two planes of motion by calculating the difference between the maximum and minimum location in each of the two planes for each test.

The relevant part of the MATLAB code was as follows.

The maximum and minimum angular values were identified from each test file.

```matlab
%calculate max and min and range for both channels
FEMAX = max(TrueAngles_task(:,1));
FEMIN = min(TrueAngles_task(:,1));
RUMAX = max(TrueAngles_task(:,2));
RUMIN = min(TrueAngles_task(:,2));
```

These were combined to give ranges of motion in each direction, taking account of whether the maximum and minimum values were “positive” (e.g. extension) or “negative” (e.g. flexion).

```matlab
if FEMAX > 0
    FERANGE = FEMAX - FEMIN;
else
```
FERANGE = -(FEMIN - FEMAX);
end

if RUMAX > 0
    RURANGE = RUMAX - RUMIN;
else
    RURANGE = -(RUMIN - RUMAX);
end

The ranges of motion in the two directions are given in Figures 3.45 and 3.46, again using values averaged over all of the tests carried out for each task.

![Figure 3.45: Mean range of flexion/extension during tasks](image)

The three tasks in which subjects used the greatest amounts of flexion and extension range were:

- buttoning a shirt
- washing dishes
- tying shoelaces
The three tasks in which subjects used the greatest amounts of radial/ulnar deviation range were:

- washing dishes
- tying shoelaces
- eating with a knife and fork

Comparing these figures with those found by Palmer et al in their study of 52 occupational and daily living tasks, the range of motion in the flexion/extension direction found in that study was 30 degrees of extension and 5 degrees of flexion, i.e. a total range of 35 degrees. The results given in Figure 3.45 showed that six of the twelve measured tasks were completed using a range of more than thirty degrees, and two of the tasks used a range of over 60 degrees.

Figures 3.45 and 3.46 indicate that where subjects used a large range of motion in one direction, they also used a large range of motion in the other direction. A similar effect can be seen for small ranges of motion. This shows that the tasks tended to involve both of the two measured planes of motion to a similar extent. The use of range data from either one of the two directions could therefore be used as a simple indicator of the spread of the data for any of the measured tasks.
3.5.4 Variability of parameters
In addition to mean values of the parameters for each test, the spread of the parameter data was also so considered to be a useful measure, as it was an indication of how consistent the different subjects were at performing each task.

The standard deviations for the tasks, as shown on the “mean value” parameter graphs, are given in Table 3.1 for clarity.

<table>
<thead>
<tr>
<th></th>
<th>Standard Deviation of each parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area Ratio (x1000)</td>
</tr>
<tr>
<td>Turn a doorknob</td>
<td>0.58</td>
</tr>
<tr>
<td>Pick up a coin</td>
<td>0.68</td>
</tr>
<tr>
<td>Hold a glass of water</td>
<td>0.09</td>
</tr>
<tr>
<td>Turn a key in a lock</td>
<td>0.28</td>
</tr>
<tr>
<td>Hold a frying pan</td>
<td>0.05</td>
</tr>
<tr>
<td>Open a jar</td>
<td>0.40</td>
</tr>
<tr>
<td>Button a shirt</td>
<td>2.05</td>
</tr>
<tr>
<td>Use a knife and fork</td>
<td>1.57</td>
</tr>
<tr>
<td>Carry a grocery bag</td>
<td>1.24</td>
</tr>
<tr>
<td>Wash dishes</td>
<td>2.56</td>
</tr>
<tr>
<td>Wash your hair</td>
<td>2.27</td>
</tr>
<tr>
<td>Tie shoelaces/knots</td>
<td>3.11</td>
</tr>
</tbody>
</table>

*Table 3.1: Variability of parameters (highest 3 values for each parameter highlighted in bold)*

The bold values are the three highest standard deviations for each parameter, indicating the tasks which showed the least consistency between subjects.

3.6 Reducing the task list
By combining the information described above and the practical aspects of setting up each task for measurement, it was possible to consider reducing the number of tasks on the original Michigan Hand Questionnaire list to give a shortlist of tasks which were suited both to clinical measurement, and were also
representative of the original list. These could then be used in a hand clinic to capture a useful picture of a patient’s wrist motion.

3.6.1 Step One: Eliminating variable tasks
The following tasks were discounted because the test results showed that there was too much variability in their results (i.e. that they were in the top three tasks for variability in at least two parameters, as shown in Table 3.1), thus making them prone to producing less useful results in clinic than the other tasks:

- Eating with a knife and fork
- Opening a jar
- Washing dishes
- Washing hair

The remaining tasks were then considered in terms of the overall physical ability of the patient.

3.6.2 Step Two: Considering patients’ abilities
The ability of the patient to use their whole body had to be considered when selecting tasks. Patients with some conditions, for example rheumatoid arthritis, could well have other affected joints that would mask or hinder the wrist motion used during the tasks.

Each of the remaining tasks was considered in turn in this context:

<table>
<thead>
<tr>
<th>Task</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning a doorknob</td>
<td>This required grip strength and dexterity of the fingers</td>
</tr>
<tr>
<td>Picking up a coin</td>
<td>This required dexterity of the fingers</td>
</tr>
<tr>
<td>Holding a glass of water</td>
<td>Little movement was required of other joints, even in the upper limb.</td>
</tr>
<tr>
<td>Turning a key in a lock</td>
<td>This required little movement of other joints</td>
</tr>
<tr>
<td>Holding a frying pan</td>
<td>This required little movement of other joints</td>
</tr>
<tr>
<td>Buttoning a shirt/blouse</td>
<td>Some elbow motion was required</td>
</tr>
<tr>
<td>Carrying a grocery bag</td>
<td>This required walking</td>
</tr>
<tr>
<td>Tying shoelaces /knots</td>
<td>This required significant flexibility at the hips and knees</td>
</tr>
</tbody>
</table>
As a result of this, the following tasks were eliminated:

- Turning a doorknob
- Picking up a coin
- Carrying a grocery bag
- Tying shoelaces/knots

This left four tasks in the list:

- Holding a glass of water
- Turning a key in a lock
- Holding a frying pan
- Buttoning a shirt/blouse

All of these tasks could be carried out while sitting down, which would make them accessible to patients with lower limb difficulties.

**3.6.3 Step Three: Checking that remaining tasks involved a range of aspects of wrist motion**

The next step was to check that these tasks did not duplicate one another, and represented, between them, different aspects of wrist motion.

- Holding a glass of water: This represented a static task i.e. with a small range of motion in both directions of motion, in a neutral radial/ulnar deviation position with a small amount of extension.

- Turning a key in a lock: This represented a moderate range of motion in both planes of motion, and extremes of mean location in both extension and radial deviation. It was also a task that involved twisting of the hand, which was not required in the other three short-listed tasks.

- Holding a frying pan: This task represented another static task, this time with more weight than a glass of water. As with holding a glass of water, the task required the subjects to hold the frying pan not just in any way but also in a controlled way. It also represented extreme ulnar deviation, which the glass-holding task did not.

- Buttoning a shirt/blouse: This final task represented a large range of motion in flexion/extension and a moderate range of motion in
radial/ulnar deviation. This also had a high value of the parameter “area ratio”, being in the top three tasks for this parameter, indicating that this task encompassed a large proportion of the subject’s possible range of motion envelope.

- A one-way ANOVA (analysis of variance) was also performed on the four short-listed tasks, based on the mean location parameters in both the flexion/extension and radial/deviation planes. The results indicated that, for both of those planes, there were significant differences between the tasks. In the cases of both flexion/extension (F=9.2) and radial/ulnar deviation (F=27.7), there were significant differences with a confidence interval of P=0.001.

The descriptions and analysis above indicate that the four tasks chosen for the shortlist encompassed a wide range of aspects of functional wrist motion and were therefore a sensible choice to represent the twelve original tasks.

3.6.4 Practical consideration of setting up the four tasks
As for the laboratory experiments, the short list of tasks had to be easy to set up in a clinical context, where space, time and funding are both limited. The props required for the short-listed tasks were:

- A glass (or other drinking container)
- Access to water – easily available in clinical environments
- A key-and-lock set-up
- A frying pan
- A shirt/blouse

All of these would be low cost and simple to provide and would take up very little space when being stored or used. Patients could provide their own shirt as in the laboratory test, as this would eliminate the need for a clinic to provide a range of sizes of shirt to suit a wide range of patients. However this would involve additional co-operation with the patient and might not be reliably provided. An alternative would be to develop an “adjustable shirt” which could be provided by the clinic and adapted to fit each patient.
3.6.5 Task shortlist
Following the assessments above, the original twelve tasks taken from the Michigan Hand Questionnaire were successfully reduced to the following shortlist of four tasks:

- Hold a glass of water
- Turn a key in a lock
- Hold a frying pan
- Button a shirt/blouse

3.6.6 Verifying the shortlist on angle-angle plots
In order to test further whether this shortlist was a valid substitution for the original list, graphs of some subjects’ test data were produced. These were identical in format to the “all task” graphs produced for each subject, on angle-angle plots, so that the overall effect of reducing the shortlist could be seen. These results are shown for two subjects in Figure 3.47 and 3.48. Appendix E gives shortlist graphs for all subjects.

![Figure 3.47: (a) All tasks and (b) the short-listed tasks, for one subject](image)

*Figure 3.47* (a) All tasks and (b) the short-listed tasks, for one subject
The two examples above are typical of the results seen in all subjects. On initial examination it appeared that much of the data was left out when the task list was reduced to just four tasks. However, the dishwashing task accounted for the majority of the missing data, and the four short-listed tasks gave a good representation of the flexion/extension range for all of the tasks. The extreme ulnar deviation data which was typically covered by the dish washing task was accounted for by the single location of the frying pan task, which could be seen clearly in isolation on the left hand side of most subjects’ shortlist graphs.

This confirmed that the choice of short-listed tasks was a good compromise and gave a reasonable representation of many of the aspects of functional wrist motion for the measured subjects.
3.7 Summary of the results

3.7.1 Data

The data collected in this work is clearly only representative of the subjects whose wrist motion was measured. Distinctions between, for example, male and female subjects cannot be drawn from the small number of subjects involved. However, the method was set up to include the data that would be needed to allow comparison between the wrist motion of different groups, e.g. by occupation or sex. This could be further extended by defining types of wrist injury or disease in patients to compare the results from, say, rheumatoid arthritis patients with osteoarthritis patients.

The data in this study was gathered only from one hand - the dominant, right hand - and this would have to be considered when adapting the measurement method for clinical use. It would clearly not be possible to control which hand (left or right, dominant or non-dominant) the patient presented to the clinician with regard to injury or disease. It is interesting to note that outcomes measures such as the Michigan Hand Questionnaire do not appear to weight the scores in relation to the dominance of the hand or wrist and the resulting impact on the patient.

As it stands, the data from this study could certainly be used as sample data in biomechanics settings, such as in the wrist joint simulator developed at the University of Bath. This would allow the simulator to run using real input data from normal subjects.

3.7.2 Methods

The methods described in this thesis for collecting and handling wrist motion data are intended to give rise to practical applications, and as such may not provide a level of accuracy that might be expected of detailed biomechanical measurement studies. However, there are several fundamental benefits to using the methods developed here in practical, clinical applications.

The single most effective means of displaying the data appears to be the use of elliptical estimated motion envelopes for individual subjects or patients. This simple addition to an angle-angle plot of any measured data immediately puts the data into a meaningful context for an individual. The accuracy of the envelope and the datum used to place it on the axes could be refined, but it is believed that the approach used here is useful in its current form.
The development of frequency plots to map out the frequency of occurrence of the motion data has not been explored extensively, but immediately gives an extra dimension to the data which cannot be appreciated from the angle-angle plots alone.

The biggest practical tool developed in this work has been the combination of a reduced list of four key tasks with the method of displaying the measured task data in the context of each individual’s possible motion envelope. The simple approach of using commercially available, portable measurement equipment to measure just four tasks using only simple, low-cost props provides a practical, quick and easy to use method of capturing key data from patients about a wide range of the aspects of their wrist motion.

The results of this work were discussed with Mr Giddins, the consultant orthopaedic and hand surgeon, who agreed that while there was still some work to be done in developing the measurement approach into a practical clinical tool, the data plots showed valuable information about the individual tasks, and could be used to prompt further research questions. These questions included further investigation of the extremes of motion plot data, for example in Figure 3.7, to determine the angles of offset from horizontal and vertical axes seen when subjects were asked to perform unrestricted “in-plane” motions; and more detailed study of the relationship between the motions used during tasks and the maximum possible motions. Further work measuring patients with known wrist pathologies would also be a useful direction to take following the work carried out in this thesis.
4 Conclusions

The wrist is known to be a complex joint, although its motion can be considered broadly in terms of just two planes of motion. The early part of this thesis established that there was a need for more data on wrist motion, and in particular the “functional wrist motion” used by people carrying out every day tasks. In a clinical setting, there was a need for straightforward, practical means of evaluating patients’ wrist function based on their ability to achieve certain wrist motions and postures.

The purpose of this study was to develop and use methods for measuring the wrist motion of healthy subjects during a series of tasks, with a view to building a useful measurement tool for clinical use.

The original objectives are listed below, and reviewed in terms of the work carried out and the results obtained.

To choose a set of relevant tasks to use to study wrist motion

The set of tasks chosen for study were taken from an outcome measure, which was not originally intended for a measurement context. It did however give a useful starting point, as the tasks listed in the Michigan Hand Questionnaire were all included because they gave an indication of a patient’s ability to use their wrist or wrists in everyday living.

The list of twelve tasks was not intended to be all encompassing, and did not necessarily include the most extreme tasks, but it did include ones whose impact on patients was relevant in a clinical setting. The chosen tasks were all reproducible to a large extent in a laboratory setting, so that the complete range of tasks could be assessed.

Some tasks could be considered to be more relevant to hand motion than wrist motion, as the original outcome measure applied both to the hand and the wrist. However, all of the tasks did require some involvement of the wrist, even though some required only small motions. The study could be repeated using other methods where the motion of the hand, rather than the wrist, was of particular interest, by using the same set of tasks.
To choose appropriate measurement equipment and develop experimental methods for measuring wrist motion during the chosen tasks

An electrogoniometer was chosen from several possible types of equipment. The electrogoniometer was chosen because of its suitability for both a laboratory and clinical setting, being portable and simple to use, with specific sensors being available for measuring wrist motion. It was also commercially available, and allowed simple checks to be made to check the calibration of the sensors in a clinical setting where time is limited.

While the goniometer could suffer from some cross-talk between channels, and by skin movement in forearm rotation to some extent, these were both considered and found to be small enough to be tolerated in the context of the required level of accuracy.

The sample rate could be reasonably increased from 50Hz to 100Hz to allow increased accuracy of data collection, particularly if rapid motions were to be measured, given that larger amounts of data could be stored and processed than were used in this study.

The rapid set-up time and small storage space required by the electrogoniometer system made it well-suited to a clinical setting, and the small size of the sensor did not appear to inhibit the subject’s normal motion during the measurement of the different tasks.

The design of the neutral datum for the equipment was simple to use, and although its accuracy could be improved this would add to the time and complexity of the set-up when measuring patients' wrist motion. The datum position used was considered to be a useful compromise between ease of set-up and accuracy.

Measurements of extremes of motion at the end of each subject’s testing, as well as at the beginning, could provide a useful indicator of the consistency of maximal wrist motion.

To measure the functional wrist motion of a group of normal subjects during the chosen tasks

A set of experiments was designed for all twelve tasks, using props where necessary, being careful to strike a balance between realistic and
accurate reproductions of the tasks and simplicity of set-up. The concept of measuring the tasks “as they would normally be performed” was adhered to as much as possible in the design of the tasks and the experimental protocol with the subjects.

All twelve chosen tasks were successfully measured using the methods and protocol designed at the start of the experimental work. The mock-ups of the tasks were outlined in detail, so that the results of this study could be considered by other researchers in appropriate terms.

To develop programs to display this data in ways which show useful context to an individual subject’s motion patterns

Programs were written using MATLAB to: manipulate the raw data to produce two-channel motion data in degrees; to demonstrate a motion envelope in an angle-angle plot of the wrist motion in two planes; and to display the space plots in terms of frequency of occurrence of each of the co-ordinate points.

The single most effective piece of programming was the code that generated the elliptical motion envelope for each individual’s maximum motion ranges. This gave a very clear and immediate indication of where the motion data lay in the context of an individual’s own capabilities, not simply in terms of a neutral position on a set of axes. While the data used to generate the elliptical motion envelopes could be more refined, the method used was simple and therefore convenient to gather, and was considered to be appropriate in the context of this study.

The frequency plots provided an additional means of looking at the data in order to highlight features that might not be apparent on simple angle-angle plots.

To identify, qualitatively and quantitatively, characteristics of the wrist motions used to carry out the tasks

Angle-angle plots of each task were presented and discussed and key qualitative aspects of all of the tasks were identified. Some tasks, such as holding a glass of water and a frying pan proved to be static tasks, as expected, whereas buttoning a shirt proved to use a surprisingly large range of motion in both measured planes of motion.
The magnitudes of the wrist motions measured during the tasks were consistent with those found in the literature.

Quantitative parameters were also used to define each of the tasks numerically, so that they could be compared. The standard deviations of the parameters were also used to give a measure of how consistent the wrist motion was between subjects and tests for each task.

*To produce a clinically useful shortlist of tasks from the original list of tasks*

Using the quantitative parameters and the practical knowledge gained from designing and measuring the twelve tasks, the original list of twelve tasks was reduced to include only the following four tasks:

- Holding a frying pan
- Turning a key in a lock
- Buttoning a shirt
- Holding a glass of water

This shortlist was validated by comparing a graph combining all twelve tasks for a subject against a graph combining only the four short-listed tasks. The four tasks were shown to incorporate, between them, most aspects of the twelve tasks.

The combination of this shortlist of tasks with the ability to display the measured data from these tasks within the context of an individual’s own possible motion envelope was considered to be a very powerful potential tool for clinical use, as it could allow clinicians to gain a picture very rapidly of many aspects of a patient’s wrist motion and hence a significant aspect of the overall function of their wrist.

Overall, the objectives set out at the start of this thesis were met successfully, although it is acknowledged that there was scope for refining some of the details of the methodology. The different aspects of the work not only provided scope for further study but also lent themselves to applications above and beyond the direct clinical tool implied by the measurement of the short-list of tasks, which are discussed in the following chapter.
5 Further Work and Applications

The work described in this thesis has drawn on different aspects of biomechanical measurement and clinical need, and therefore had the potential to form the basis for further study in this area. Some of these potential methods and applications arising from this work are outlined in this chapter.

5.1 Motion studies

The use of electrogoniometers to measure wrist motion was found to be a practical approach with an appropriate level of accuracy, and the portability of the equipment lends itself to other studies. For example, the equipment could be attached to a subject for longer duration measurements so that, for example, different occupational or recreational activities could realistically be studied over several hours.

The commercially available electrogoniometers could also be used to measure the motion of other joints in the body, as many specifically designed sensors exist for different types of joint.

The scope for clinical studies is wide ranging, and could include inter- and intra-patient measurements over time to evaluate a patient’s progress and the changes in motion caused by disease, injury and treatment. The use of the shortlist of tasks would be a sound basis for further study of different patient groups, and the measurement of “baseline” data from a large number of normal subjects could be used to place a patient’s data in relation to a person whose wrists were not injured or diseased.

5.2 Data handling and display

Setting the task data in the context of each individual’s own motion envelope was found to be a very usual visual aid to understanding the motion used by each individual, and made comparison between individuals much clearer than simple data plots. This approach could be extended for use in other joints, provided that a suitable method for generating a relevant motion envelope for the joint in question.

Similarly, the use of simple programs to generate frequency plots of the data could be applied to the measurement of other joints.
5.3 Using the acquired data

The data obtained in this study could be used to drive the wrist simulator which has been designed and built in the Department of Mechanical Engineering. The raw data would simply need to be adapted into the correct file format and read by the simulator’s controller, so that the artificial wrist joint mounted in the simulator could be moved through the real motions captured from the subjects in this study, and hence “copy” real wrist motions. This allows one of the key aspects of wrist joint design, namely possible dislocation, to be studied as though the joint were implanted into a healthy wrist.

In more general terms, the graphs of the data that are provided in Appendix E of this thesis give clear indications of the key features seen when normal subjects performed all of the tasks in the Michigan Hand Questionnaire, which could be used by clinicians or in biomechanical studies for information and for comparison with their own work.

5.4 Data glove work

The data gloves discussed in the early part of this thesis provide scope for related work, and by establishing carefully the accuracy of the available data gloves and developing appropriate calibration methods, these could be used to capture rapidly data from the hand and fingers during the tasks which were studied here using the goniometer. The results of these measurements could be compared with the data from the goniometer, provided that the underlying assumptions were carefully considered and that like measurements were compared.

This approach could be further enhanced by incorporating pressure sensors into the fingertip of a data glove. There is currently a set of equipment in the Department which is intended for this type of measurement: Novel pressure sensors (see Appendix A). These are round, low profile pressure sensors suitable for measuring fingertip pressure, and by using these inside the fingers of the data glove an extra dimension could be added to the gathered data. The use of these two types of equipment together, which are both portable, would allow a great deal of information to be gathered about a task or action with minimal disruption to the activity itself.

5.5 Designing interfaces

One of the barriers that can prevent medical professionals from adopting new equipment is the “laboratory” nature of their use and the unfamiliarity of the
output data format. These can require time that is simply not available in a clinical setting, and hence remain unused despite the potential benefits both the patient and the clinician.

There is therefore potential for the design of user interfaces which are tailor made to the needs of the clinician and provide the required information “at a glance” so that it is desirable to use. For example, a simple screen which allowed the display of a single patient’s data from several different clinic visits over time at the touch of a button would be much more useful than a combination of separate screens derived from different software.

Detailed consultation with the medical practitioners who would be using the equipment could certainly produce valuable interfaces that would encourage the adoption, not just the theoretical design, of the wrist motion measurement methods.
References


the United Kingdom: new estimates for a new century, Rheumatology, 41(793-800.


Appendix A: Specification Details

Goniometer

Equipment supplied by Biometrics Ltd, Gwent, Wales

SG65 wrist sensor used with Biometrics datalogger and ADU301 angle display unit

Biometrics software DL1001, Version 3.2

Data gloves

Custom-made glove by noDna GmbH, Cologne, Germany, supplied by Inition Ltd, London

Commercial 14-sensor data glove and GloveManager software by 5DT, supplied by Inition, London

Animation software Motionbuilder 7 by Autodesk, California

Programming software

MATLAB version 6.5.0 by The MathWorks Inc

Pressure sensors

S2011 single sensors by Novel GmbH, Munich, Germany
Appendix B: Michigan Hand Questionnaire

Full Michigan Hand Questionnaire

Study ID _______

MICHIGAN HAND OUTCOMES

QUESTIONNAIRE (MHQ)

Today's date: __________

Month  Day  Year

Copyright by the Regents of the University of Michigan
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 EACH 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 EACH question, even if you do not experience any problems with the hand or 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. How well did your right thumb move?</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>3</td>
<td>4</td>
<td>5</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. How well did your left thumb move?</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>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
2. The following questions refer to the ability of your hand(s) to do certain tasks during the past week. (Please circle one number for each question). If you do not do a certain task, 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></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 a coin</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 frying pan</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></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 a coin</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 frying pan</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></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 button</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. Eat with a knife and fork</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. Tie shoelaces</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
III. The following questions relate to how you did in your normal work (including both homework and school work) during the past/our week. (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. How often were you unable to do your work because of problems with your hand(s)/wrist(s)?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. How often did you have to share your work day because of problems with your hand(s)/wrist(s)?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. How often did you have to take a day off work because of problems with your hand(s)/wrist(s)?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. How often did you accomplish less in your work because of problems with your hand(s)/wrist(s)?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5. How often did you take longer to do the tasks in your work because of problems with your hand(s)/wrist(s)?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
IV. The following questions refer to how much pain you had in your hand(s)/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-A1 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

<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>3. How often did the pain in your right hand/wrist interfere with your sleep?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. How often did the pain in your right hand/wrist interfere with your daily activities (such as eating or bathing)?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5. How often did the pain in your right hand/wrist make you unhappy?</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 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 IV-31 above, please skip the following questions and go to the next page.

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

<table>
<thead>
<tr>
<th>Always</th>
<th>Often</th>
<th>Sometimes</th>
<th>Rarely</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

3. How often did the pain in your left hand/wrist interfere with your sleep?

<table>
<thead>
<tr>
<th>Always</th>
<th>Often</th>
<th>Sometimes</th>
<th>Rarely</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

4. How often did the pain in your left hand/wrist interfere with your daily activities (such as eating or bathing)?

<table>
<thead>
<tr>
<th>Always</th>
<th>Often</th>
<th>Sometimes</th>
<th>Rarely</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

5. How often did the pain in your left hand/wrist make you unhappy?

<table>
<thead>
<tr>
<th>Always</th>
<th>Often</th>
<th>Sometimes</th>
<th>Rarely</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
V. A. The following questions refer to the appearance (look) of your right hand during the past week. (Please circle one answer for each question.)

<table>
<thead>
<tr>
<th></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>

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

<table>
<thead>
<tr>
<th></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>
<tr>
<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>
VI. A. The following questions refer to your satisfaction with your right hand/wrist during the past week. (Please circle one number for each question.)

<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>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. Motion of the finger in your right hand</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. Motion of your right wrist</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. Strength of your right hand</td>
<td>1</td>
<td>2</td>
<td>3</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>3</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>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

B. The following questions refer to your satisfaction with your left hand/wrist during the past week. (Please circle one number for each question.)

<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>
<td>1</td>
<td>2</td>
<td>3</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>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. Motion of your left wrist</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. Strength of your left hand</td>
<td>1</td>
<td>2</td>
<td>3</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>3</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>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
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 problem with your hand(s)?
   a. Yes
   b. No

   Please describe the type of job you did before you had problem 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. Hispanic
   d. Asian or Pacific Islander
   e. American Indian or Alaskan Native
   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
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

Thank you very much for completing this questionnaire.
Appendix C: Ethical Approval Samples

Ethical approval forms

Projects Involving Human Subjects

Department of Mechanical Engineering

Consent Form

Researcher: .................................................. Position (U/D/FO): ..................
Supervisor: ..................................................
Project Title: ..................................................
Project Number (if applicable): ........................................

Each person participating in this study should complete the following:

Yes No
1. Have you read the information sheet?   
2. Have you had the opportunity to ask for more information about the study?   
3. Are you happy with the answers to any questions you had, if any?   
4. Do you understand that you may choose to withdraw from the study at any time?   
5. Do you agree to take part in this study?

Signed (Participant): ..........................................
Print Name (Participant): .................................. Date: .................

Signed (Researcher): ........................................... Date: ..................

Department of Mechanical Engineering

Page 1 of 1

November 2006
Department of Mechanical Engineering
Information Sheet

Researcher: ........................................ Position (U/G/PG/RC): ........................................
Supervisor: ................................................ Project Title: ................................................
Project Number (if applicable): ................................................

You are being asked to take part in a study to help with a research project.

The overall purpose of this study is:
........................................................................................................................................................................
........................................................................................................................................................................
........................................................................................................................................................................
........................................................................................................................................................................

The experiments will be carried out as follows:
........................................................................................................................................................................
........................................................................................................................................................................
........................................................................................................................................................................
........................................................................................................................................................................

The duration of your involvement in the experiments is likely to be:
........................................................................................................................................................................
........................................................................................................................................................................
........................................................................................................................................................................
........................................................................................................................................................................

If you decide to take part in this study, you may choose to withdraw from this study at any time, and for any reason. Any data collected during these experiments will be kept anonymous and confidential.

If you would like any further information about this study, please contact:

Researcher: ........................................ Department: ........................................
Telephone: ........................................ Email: ........................................
Department of Mechanical Engineering

Ethical Considerations for Projects Involving Human Subjects

Researcher: ........................................ Position (UG/PG/VRO): ................
Supervisor: ........................................ Project Title: .................................................................
Project Number (if applicable): .................................................................

Brief description of project and/or relevant experiments:
........................................................................................................................................
........................................................................................................................................
........................................................................................................................................

Complete the questions below:

1. Are the subjects healthy, willing to enroll?
   [ ] Yes [ ] No [ ] N/A

2. Will informed consent be obtained from each participant (see attached sample consent form and information sheet)?
   [ ] Yes [ ] No [ ] N/A

3. Will the participants be free to withdraw from the experiment if they wish?
   [ ] Yes [ ] No [ ] N/A

4. Will all data collected (personal data and measured data) be confidential and encrypted?
   [ ] Yes [ ] No [ ] N/A

5. Will the experiments involve any invasive procedures?
   [ ] Yes [ ] No [ ] N/A

6. Are the participants likely to be subjected to any physical discomfort?
   [ ] Yes [ ] No [ ] N/A

7. Are the participants likely to be subjected to any higher risks than those normally expected in everyday activities?
   [ ] Yes [ ] No [ ] N/A

Details:
........................................................................................................................................
........................................................................................................................................
........................................................................................................................................

Department of Mechanical Engineering ........................................ Page 1 of 2 ........................................ November 2005
Supervisor's comments

______________________________________________________________________

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______________________________________________________________________

Is LREC ethical approval required for the work? (where as appropriate) Yes/No

If yes, refer to Research Committee/Head of Department

If not, file copy to Head of Department's Office

Combined data sheet form and information sheet to be stored by the researcher with other project information.

Supervisor's signature: ___________________________ Date: ________________

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Appendix D: MATLAB programs

Program to calibrate 5DT 14-sensor data glove

%==========================================================
% Gather data from 5DT 14 sensor dataglove output file
%==========================================================
% This uses a simple linear relationship to calibrate the
% numerical output from each sensor in degrees. The
% variables y, m, x and c in the code reflect this
% relationship.

% Data must be pure data text file minus all header info
% etc.
clc; clear; clf;

%----------------------------------------------------------
% Request and open relevant data file
%----------------------------------------------------------

disp(' ');
FName = input('Filename?','s');
fid = fopen(strcat(FName,'.txt'))

%----------------------------------------------------------
% Define data matrix (RawAll] as many-column matrix and a
% line break (|n) per row, with proportions (no of columns,
% inf) and
% counts total number of samples (all channels at all
% times, e.g.
% sample freq x no. columns)
%----------------------------------------------------------

[RawAll,count]=fscanf(fid,'%f %f %f %f %f %f %f %f %f
%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f',[15 inf]);
RawAll = RawAll';

[a,b] = size(RawAll); % states b columns and a rows as
%size of data
fclose(fid);

%----------------------------------------------------------
% Request and open "zeros" calibration file to extract "c
% values"
%----------------------------------------------------------

disp(' ');
ZerosFile = input('Name of "Zeros" calibration
file?','s');
 fid = fopen(strcat(ZerosFile,'.txt'));
allzeros = fscanf(fid,'%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f',[15 inf])';
fclose(fid);

thumbnzero = mean(allzeros(:,2));
thumbfzero = mean(allzeros(:,3));
indexnzero = mean(allzeros(:,5));
indexfzero = mean(allzeros(:,6));
middlenzero = mean(allzeros(:,8));
middlefzero = mean(allzeros(:,9));
ringnzero = mean(allzeros(:,11));
ingelfzero = mean(allzeros(:,12));
littlenzero = mean(allzeros(:,14));
littlefzero = mean(allzeros(:,15));

cvals = [thumbnzero thumbfzero indexnzero indexfzero
middlenzero middlefzero ringnzero ringfzero littlenzero
littlefzero]
%---------------------------------------------------------
% Request and open "maxes" calibration file to extract "y
%values"
%---------------------------------------------------------
disp(' ');
MaxesFile = input('Name of "Maxes" calibration
file?','s');
fi = fopen(strcat(MaxesFile,'.txt'));

allmaxes = fscanf(fi,'%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f',[15 inf])';
fclose(fi);

thumbnmax = mean(allmaxes(:,2));
thumbfmax = mean(allmaxes(:,3));
indexnmax = mean(allmaxes(:,5));
indexfmax = mean(allmaxes(:,6));
middlenmax = mean(allmaxes(:,8));
middlefmax = mean(allmaxes(:,9));
ringnmax = mean(allmaxes(:,11));
ingelfmax = mean(allmaxes(:,12));
littlenmax = mean(allmaxes(:,14));
littlefmax = mean(allmaxes(:,15));

yvals = [thumbnmax thumbfmax indexnmax indexfmax
middlenmax middlefmax ringnmax ringfmax littlenmax
littlefmax]
%---------------------------------------------------------
% Request and open "maxangles" calibration file to extract
"x" values"
%---------------------------------------------------------
disp(' ');
MaxAnglesFile = input('Name of "MaxAngles" calibration
file?','s');
fi = fopen(strcat(MaxAnglesFile,'.txt'));


allmaxangles = fscanf(fid,'%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f',[15 inf])';
fclose(fid);


thumbnmaxang = mean(allmaxangles(:,2));
thumbfmaxang = mean(allmaxangles(:,3));
indexnmaxang = mean(allmaxangles(:,5));
indexfmaxang = mean(allmaxangles(:,6));
middlenmaxang = mean(allmaxangles(:,8));
middlefmaxang = mean(allmaxangles(:,9));
ingnmaxang = mean(allmaxangles(:,11));
ingfmaxang = mean(allmaxangles(:,12));
littlenmaxang = mean(allmaxangles(:,14));
littlefmaxang = mean(allmaxangles(:,15));

xvals = [thumbnmaxang thumbfmaxang indexnmaxang
indexfmaxang middlenmaxang middlefmaxang ringnmaxang
ringfmaxang littlenmaxang littlefmaxang]

%----------------------------------------------------------
% Use above values to calculate "m" values
%----------------------------------------------------------

for j=1:10
    mvals(1,j) = (yvals(1,j)-cvals(1,j))/xvals(1,j);
end
mvals

%----------------------------------------------------------
% Identify channels from raw data
%----------------------------------------------------------

Thumbn = RawAll(:,2);
Thumbf = RawAll(:,3);
Indexn = RawAll(:,5);
Indexf = RawAll(:,6);
Middlen = RawAll(:,8);
Middlef = RawAll(:,9);
Ringn = RawAll(:,11);
Ringf = RawAll(:,12);
Littlen = RawAll(:,14);
Littlef = RawAll(:,15);

%----------------------------------------------------------
% Convert raw data to degrees using conversion file
%----------------------------------------------------------

Thumbn = (Thumbn - cvals(1,1))/mvals(1,1);
Thumbf = (Thumbf - cvals(1,2))/mvals(1,2);
Indexn = (Indexn- cvals(1,3))/mvals(1,3);
Indexf = (Indexf - cvals(1,4))/mvals(1,4);
Middlen = (Middlen - cvals(1,5))/mvals(1,5);
Middlef = (Middlef - cvals(1,6))/mvals(1,6);
Ringn = (Ringn - cvals(1,7))/mvals(1,7);
Ringf = (Ringf - cvals(1,8))/mvals(1,8);
Littlen = (Littlen - cvals(1,9))/mvals(1,9);
Littlef = (Littlef - cvals(1,10))/mvals(1,10);

DegAll = [Thumbn Thumbf Indexn Indexf Middlen Middlef Ringn Ringf Littlen Littlef];
MeansDegAll = [mean(DegAll(:,1)), mean(DegAll(:,2)), mean(DegAll(:,3)), mean(DegAll(:,4)), mean(DegAll(:,5)), mean(DegAll(:,6)), mean(DegAll(:,7)), mean(DegAll(:,8)), mean(DegAll(:,9)), mean(DegAll(:,10))];
MeansDegNear = [MeansDegAll(:,1), MeansDegAll(:,3), MeansDegAll(:,5), MeansDegAll(:,7), MeansDegAll(:,9)]';
MeansDegFar = [MeansDegAll(:,2), MeansDegAll(:,4), MeansDegAll(:,6), MeansDegAll(:,8), MeansDegAll(:,10)]';
MeansGrouped = [MeansDegNear MeansDegFar]

% Display mean values of converted data as bar graph
%-----------------------------------------------
colormap(gray)
bar(MeansGrouped,'group')
xlabel('Digit number (1=thumb)')
ylabel('Mean flexion angle (degrees)')
title(FName)
legend('MCP Joint','PIP Joint')
axis([0 6 -10 90])

% Save whole plot to file
%-----------------------------------------------
disp(' ');
print('-dtiff',strcat('image'));
Program to extract raw data from goniometer datalogger:

**gather_raw_angles**

This program can be used to extract data from Biometrics Goniometer data files in text (.txt) format.

%==================================================
% Gathers raw data from a specified task file
%==================================================

%Get text data lines (Line 1 to Line 7) from beginning of file
L1 = fgets(fid);
L2 = fgets(fid);
L3 = fgets(fid);
L4 = fgets(fid);
L5 = fgets(fid);
L6 = fgets(fid);
L7 = fgets(fid);

%Find total number of characters in first few lines and call this value "Totalsize"
sL1 = size(L1,2);
sL2 = size(L2,2);
sL3 = size(L3,2);
sL4 = size(L4,2);
sL5 = size(L5,2);
sL6 = size(L6,2);
sL7 = size(L7,2);
Totalsize = sL1+sL2+sL3+sL4+sL5+sL6+sL7;

%Get numerical data from rows after L7
fseek(fid, Totalsize, 'bof');

%only reads data after Totalsize characters have been found (i.e. first 7 lines

[RawAngles,count]=fscanf(fid,'%f %f\n',[2,inf]);
%Defines RawAngles as a matrix with 2 columns (%f %f) %and a line break(\n)per row and data of proportions (%"2, inf"), and calculates the total number of data % samples collected from row 8

%close file when all relevant data has been gathered
fclose(fid);

%transpose RawAngles into a (many x 2) matrix
RawAngles = RawAngles';
Program to display data from a single task, relative to initial neutral position: \texttt{plot\_task}

```matlab
%==================================================================
% Convert and plot raw data from goniometer
%==================================================================
clf; clc; clear;

%----------------------------------------------------------
% choose subject to study
%----------------------------------------------------------
disp(' ');
subject = input('Which subject do you want to look at (one letter)?','s');

%----------------------------------------------------------
% extract "neutral" datum values from initial neutral task, %
% file 02 for any subject
%----------------------------------------------------------

fid = fopen(strcat((subject),',02','.',txt'));
gather\_raw\_angles;
FENeutralDatum = mean(RawAngles(:,1))
RUNeutralDatum = mean(RawAngles(:,2))

%----------------------------------------------------------
% generate and plot ellipse to approximate boundary of %
% angular motion
%----------------------------------------------------------

% open file containing extremes of motion
fid = fopen(strcat((subject),',03','.',txt'));

% call subroutine to gather raw data as a two-column %matrix
gather\_raw\_angles;

% convert raw data into degrees relative to initial %neutral
ADeg = (RawAngles(:,1)-FENeutralDatum)*1.8;
BDeg = (RawAngles(:,2)-RUNeutralDatum)*1.8;
TrueAngles\_ellipse = [ADeg BDeg];

% define max and min values for each channel, in %degrees
MaxActiveFE = max(TrueAngles\_ellipse(:,1));
MinActiveFE = min(TrueAngles\_ellipse(:,1));
MaxActiveRU = max(TrueAngles\_ellipse(:,2));
MinActiveRU = min(TrueAngles\_ellipse(:,2));

% plot ellipse of max and min active range
FEActiveRange = MaxActiveFE-MinActiveFE
RUActiveRange = MaxActiveRU-MinActiveRU
rectangle('Position', [MinActiveRU,MinActiveFE, RUActiveRange, FEActiveRange])
```

rectangle('Position', [MinActiveRU,MinActiveFE, RUActiveRange, FEActiveRange])

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eRange,FEActiveRange],'Curvature',[1,1],'LineStyle','.','FaceColor','none','EraseMode','xor')

hold on % keeps ellipse on plot while task data is gathered

%----------------------------------------------------------
% extract task data and convert to degrees, relative to %initial "neutral" datum
%----------------------------------------------------------

disp(' '); task = input('Which task do you want to plot? (give file number e.g. "01")','s'); fid = fopen(strcat((subject),(task),'.txt'));
% call subroutine to gather raw data as a two-column %matrix
gather_raw_angles;

% convert raw data into degrees relative to "neutral" clc
ADeg = (RawAngles(:,1)-FENeutralDatum)*1.8;
BDeg = (RawAngles(:,2)-RUNeutralDatum)*1.8;
TrueAngles_task = [ADeg BDeg];

%----------------------------------------------------------
% plot task data by overlaying onto boundary ellipse data %----------------------------------------------------------

%define and plot data
a = TrueAngles_task(:,1);
b = TrueAngles_task(:,2);
plot(b,a,'.k','MarkerSize',8);

%plot x=0 and y=0 lines for clarity
hold on
c = [0,0,0];
d = [-120,0,120];
plot(c,d,'k')
hold on
plot(d,c,'k')

%show and define grid, and define axis limits
grid on
axis([-80 80 -80 80]);

%define fontsize for axis numbering
set(gca,'Fontsize',[14]);

%define tick mark locations
set(gca,'XTick',[-120:20:120]);
set(gca,'YTick',[-120:20:120]);

%add title
title = input('Title for graph?','s');
title(strcat((subject),(task)));

%add axis titles
xlabel('Radial/Ulnar Deviation (Rad +ve) in degrees');
ylabel('Flexion/Extension (Ext +ve) in degrees');

%ensure square plot
axis square

%---------------------------------------------
% save plot to file
%---------------------------------------------

disp(' ');
print('dtiff',(strcat('c:\graphs\', (subject), (task))));
Programs to display a task in terms of frequency

%===============================================================================
% Find and plot frequency data
%===============================================================================
clf; clc; clear;

%----------------------------------------------------------
% choose subject to study
%----------------------------------------------------------
disp(' ');
subject = input('Which subject do you want to look at (one letter)?','s');

%----------------------------------------------------------
% extract "neutral" datum values from initial neutral task, %file 02
%----------------------------------------------------------
fid = fopen(strcat((subject),'02','.txt'));
gather_raw_angles;
FENeutralDatum = round(mean(RawAngles(:,1)));
RUNeutralDatum = round(mean(RawAngles(:,2)));

%----------------------------------------------------------
% extract task data and convert to degrees, relative to %initial "neutral" datum
%----------------------------------------------------------
disp(' ');
task = input('Which task do you want to plot? (give file number e.g. "01")','s');
fid = fopen(strcat((subject),(task),'.txt'));
gather_raw_angles;
ADeg = (RawAngles(:,1)-FENeutralDatum)*1.8;
BDeg = (RawAngles(:,2)-RUNeutralDatum)*1.8;
TrueAngles_task = [ADeg BDeg];

%divide by resolution of 1.8 to give integers
ADeg = (ADeg)/1.8;
BDeg = (BDeg)/1.8;

%restate TrueAngles as integer TrueAngles
IntTrueAngles = [ADeg BDeg];
AMax = max(ADeg);
BMax = max(BDeg);
AMin = min(ADeg);
BMin = min(BDeg);

%state size of rounded matrix values
[m,n]=size(IntTrueAngles);
%find shift values to shift all data to be positive so 
%that co-ordinates can be used as matrix row numbers (if not 
%already positive)

if AMin <= 0 
    ADegShift = (sqrt(AMin*AMin))+1+80;
elseif AMin == 1 
    ADegShift = 0+80
elseif AMin > 1 
    ADegShift = -(AMin-1) +80
end

ADeg = ADeg+ADegShift;

if BMin <= 0 
    BDegShift = (sqrt(BMin*BMin))+1+80;
elseif BMin == 1 
    BDegShift = 0+80
elseif BMin > 1 
    BDegShift = -(BMin-1)+80;
end

BDeg = BDeg+BDegShift;

%define size of matrix and populate this matrix with zeros

TMax = 150;
SMax = 150;
Freq(SMax,TMax) = 0;

%scan the raw data and populate the matrix with frequency 
%data about each co-ordinate point

for i=1:m 
    s=ADeg(i,1);
    t=BDeg(i,1);
    Freq(s,t) = Freq(s,t)+1;
end

Freq;
% this is the complete Frequency matrix, still shifted to 
% give positive, not true, values

%% to show all points as having a value of 1, the matrix 
%% "Freq_count" sets 
%% all non-zero values to be 1

% for i=1:TMax 
%     for j=1:SMax 
%         if Freq(i,j)>0;
%             Freq_count(i,j) = 1;
%         end
%     end

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% end

%------------------------------------------------------
% Display pseudo-color plot of Freq matrix
%------------------------------------------------------

colormap('default')

% EITHER: determine maximum frequency value for
colourscale
    disp(' ');
% C1 = 10; % i.e. a point appearing 10 or more times will
% show as black

% OR: alternatively, determine maximum normalised
% frequency value for colourscale

% Normalised Freq matrix is simply the values in Freq
% divided by the total number of (non-zero?) values in the
% frequency matrix

    sumfreq = sum(sum(Freq));
% gives total number of samples occurring in Freq %matrix
    Freq_norm = 100*Freq/sumfreq;
    Colour_ceiling = round(max(max(Freq_norm))); % defines max value in normalised Freq matrix
    C1 = Colour_ceiling;

% define colormap for colour plot
    a = [.2 .4 .6 .8 1]' % this gives 5 colour bands
    cm = [a a a];
    colormap(flipud(cm));

% Scale grid axes to display (real) data values
    Sx = BDegShift;
    Sy = ADegShift;
    X = 1:size(Freq,2);
    Y = 1:size(Freq,1);

% plot colour plot using scaled grid values
    subplot(1,3,2)
    pcolor((X-Sx)*1.8, (Y-Sy)*1.8, Freq)

% remove black lines from colour plot
    h = pcolor((X-Sx-u)*1.8, (Y-Sy-v)*1.8, Freq);
    h = pcolor(((X-Sx)*1.8), ((Y-Sy)*1.8), Freq);
    set(h,'EdgeColor','none');

% set max and min values on colour scale
    set(gca,'CLim', [0,C1])

% define fontsize for axis numbering
    set(gca,'Fontsize',[14]);
% add colour bar
colorbar('vert')
ch = colorbar
set(ch,'fontsize',14);

% add title
title(strcat('Frequency plot',',',subject,',',task))

% add axis titles
xlabel('Radial/Ulnar Deviation (Rad +ve)')
ylabel('Flexion/Extension (Ext +ve)')

axis square
%------------------------------------------------------
% Save whole plot to file
%------------------------------------------------------

disp(' ');
print('-dtiff', strcat((subject),(task),'frequency'));
Programs to calculate parameter values
Find_parameters or something

%=================================================================
% Convert and plot raw data from goniometer
%=================================================================

clf; clc; clear;

%----------------------------------------------------------
% choose subject to study
%----------------------------------------------------------

disp(' '); 
subject = input('Which subject do you want to look at (one letter)?','s'); 

%----------------------------------------------------------
% extract "neutral" datum values from initial neutral, file 02 
%----------------------------------------------------------

fid = fopen(strcat((subject),'02','.txt'));
gather_raw_angles;
FENeutralDatum = round(mean(RawAngles(:,1))); 
RUNeutralDatum = round(mean(RawAngles(:,2)));

%----------------------------------------------------------
% extract task data and convert to degrees, relative to 
% initial "%neutral" datum
%----------------------------------------------------------

disp(' '); 
task = input('Which task do you want to plot? (give file number e.g. "01"),'s'); 
 fid = fopen(strcat((subject),(task),'.txt'));
gather_raw_angles; 
ADeg = (RawAngles(:,1)-FENeutralDatum)*1.8; 
BDeg = (RawAngles(:,2)-RUNeutralDatum)*1.8;

%----------------------------------------------------------
% calculate parameters
%----------------------------------------------------------

%calculate max and min and range for both channels 
FEMAX= max(TrueAngles_task(:,1)); 
FEMIN = min(TrueAngles_task(:,1)); 
RUMAX = max(TrueAngles_task(:,2)); 
RUMIN = min(TrueAngles_task(:,2));
if FEMAX > 0
    FERANGE = FEMAX - FEMIN;
else
    FERANGE = -(FEMIN - FEMAX);
end

if RUMAX > 0
    RURANGE = RUMAX - RUMIN;
else
    RURANGE = -(RUMIN - RUMAX);
end

%calculate region covered, by summing all non-zero values in Freq matrix

%divide by resolution of 1.8 to give integers
ADeg = (ADeg)/1.8;
BDeg = (BDeg)/1.8;

%restate TrueAngles as integer TrueAngles
IntTrueAngles = [ADeg BDeg];
AMax = max(ADeg);
BMax = max(BDeg);
AMin = min(ADeg);
BMin = min(BDeg);

[m,n]=size(IntTrueAngles);

if AMin <= 0
    ADegShift = (sqrt(AMin*AMin))+1+80;
elseif AMin == 1
    ADegShift = 0+80
elseif AMin > 1
    ADegShift = -(AMin-1)+80
end
ADeg = ADeg+ADegShift;

if BMin <= 0
    BDegShift = (sqrt(BMin*BMin))+1+80;
elseif BMin == 1
    BDegShift = 0+80
elseif BMin > 1
    BDegShift = -(BMin-1)+80;
end
BDeg = BDeg+BDegShift;

TMax = 210;
SMax = 210;
Freq(SMax,TMax) = 0;

for i=1:m
    s=ADeg(i,1);
    t=BDeg(i,1);
    Freq(s,t) = Freq(s,t)+1;
end

for i=1:TMax
    for j=1:SMax
        if Freq(i,j)>0;
            Freq_count(i,j) = 1;
        end
    end
end

Freq_count;

%calculate location of average FE and average RU relative to neutral

LOCATIONFE = mean(TrueAngles_task(:,1));
LOCATIONRU = mean(TrueAngles_task(:,2));

%state all parameters

Parameters = [FEMAX FEMIN FERANGE RUMAX RUMIN RURANGE LOCATIONFE LOCATIONRU]

======================================================================
Program to calculate the “area ratio” parameter

```matlab
%----------------------------------------------------------
% Calculate "area used" ratio
%----------------------------------------------------------
clf; clc; clear;
%----------------------------------------------------------
% choose subject to study
%----------------------------------------------------------
disp(' ');
subject = input('Which subject do you want to look at (one letter)?','s');
%----------------------------------------------------------
% extract "neutral" datum values from initial neutral task, %file 02
%----------------------------------------------------------
fid = fopen(strcat((subject),'02','.txt'));
gather_raw_angles;
FENeutralDatum = round(mean(RawAngles(:,1)));
RUNeutralDatum = round(mean(RawAngles(:,2)));
%----------------------------------------------------------
% extract task data and convert to degrees, relative to %initial "neutral" datum
%----------------------------------------------------------
disp(' ');
task = input('Which task do you want to plot? (give file number e.g. "01")','s');
fid = fopen(strcat((subject),(task),'.txt'));
gather_raw_angles;
% call subroutine to gather raw data as a two-column matrix
% convert raw data into degrees relative to "neutral"
clc
ADeg = (RawAngles(:,1)-FENeutralDatum)*1.8;
BDeg = (RawAngles(:,2)-RUNeutralDatum)*1.8;
TrueAngles_task = [ADeg BDeg];
% calculate region covered, by summing all non-zero %values in Freq matrix
%divide by resolution of 1.8 to give integers
ADeg = (ADeg)/1.8;
BDeg = (BDeg)/1.8;
%restate TrueAngles as integer TrueAngles
IntTrueAngles = [ADeg BDeg];
AMax = max(ADeg);
BMax = max(BDeg);
```
AMin = min(ADeg);
BMin = min(BDeg);

[m,n]=size(IntTrueAngles);

if  AMin <= 0
   ADegShift = (sqrt(AMin*AMin))+1+80;
elseif AMin == 1
   ADegShift = 0+80
elseif AMin > 1
   ADegShift = -(AMin-1)+80
end
ADeg = ADeg+ADegShift;

if  BMin <= 0
   BDegShift = (sqrt(BMin*BMin))+1+80;
elseif BMin == 1
   BDegShift = 0+80
elseif BMin > 1
   BDegShift = -(BMin-1)+80;
end
BDeg = BDeg+BDegShift;

TMax = 210;
SMax = 210;
Freq(SMax,TMax) = 0;

for i=1:m
   s=ADeg(i,1);
   t=BDeg(i,1);
   Freq(s,t) = Freq(s,t)+1;
end

for i=1:TMax
   for j=1:SMax
      if Freq(i,j)>0;
         Freq_count(i,j) = 1;
      end
   end
end
Freq_count;

%----------------------------------------------------------
% generate and plot ellipse to approximate boundary of
% angular motion
%----------------------------------------------------------
% open file containing extremes of motion
fid = fopen(strcat((subject),'03','.txt'));

% call subroutine to gather raw data as a two-column
% matrix
gather_raw_angles;
% convert raw data into degrees relative to initial neutral position
ADeg = (RawAngles(:,1)-FENeutralDatum)*1.8;
BDeg = (RawAngles(:,2)-RUNeutralDatum)*1.8;
TrueAngles_ellipse = [ADeg BDeg];

% define maximum and minimum values for each channel, in degrees
MaxActiveFE = max(TrueAngles_ellipse(:,1));
MinActiveFE = min(TrueAngles_ellipse(:,1));
MaxActiveRU = max(TrueAngles_ellipse(:,2));
MinActiveRU = min(TrueAngles_ellipse(:,2));

% plot ellipse of max and min active range
FEActiveRange = MaxActiveFE-MinActiveFE
RUActiveRange = MaxActiveRU-MinActiveRU

%==========================================================================
% combine values to give "area used" ratio
%==========================================================================
AREAUSED = sum(sum(Freq_count))/(FEActiveRange*RUActiveRange*pi)
Appendix E: Results

Extremes of motion: ellipses for all subjects, all plotted on similar axes
All tasks for each subject, displayed with elliptical motion boundaries, scaled to make all ellipses of a similar size for easy comparison of data

Turn a doorknob
Pick up a coin
Hold a glass of water
Turn a key in a lock
Button a shirt/blouse
Eat with a knife/fork
Open a jar
Wash dishes
Wash your hair
Carry a grocery bag
Tie shoelaces/knots
All twelve tasks displayed together on a single graph, for each subject
Shortlist tasks displayed together on a single graph, for each subject