A FUNCTIONAL TASK ANALYSIS AND MOTION SIMULATION FOR THE DEVELOPMENT OF A POWERED UPPER-LIMB ORTHOSIS

by

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ABSTRACT

The objective of this thesis is to determine an optimal configuration of a powered upper-limb orthosis. The criterion is to minimize the complexity, defined as the number of degrees of freedom of the orthosis, while maintaining the ability to perform specific tasks. This goal was realized in three stages of research. In the first stage, potential users were interviewed to determine their task priorities. In the second stage, the natural arm motions of able-bodied individuals performing the tasks identified as high priority were profiled with a video tracking system. Finally, a kinematic simulation algorithm was developed to evaluate whether a given orthosis configuration is able to perform the identified high-priority tasks.

It was found that the task functionality was overly compromised for any configuration with less than five degrees of freedom. Two different configurations with five degrees of freedom are recommended. The recommendations are: (1) to power all but the motions of elevation and wrist yaw, or (2) to power all but wrist flexion and wrist yaw.

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CHAPTER 1: INTRODUCTION

A powered upper-limb orthosis is an exoskeleton worn on one arm by a person with flail arms, that is, having severe muscle weakness or paralysis in the arms. This is in contrast to a prosthesis, which replaces an amputated limb, or a robotic assistive device, which operates separately from the user. By activating controls, the orthosis user directs the supported arm to perform various tasks such as reaching for objects, washing the face or eating. By regaining some function in the assisted limb, the user achieves a higher degree of independence.

The typical user has a neuromuscular disease such as poliomyelitis [40], muscular dystrophy [108] or amyotrophic lateral sclerosis (called ALS or Lou Gehrig's disease) [111], with two flail arms but full sensation. Because the user has two flail arms, the powered orthosis is used to perform the entire task instead of acting as a secondary support. Full sensation of temperature, pressure and texture is important both for safety reasons and because this makes it worthwhile to move the user's own arm. Otherwise, a robotic device may be more suitable.

Achieving the functionality, strength and aesthetics of the human arm in a practical and affordable orthosis is currently infeasible. Thus, design compromises are necessary. The most significant compromise is in the choice of degrees of freedom provided by the orthosis. It may be possible to reduce the degrees of freedom while the functionality of the device, defined as the ability to perform the most important tasks, remains acceptable. A simpler device is normally less expensive, less bulky and less prone to break down. It is the goal of this work to discover an optimal compromise with regards to the necessary degrees of freedom in a user-acceptable orthosis design.

The following objectives were set out for the research outlined in this thesis:

1) To research the needs and wants of potential users of a powered upper-limb orthosis;
2) To establish the priority of various daily-living tasks;
3) To record the motions of able-bodied people performing the identified high-priority tasks;
4) To analyse these motions in terms of the joint rotation angles, hand orientations and paths taken during each task;
5) To develop a kinematic simulation program to evaluate possible configurations of a powered upper-limb orthosis; and,
6) To use this simulation program to determine the simplest orthosis configuration that is still capable of performing the highest priority tasks.

These objectives were achieved in three stages: a task analysis, a motion analysis and a kinematic simulation. The literature review (Chapter 2) gives a background to these three areas and to powered upper-limb orthoses. In the first stage, interviews were conducted with potential users to establish the high-priority tasks (Chapter 3). In the second stage, these and other tasks were profiled as performed by able-bodied subjects (Chapter 4). In the third stage, the motion analysis data were used as inputs to a simulation program to find acceptable orthosis configurations (Chapter 5).

Control strategies were not examined in detail as they were beyond the scope of this thesis.

No powered upper-limb orthosis has yet been made which is acceptable to users and can be manufactured at a reasonable cost and skill level. Although other researchers have proposed designs based on a ranking of joint rotations or on tests with mechanical models, the unique contribution of this research is the use of an orthosis simulation to test functionality. Furthermore, the number of functional tasks analysed for whole arm motion exceeds that of previous researchers. The analysis of motion provided an extensive set of data for the kinematic simulations as well as providing a detailed characterization of human arm movement.

A prototype orthosis will be built at the University of British Columbia using the recommendations of this thesis.

CHAPTER 2: LITERATURE REVIEW

A review of the literature provided background information for the proposed research work as well as direction for further research. For clarity this literature review is divided into four categories corresponding to the different aspects of the project: 1) previously developed powered upper-limb orthoses, 2) potential users and their task priorities, 3) motion analyses, and 4) kinematic analyses.

2.1 Powered Upper-Limb Orthoses

An orthosis supports or controls deformities in an intact limb. Externally powered orthoses represent only a subset of these. Many unpowered static, spring-operated or ratchet-operated hand and arm orthoses have been developed [117] but will not be discussed because they do not address as severe a problem as the bilateral flail arm user. Similarly, those powering only the elbow [51,109] or only the hand [26,27,49,81,82] will not be included in the discussion below. Robotic manipulators will not be described because the design and purpose of autonomous manipulators are different from that of an exoskeletal device moving the user's own arm.

The development of powered upper-limb orthoses began in the 1960s as a result of the polio epidemic, the thalidomide tragedy and a growing number of surviving quadriplegics, all of which generated interest in restoring function to the upper limb. In the following two decades such work was almost nonexistent. Recently, further research towards improving powered upper-limb orthoses has been conducted.

The human arm has seven degrees of freedom, excluding finger motion and complex shoulder motion. This includes three degrees of freedom at the shoulder plus elbow flexion, forearm rotation and two degrees of freedom at the wrist. Each of the orthoses discussed below has a different set of powered degrees of freedom, including variations in the sequence of shoulder rotation axes.

The first attempt at developing a powered orthosis was the Rancho Los Amigos Hospital wheelchair-mounted electrically-powered arm orthosis developed in the 1960s by Nickel *et al.* [28,49,81,82,89,90,116]. Having six degrees of freedom plus grasp the orthosis was capable of all of the basic motions of the human arm except wrist yaw (radial/ulnar deviation) (see Figure 2-1). The Rancho orthosis was developed as a clinical device "to provide severely paralysed patients with the best voluntary arm motions possible" [49].


Figure 2-1: Rancho Los Amigos Orthosis (After [28])

Each joint rotation was controlled by a separate bidirectional tongue switch, making it slow and demanding to control properly. (Even "one of the best performers, a polio patient, used 150 motions to take five bites of food and 45 motions to pick up a cup and drink from it" [90].) There were "successful fittings leading to measurable functional independence" [28]. However, patient rejection was high [37]. The device was cumbersome and costly. Its major problem was the frequency of breakdown [53]. Safety was also a concern because of the lack of sensory feedback among most of the quadriplegic users.

In the latter half of the 1960s, Case Western Reserve University and the Case Institute of Technology conducted a research program into 'cybernetic systems for the disabled'. In combination with related developments, Case designed and built a floor-mounted pneumatically-powered Case Research Arm Aid (see Figure 2-2) [4,48,52,56,98,116]. Although the arrangement of shoulder rotations was different than for the Rancho orthosis, the Case orthosis also powered all of the degrees of freedom except wrist yaw. The arm aid was used exclusively for research, in combination with a programmable, real-time Cybernetic Orthotic/Prosthetic Simulator that was designed primarily to test control strategies, including endpoint control. While the ideas were impractical to implement in a clinical device at the time, it is possible that they could be implemented using the significantly smaller and more powerful microcomputers available today.

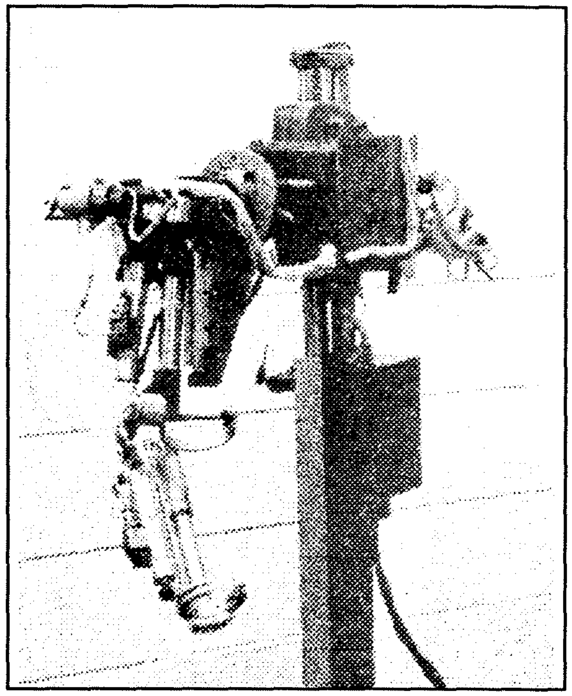

Figure 2-2: Case Western Reserve University Orthosis (After [98])

Another development in the 1960s, by Engen and Spencer at the Texas Institute for Rehabilitation Research (TIRR), was a pneumatically-powered arm orthosis, as shown in Figure 2-3 [26,27,65,97]. The power actuator was a helical-wound bladder that contracts when pressurized, called a McKibben muscle substitute. The two degree of freedom wheelchair-mounted arm orthosis used one actuator to flex the elbow and simultaneously rotate the forearm and the other actuator to elevate the arm using a parallelogram elevation mechanism. These could be controlled separately or in combination. Both the position of forearm rotation (pronation/supination) and the desired degree of coupling could be preset. Alternatively, if the user retained the ability to pro/supinate, the action was not restricted. Grasp was optionally powered [27,85]. Azimuth rotation, occurring about a vertical axis through the shoulder, was unpowered but could be moved under the user's own power. Friction was reduced to a negligible amount with ball bearings so that azimuth movement could be effected with weak but functioning muscles.

Figure 2-3: Texas Institute of Rehabilitation Research Orthosis (After [25])

The pivoting of the TIRR orthosis is similar to the unpowered mobile arm support (MAS) which is commonly used by people with weak but functioning muscles [49,65,97]; the powered orthosis addressed the needs of those with arms too weak or paralysed even for the MAS. The TIRR orthosis represents a good compromise between simplicity and functionality. It also utilized the remaining abilities of the user. Virtually all (90%) of those who received a prototype version of the device are still using it, as of 1992. However, the orthosis required such precision machining and specialized training that it was not commercialized [29].

An electrically-powered clinical orthosis was also developed in the 1960s by Lehneis at the Institute of Rehabilitation Medicine in New York [59,60]. It, too, was based on the pivoting design of the unpowered mobile arm support orthosis (see Figure 2-4). Elevation, elbow flexion, forearm rotation and grasp were powered. As with the TIRR orthosis, horizontal movement (azimuth) was permitted but unpowered since the users had sufficient residual shoulder control once the effects of gravity were eliminated. A friction-controlled wrist joint allowed the user to preset wrist flexion. Thus, all of the degrees of freedom except wrist yaw were accounted for, with azimuth unpowered, wrist flexion passive and the remaining degrees of freedom powered. The design used flexible Bowden cables to locate the drive mechanisms remote from the arm. No further mention is made of this orthosis, so it was presumably unsuccessful.

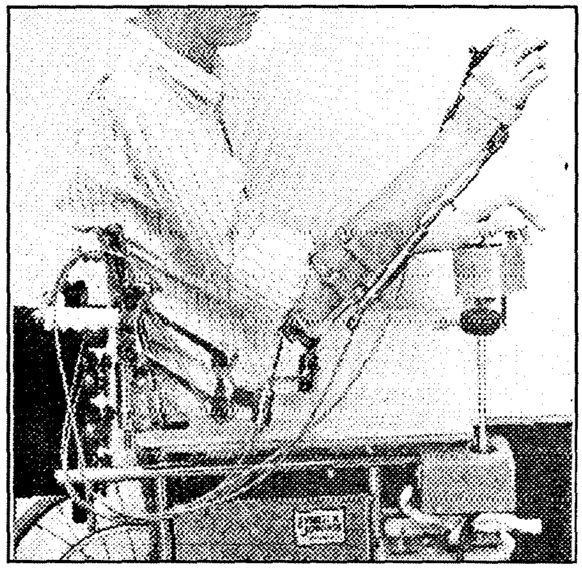

Figure 2-4: Institute of Rehabilitation Medicine Orthosis (After [57])

Because of the lack of success of these early attempts as well as lack of funding, no further attempts were made until the 1980s when efforts were put into robotic manipulators ([80], [100]). Robotic manipulators address the needs of those with quadriplegia but make no use of weak but sensate arms. This realization in combination with advances in computers and other technology favoured a renewed investigation of powered upper-limb orthoses.

In 1987, the Hugh MacMillan Rehabilitation Centre (HMRC) in Toronto developed a one degree of freedom plus grasp portable powered orthosis (see Figure 2-5a,b). It was designed primarily to allow a person with severe upper arm weakness to eat [34,35,106]. Until this time, there had been little success in developing powered upper-limb orthoses for ambulatory users mostly due to the weight of the actuators and power source that had to be carried on the person. Thus, most powered orthoses were developed for wheelchair users. The HMRC's target was people with ALS, a disease that leads to rapid progressive muscle weakness. Those with ALS are normally ambulatory at the initial stages only requiring a wheelchair at later stages of the disease progression.

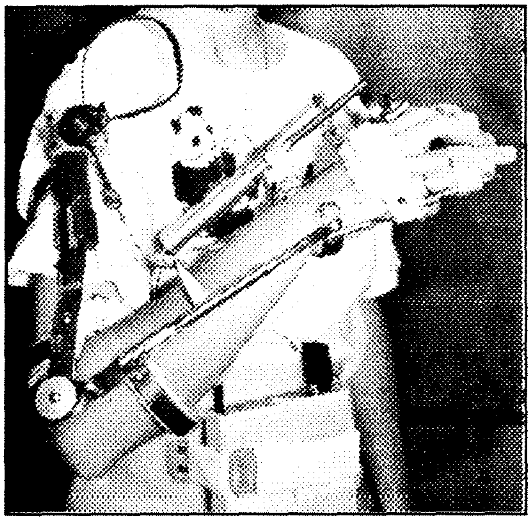

Figure 2-5a: Hugh MacMillan Rehabilitation Centre Orthosis: Lateral View

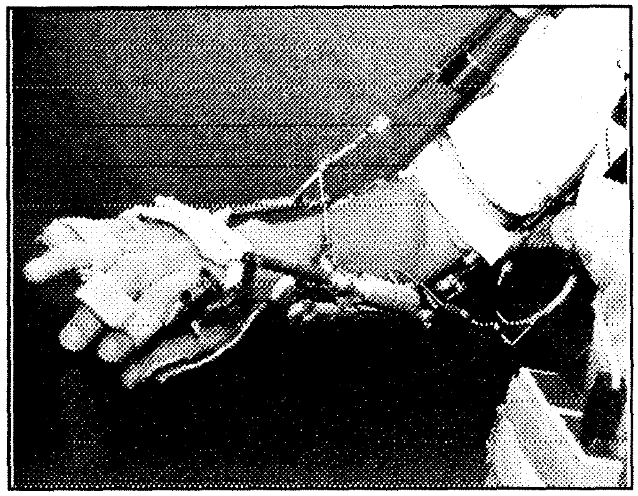

Figure 2-5b: Hugh MacMillan Rehabilitation Centre Orthosis: Medial View

The HMRC orthosis flexes the elbow while simultaneously rotating the forearm in order to put the hand in a suitable position when at table level and when at the mouth. The coupling is accomplished by a cable crossing over the arm. A linear actuator powers the grasp. A powered winch unit drives the elbow motion with a timing belt [34].

The first user was very successful: using the orthosis to access the keyboard, he wrote a book, graduated from university and held a part-time job. Encouraged by this success the HMRC built five more prototypes but none were as successful as the first for varying reasons [35]. In reality, the first user primarily utilized the orthosis to hold his arm in a useful position (rather than hanging by his side) then used his trunk to move the endpoint. The control system, myoelectric control with the forehead frontalis muscles alternately activating the hand or the arm, is a major handicap in dynamic use of the orthosis because the system is difficult and tiring to use reliably.

Upon further evaluation of the HMRC design at the University of British Columbia (UBC), a project of which this thesis forms a part, many possibilities for improvements were noted [44]. Modifications were made to the HMRC orthosis to make it lighter (by 28%), easier to fabricate and easier to repair. The modifications also included improved cosmesis and a more functional hand position (see Figures 2-6a,b) [95]. However, due to the pre-defined scope of the modifications, the actuators were kept the same. Thus, while the UBC-enhanced orthosis has many improvements over the original HMRC version, the device functionality is still too limited to make its use widespread.

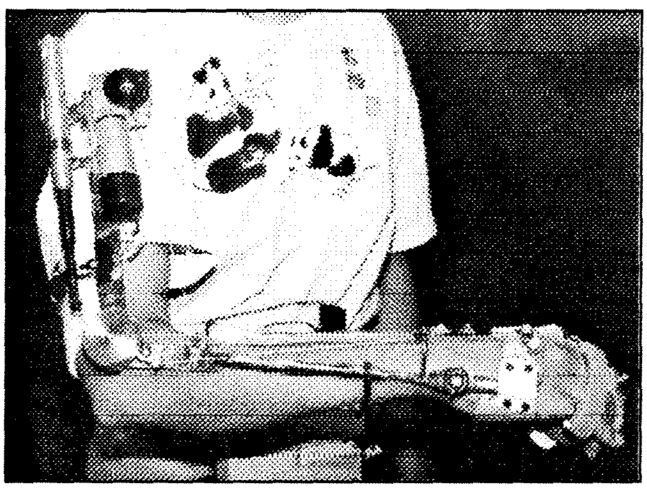

Figure 2-6a: UBC-Enhanced HMRC Orthosis: Lateral View

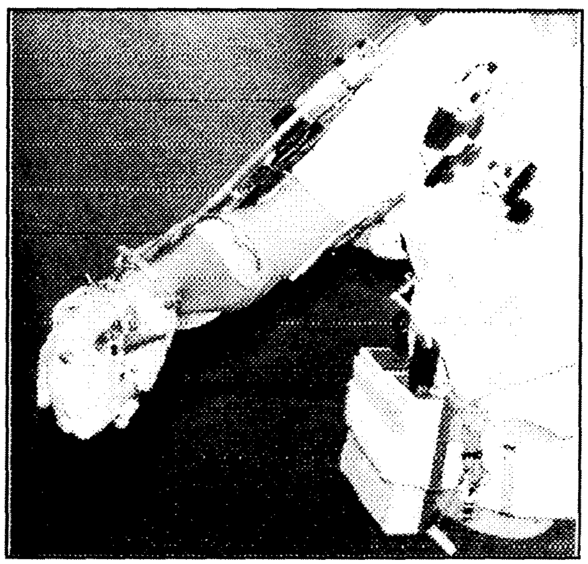

Figure 2-6b: UBC-Enhanced HMRC Orthosis: Medial View

The newest multi-degree of freedom endeavour, developed by From at the University of Toronto [32], is a wheelchair-mounted, voice-controlled orthosis incorporating all of the degrees of freedom up to but not including the wrist, as shown in Figure 2-7. It was designed as a research tool, "to evaluate the functionality and acceptability of a voice-controlled exoskeletal powered upper-extremity orthosis" [32]. The intention is to add a shape-memory-alloy orthosis [25] or to use functional neuromuscular stimulation [88] to control grasping. The target population is those with high-level quadriplegia due to spinal cord injury. Borrowing from the rehabilitation robotics field, the orthosis includes many new orthosis concepts including endpoint control and several layers of mechanical, electrical and operational safety. This orthosis has been laboratory tested but has not yet been clinically tested.

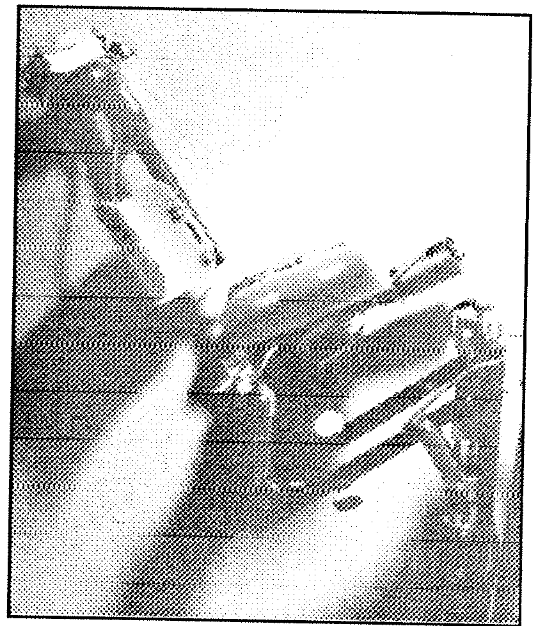

Figure 2-7: University of Toronto Orthosis (After [32])

2.1.1 Summary

Although not discussed here, single joints, specifically the hand and the elbow, have been successfully powered [27,49,51,85,109]. The above review has demonstrated, however, that orthoses that powered almost all of the degrees of freedom of the arm were too complex to be successful. Despite the need for a powered upper-limb orthosis by a wide variety of users, an acceptable one has yet to be developed.

2.2 Task Priority Surveys

The functionality of an orthosis is established by the tasks that can be performed with it and the ease with which these tasks can be performed. Both the number of tasks and the priority of those tasks are of interest. Since the priority of tasks affects both the design and its ultimate success, it was an important first step in this research to discover task priorities from potential users.

Previous researchers have surveyed potential users and their task priorities but none of the surveys were intended for use in designing a powered orthosis. While it was necessary to perform our own interviews because of this difference, the results from other surveys are of interest and, for the most part, are applicable to users of a powered orthosis.

The first reported classification of task priorities was performed by McWilliam in 1970 [70]. Seventeen able-bodied people recorded and rated their activities-of-daily-living; the most essential tasks formed the basis for the design of a prosthesis. Paid work and recreational tasks were not included. The tasks that were rated essential by all subjects (listed in no particular order) were:

- brushing the teeth
- loading a spoon from a plate
- unloading food into the mouth
- public transport
- lifting and tilting either a cup or tumbler
- stirring with a spoon
- toileting
- turning pages
- writing

It will be seen that the priorities set by people with disabilities are moderately different from those set by able-bodied people.

In the last decade, several rehabilitation robots have been developed. Just as with powered orthoses the priority of various tasks is a primary issue if the design is to be tailored to the needs and wants of the users. The Neil Squire Foundation conducted interviews with five potential robotic arm users, all of whom had quadriplegia, prior to and following their first contact with the prototype vocational robot [39]. It was found that user expectations were in some cases unrealistically high prior to contact due to the fictional depictions of robots in movies. After exposure to the robot the desired tasks, in response to an open-ended question, were defined (listed in no particular order) as:

- turning pages
- loading cassettes and compact discs
- opening drawers & closets for clothes
- changing volume & station on stereo
- performing personal hygiene tasks (brushing teeth, washing face, shaving)
- repositioning hands on the armrests
- picking up books & papers
- serving drinks
- manipulating floppy disks
- brushing debris from the eyes
- fetching manuals

While this "wish list" was compiled for a robotic manipulator, the results are applicable to an orthosis because the individuals wished to regain these tasks, however that may be achieved. Further interviews were conducted during clinical trials of the robot [9] which had greater emphasis on vocational activities.

Despite the desire for the daily-living activities outlined in the Neil Squire task list, the resulting robot is essentially restricted to vocational tasks. Vocational tasks can be performed in a structured environment, they encourage the integration of disabled people into the workplace and they are safer because the robot usually operates out of range of the user. In contrast, activities-of-daily-living require a more versatile device and more intimate human-device interaction.

An individual's current abilities, pastimes and living situation may also affect the design. To examine these areas as well as task priorities, the Bath Institute of Medical Engineering (BIME) interviewed 42 potential users of a robotic manipulator [45]. Twenty-five had multiple sclerosis, ten were spinal cord injured and the others had miscellaneous diseases causing upper-limb weakness. The most common suggestions for robot use in answer to an open question (the frequency of suggestion is given in brackets) were:

- making a hot drink (18)
- feeding (4); picking items up from the floor (4); kitchen use (4)
- loading a cassette-tape (3).

The emphasis on making a hot drink may have occurred because the interviewer used making a cup of tea as an example of a task that the robot could perform or because the majority of subjects had multiple sclerosis with which hand tremors are common. Although the subjects were shown a conceptual drawing of the robot, several remarked that they would need to use the system before being able to determine more uses for it, making the design process and the task list iterative. After progressing through three basic systems with continued user feedback, the result has been a robotic workstation capable of loading a floppy disk into a computer, retrieving books from a shelf and operating a cassette recorder/radio, among other tasks. Feeding was not considered a desirable activity by the users since it would reduce social interaction.

Building upon the Bath survey, Middlesex Polytechnic conducted a survey of 50 potential users of an electric-wheelchair-mounted robotic arm [94]. Of the 17 different disabilities represented, the most common were spinal cord injury (11 subjects) and multiple sclerosis (8 subjects). Although not wishing to influence the subjects' answers, a computer simulation video was shown to the subjects before filling in the questionnaire to give them some concept of what the robot could do. The top five tasks in answer to "what would you most like to do but cannot?" were:

- reaching, stretching, gripping (22)
- gardening (13)
- reaching to the floor (12)
- cooking (10)
- eating (9)

Others listed were:

- lifting large objects (6); dressing (6)
- drinking (5); driving (5)
- standing / walking (4); getting in & out of the wheelchair (4)
- do-it-yourself (3); getting tight grip on lids (3); washing/bathing (3); playing sports (3); emptying bladder(3); and cleaning/wiping (3).

Reaching to pick up objects has the highest priority, especially from the floor, as mentioned in the Bath results. Cooking and eating also have a high rating, confirming the Bath results, but without the emphasis on preparing hot drinks.

The Arbutus Society for Children also developed a questionnaire for electric wheelchair users. They have not analysed the task priorities, but noted that "certain tasks are identified clearly as being performed with difficulty, e.g. picking and placing objects" [42]. This again confirms the importance of reaching tasks.

In an evaluation following development of the Stanford/VA Desktop Vocational Assistant Robotic Workstation (DeVAR), the tasks that the 24 high-level quadriplegic users "would most like to have the robot do" were [41]:

- performing hygiene tasks, e.g. brushing teeth, shaving and washing (9)
- preparing a meal and feeding (6); getting a drink of water (6)
- fetching and carrying objects (4); operating environmental appliances, e.g. phone, TV, stereo (4)

• setting up a splint for feeding/writing (2); performing tasks at bedside (2)
• turning book pages (1); writing letters (1); and lighting a cigarette (1).

This list puts a greater emphasis on personal hygiene tasks than the previous surveys. Since the accent was on activities-of-daily-living (ADL) the first three versions of the robot emphasized ADL, recreational and personal clerical tasks. The fourth version is configured for vocational tasks as well. The robot is reported to be preferred to an attendant or family member because the robot performs tasks according to the user's own schedule.

An extensive evaluation of the MANUS robotic manipulator was performed in ADL, vocational and school settings [72]. The tasks that received the highest number of ratings in the "want to do" category were:

• picking up a book (13); placing a book on a shelf (13)
• pouring liquid (12); fetching objects from shelves (12)
• turning knobs (10)
• drinking from a cup or glass (9); using standard fork, knife and spoon (9); opening cupboard door (9); retrieving books (9); operating wall switches (9); and, grasping and releasing (9).

Once again, the emphasis is on picking and placing objects. This is in contrast to the task priorities compiled by the able-bodied subjects earlier. Both, however, consider eating and drinking important.

2.2.1 Summary

The literature indicates the importance of contacting potential users directly before developing a new device. In response to task priorities, potential users of a robotic device indicated the importance of reaching and picking up objects. Cooking and eating also had a high priority although some people were concerned about losing the social contact that occurs at mealtimes.

The importance of personal hygiene varied from survey to survey but is among the highest priority tasks. Other factors, such as living at home or an institution will also affect the priority of tasks and thus the design of the device. The next chapter discusses the interviews performed for this research with potential users of a powered upper-limb orthosis.

2.3 Motion Analyses

In order to determine the motions associated with the higher priority tasks defined above, a motion analysis was performed. This analysis recorded the free movements of a subject performing the higher priority tasks, then calculated the associated joint movements. While the majority of this work is original, the development of the system used for this purpose benefitted from previous work in the area, as described below.

The functional movement of the entire upper limb has only been recorded previously by a few researchers. Single joints have been studied more thoroughly, but this provides little insight towards the simultaneous movement of all joints. Most human motion studies have concentrated on gait analysis, which until recently has largely been done in two dimensions, whereas the study of upper-limb movement requires three. Many techniques have been used for gait analysis and single arm joint recordings including LED infrared markers [73,83], reflective markers [8,71,75,87], electrogoniometers [13,15,52,74,83,101], optical scanners with prismatic markers [76], electromagnetic sensors [2,67] and laser scanners with photodetectors [63].

In 1947, Keller *et al.* conducted studies of able-bodied subjects to determine the functional requirements of hand and arm prostheses [50, 66]. The most common motion, based on 51 activities-of-daily-living, was found to be elbow flexion, which represented 16.5 percent of all motion. Table 2-1 shows the relative frequencies of each joint rotation. Shoulder flexion/extension refers to movement of the arm forward and back; shoulder abduction refers to movement of the arm to the side.

Joint Rotation	Frequency (%)
Elbow Flexion	16.5
Shoulder Flexion/Extension	15.1
Grasp	14.1
Upper Arm Roll	12.9
Forearm Rotation	12.8
Wrist Flexion/Extension	12.7
Shoulder Abduction	9.3
Wrist Yaw	6.6

Table 2-1: Relative Frequency of Joint Rotations

This shows that elbow flexion is critical while wrist yaw is relatively insignificant. In fact, Keller concluded that wrist yaw can be eliminated entirely without important functional loss. Many of the other joint rotations are quite similar in frequency and may vary with a different selection of tasks.

The first motion analysis of the entire upper limb was performed by Engen in the late 1960s [27]. Using mirrors mounted above and to the side of the subject he was able to capture all three views on one image. Five activities were studied: diagonal reaching, writing, page turning, hair combing and eating. Each activity was performed with and without an unpowered orthosis. The images were hand digitized to create stick-figure diagrams representing the movement in all three views. However, although the stick figure diagrams do provide visualization of common daily-living tasks, the data is difficult to adapt to other purposes since there is no explicit data concerning joint angles and the images obtained are distorted by the mirror angles. The current research updates and expands upon aspects of Engen's work.

Engen's results highlighted the importance of providing shoulder movement as the primary positioning mechanism. He postulated that a prosthetic elbow could be fixed at a given location for a particular activity without losing the ability to perform that task. It was also noted that forearm rotation and wrist flexion/extension should be powered to allow for more precise movements.

Also in the 1960s, Lake at Case Western Reserve University studied whole arm motion using a seven-axis exoskeletal goniometer [52,56,98]. Nine daily-living tasks were studied: drinking from a cup, eating with a spoon, eating a hamburger (finger food), transferring a block from one position on the lapboard to another, transferring a book from a shelf to a lapboard, sliding an object across the lapboard, drawing with a pencil, operating a push-button phone and scratching the face. However, details of the results are not available. The primary purpose of the recordings was to be able to replay the actions rather than to determine joint angle priorities.

In 1981, Langrana used side and overhead videocameras to record diagonal reaching with and without an unpowered orthosis [54]. Three-dimensional axis markers were placed at the elbow and the wrist while two position markers were placed at the shoulder. Euler angles were used to describe the rigid body motion. This was the first example of calculating joint angles from motion data. Only the shoulder and elbow were analysed, thus no information concerning the orientation of the hand or the wrist is available. The results were therefore of no further use to this project.

While other researchers, such as Maulucci [67] and Lipitkas [62], have studied reaching, this work either did not deal with the entire arm or was not analysed for functional tasks. Therefore the results are not suitable for comparison to results in this research or as input to the simulation program.

An analysis relevant to this research was performed by Safaee-Rad *et al.* at the University of Manitoba who recorded the motion associated with three eating tasks using a video-based system [102,103,104]. The three tasks were eating with a fork, eating with a spoon and drinking from a cup. In this work, seven markers were attached to the subject, three at the shoulder, one at the elbow, two at the wrist and one on the hand. Two videocameras were directed horizontally towards the subject, separated by an angle of 40°. Further details are given in Section 4.5.4. The relative importance of the joint rotations for the feeding tasks, based on the arc of motion, was found to be: forearm rotation (100°), elbow flexion (60°), shoulder flexion (40°), wrist flexion (35°), shoulder abduction (25°), roll (20°) and wrist yaw (20°). This highlights the importance of forearm rotation and elbow flexion during eating tasks.

2.3.1 Summary

The literature review revealed that few researchers have studied whole-arm motion. Given that technology is improving and there are many applications for these results, these studies should become more common. For the purposes of this research, a new motion analysis study was needed to gather quantitative joint and path data for a large number of high-priority functional tasks to be used as input to the simulation program.

2.4 Kinematic Evaluations and Results

The human arm was simulated kinematically for this research to investigate how an orthosis design can be simplified without sacrificing too much functionality. Other researchers have attempted to evaluate simplified prostheses by mechanical means; the techniques and results are described below. The difference in this research is that the investigation is performed numerically, allowing many options to be examined.

The complex three degree of freedom shoulder motion was studied by Enger in the 1960s with the objective of compressing the required motion into a single turn axis for the design of a prosthesis [30]. Using geometric relationships, stereometry and a specially-designed mechanical device to simulate the arm, his team determined that a 45° turn axis would bring the arm from the side "table" position to the front "mouth" position. All of the remaining degrees of freedom were powered independently in the prosthesis except wrist yaw, which was coupled to elbow flexion. This simplified the shoulder mechanism and control, but only allowed for eating-like activities.

By recording and rating the everyday activities of 17 able-bodied subjects, McWilliam identified 180 tasks as the most important for daily living, as described in Section 2.2 [70]. The endpoints of each action and any essential paths were noted through observation, leading to a non-quantitative characterization of the task movements [68]. Since dressing tasks were included, the requirements were different than for this project. A mechanical model was built to evaluate various selections and combinations of axes against the task requirements. The resulting minimum requirements were found to be: shoulder flexion/extension, roll coupled with shoulder abduction, elbow flexion, forearm rotation, wrist flexion and grasp, thereby eliminating one degree of freedom through coupling and one by fixing wrist yaw altogether.

Whereas the above two researchers examined motions for the purposes of design, Redding recently developed a diagnostic tool for visualizing the resulting workspace volume of a selected prosthesis [96]. The purpose was to alleviate the time-consuming process of choosing appropriate prosthesis components for an individual amputee. After selecting and joining predefined prosthesis components, all of the reachable points are displayed on the computer screen. Contact points, such as against the body or a table are shown in order to determine how functional the setup is for performing daily-living tasks. Although this provides an effective diagnostic tool, it cannot be used to analytically determine the optimal configuration.

2.4.1 Summary

The literature review demonstrates that a new kinematic analysis is required. No definitive answer exists concerning the optimal set of degrees of freedom for a powered upper-limb orthosis. Since task priorities have now been defined by potential users (as opposed to the able-bodied subjects in the McWilliam study), the results will more likely lead to an acceptable orthosis. Also, joint angle data is now available in a form suitable for the simulation program because of the motion analysis performed in this research.

2.5 Summary

This literature review has covered past work on powered upper-limb orthoses, task priorities, motion analyses and kinematic analyses. In each case there is a clear lack that needs addressing. In the following chapters, interviews with potential users are discussed, the motion analysis of the important tasks arising from the interviews is described and the kinematic simulation program, which uses the data from the motion analysis results to determine an optimal set of degrees of freedom for a powered upper-limb orthosis, is reported.

CHAPTER 3: POTENTIAL USERS OF A POWERED UPPER-LIMB ORTHOSIS AND THEIR TASK PRIORITIES

3.1 Introduction

In this chapter, the characteristic user for this study is defined, relevant medical details are given and the interviews conducted with potential users to obtain information on task priorities are described.

While market surveys are common in the development of products in other fields, they are relatively new in the rehabilitation field. Rehabilitation products have often failed in the past because the assumptions of researchers and designers were incorrect. In recognition of this, it has now become common to survey potential users before developing a product so that feedback and ideas can be incorporated into the design [10,84].

Early feedback is especially important in the design of a powered upper-limb orthosis. If function is to be compromised in a powered orthosis for the sake of simplicity, better reliability and reduced cost, the defined priority of tasks will have a major impact on the design. Furthermore, the high cost of design and manufacturing and the small population provide few opportunities for experimentation.

The task priorities defined here formed the basis of the tasks selected for the motion analysis study. Those tasks were, in turn, used to test the simulated orthosis. The tasks will also serve to evaluate the prototype orthosis.

3.2 Characteristic Description of the User

The objective is to design and build an orthosis which allows a person with severe upper-limb weakness to perform daily-living activities. The variety of disabilities, however, necessitated that a user be characterized for the design purposes of this study. The characteristics, for this study only, are:

1) two completely flail arms,
2) intact sensation (temperature, pressure, texture),
3) no spasticity,
4) a full range-of-motion of the joints,
5) full cognitive abilities and,
6) adult-sized.

The reasons for these criteria are outlined below. A person with two completely flail arms is uncommon but poses the most severe requirements in terms of the level of assistance to be provided in the design. If the user still has some abilities, such as hand function, the orthosis should allow the user to utilize that remaining function. If a function is retained, that degree of freedom can be left unpowered, thus simplifying the design.

At least partial sensation is required since artificial sensors are unlikely to be built into an orthosis. This criterion is justified because sensation is unaffected in the first three medical categories listed below and in some individuals of the other categories (see Section 3.3). If there is no sensation, then for reasons of both safety and versatility the person should be encouraged to consider using a robotic arm instead. However, if the individual retains sensation there is a strong incentive to move the user's own arm.

The uncontrollable contractions associated with spasticity can overpower an orthosis, posing a safety hazard to the user and possibly damaging the power actuators. Similarly, if the user does not have a full range of movement, which is common due to lack of regular movement, the orthosis cannot operate beyond the limited range of motion. Full cognitive abilities are required as the user must be able to learn how to control the orthosis. Since virtually all of the people affected by the diseases and injuries listed are adults, it is justified to make the orthosis adult-sized at this stage of the work.

The importance of user selection has been mentioned by previous researchers [27,35,49,90]. The individual must be highly motivated and must receive good training in the control and operation of the orthosis. It is also advantageous for the user to be introduced to the device as soon as possible after injury or the onset of the disease. Deformities must not be excessive, and good head and trunk stability are required so that the arms are not needed for support [90].

3.3 Medical Classifications

Knowledge of the medical background and consequences of the diseases and injuries causing disability is a prerequisite to understanding the difficulties faced by potential users of a powered orthosis. Certain characteristics make an upper-limb orthosis more suitable for an individual while other characteristics make its use impossible.

The diseases and injuries under consideration are poliomyelitis [40], amyotrophic lateral sclerosis (also called Lou Gehrig's disease) [12,111], muscular dystrophy [12,108], spinal cord injury (also called quadriplegia) [65,117], multiple sclerosis [57], brachial plexus injury [58], stroke (also called hemiplegia) [23,105] and Charcot-Marie-Tooth disease [22]. See Appendix A for a brief medical description of each one.

Table 3-1 gives the extent and form of upper-limb weakness commonly found in each category.

Disease/ Injury	Description of Upper-Limb Weakness
P	Polio causes muscle weakness. Although the weakness plateaued decades ago for most victims, new symptoms are now appearing, a syndrome referred to as post-polio. The legs are usually affected before the arms. Sensation is not affected and there is no spasticity.
ALS	Because of the continuing progressive dysfunction related to ALS, flail arms will always result. The weakness starts at the extremities and works upwards. Arm weakness usually occurs later in the disease. Sensation remains and there is no associated spasticity.
MD	With muscular dystrophy, the upper limb is affected most by reduced shoulder and grip strength. Sensation is not affected and there is no associated spasticity.
SCI	Injury to the spinal cord is named according to where the injury occurs, with paralysis below that point. A C4 injury involves paralysis below the 4th cervical vertebra leaving only shoulder shrug and head movement. With a C5 injury, hand and wrist function, pronation and elbow extension are lost, but shoulder function is retained. In a C6 injury, only hand function is lost. Sensation may be full, partial or nonexistent. Spasticity is common.
MS	Multiple sclerosis results in overwhelming fatigue and poor motor coordination. Sensation is usually affected. Spasticity is common.
BPI	Brachial plexus injury is a sudden severing of the nerves of one arm, most commonly due to motorcycle accidents. The arm may be totally flail if all of the nerves are affected. Sensation may or may not be affected. The arm is often amputated and a prosthesis worn to provide the individual with more function [77].
Str	Stroke affects one side only. Recovery varies widely but half of those surviving continue to need special services [105]. Spasticity is common and sensation is affected.
CMT	The greatest impact of Charcot-Marie-Tooth disease, in terms of the upper limb, is a reduction in grip strength. Loss of strength in the entire arm is uncommon but does occur.

Table 3-1: Diseases and Injuries Causing Upper-Limb Weakness

As seen from the above summary, a tremendous variety of upper-limb disabilities exist. The first three (P, ALS and MD) are the focus for our initial users because sensation is unaffected and spasticity does not result. Individuals from the other categories may also be suitable for the orthosis but will only be considered after the development of a working prototype.

3.4 Interviews Conducted with Potential Users

Although the surveys outlined in the literature review contribute to our knowledge of potential users, this project is concerned with potential users of a powered orthosis, not a robotic arm. An orthosis user may not be in a wheelchair and the disabilities differ. More importantly, regaining function of one's own arm using an orthosis differs from having an independent robotic manipulator performing the tasks. Interviews were therefore conducted in order to determine task priorities directly from potential users, to understand how people deal with their disabilities, to gather early feedback concerning the development of a powered upper-limb orthosis and to survey potential users of a powered orthosis rather than of a robotic manipulator.

An abstract describing the project and its objective was distributed at two post-polio support group meetings and through the ALS and muscular dystrophy newsletters, but unfortunately produced no response. The best response was obtained from the Limb Girdle Muscular Dystrophy (LGMD) group whose leader sent the abstract to each member of the group.

The questionnaire, included in Appendix B, was based on both the Arbutus and Middlesex surveys [42,94]. However, there were several differences from these previous surveys.

People were asked first which tasks they would most like to regain so as not to bias them to those included in the questionnaire; they were asked at the end to name the five most important tasks. Subjects were asked to rank criteria concerning acceptance of the orthosis, such as cost or cosmesis, and they were questioned about their use of daily-living aids. Personal questions were moved to the end of the survey so as to be less intrusive and to put more emphasis on task abilities and priorities.

Seven women and four men were interviewed, for a total of 11 subjects. One had post-polio, two had Kugelberg-Welander disease (a mixture of ALS and MD), one had C5/6 spinal cord injury and the remaining seven had limb-girdle muscular dystrophy (LGMD). In all but one case, which was conducted in person, the interviews were conducted by telephone.

The average age of the subjects interviewed was 44, with a range from 27 to 65. This is similar to the average age of 45 for the Bath survey and 40 for the Middlesex survey. The length of time since diagnosis ranged from 4 to 39 years, with an average of 18 years, so all were accustomed to their disability. With four single, one divorced and six married subjects there were a greater proportion of married people than in previous surveys. All lived at home although three lived in modified homes. Four had full-time jobs, one was a homemaker, another retired; the other five had no employment. The lesser degree of disability of many of the subjects in this survey as compared with other surveys likely contributed to the greater percentage of full-time workers. Pastimes included TV, reading, travel, painting, visiting, sports and computers among many others. Several watched more television than desired because they were unable to do what they wished to do. All of the subjects indicated that they would consider buying a device that could perform some of their tasks, depending on the price, and all were willing to be contacted for clinical trials of the orthosis.

The above data was not expected to be statistically representative of the population of potential users because of the low number of subjects, the greater number with LGMD and the fact that many were not disabled enough to require the whole orthosis.

All of the subjects felt that it would be easier to see the device in order to understand what it could do (hence the simulation in the Middlesex study and the conceptual drawings in the Bath study). Although the responses may be more reasonable, demonstrating a device may make respondents tailor their wishes to the capabilities of that particular device. In general, the expectations of the respondents were realistic.

Daily-living aids were reported as rarely used by the subjects. Most people seem unaware of commercially available aids or the cost was deemed prohibitive. The aids that are used are homemade, such as a back-scratcher or BBQ tongs used as a reacher.

The respondents were asked about their ability to perform a variety of specific personal hygiene, domestic, recreational and work- or school-related tasks. Of most interest, however, were the responses to the "top five tasks that you would most like to do but cannot". Table 3-2 summarizes the responses for the 11 subjects; details are given in Appendix C.

TASK	FREQUENCY
Reaching / Picking up Objects	9
Personal Hygiene	7
Hobbies / Crafts	7
Eating / Drinking	6
Housework	4
Dressing	4
Strengthening Grip	4
Cooking	2
Toileting / Transferring	2
Reading	1
Using Computer	1

Table 3-2: Task Priorities from Potential-User Interviews

Reaching has the highest priority because it is integral to many activities. This concurs with the task listings cited in the literature review, all of which gave reaching and picking up objects a high priority. 'Personal hygiene' includes brushing the teeth, washing the face, combing the hair, applying makeup, shaving, scratching and blowing the nose. Personal hygiene, eating and drinking ranked consistently high among the task priorities noted in the literature review. The desire for regaining creativity is strong, including such tasks as painting, crafts, baking, woodworking and other hobbies. This was not demonstrated in the interviews with potential users of the robotic manipulators, likely because it would be an independent assistive device performing the actions which is less personal and more intimidating than performing them oneself.

Although the ability to dress and toilet contributes to greater independence, both were deemed outside the realm of a practical orthosis and were therefore not included in the motion analysis. Both actions involve parts of the body other than the arm; transference to the toilet requires greater strength than would be designed into a practical orthosis; and dressing normally occurs only twice a day when a helper would normally be available. Vocational, educational and recreational activities have not been directly included but many of the actions are similar to those in the daily-living tasks listed.

Another use for an orthosis is to hold the arm in a single position, such as for keyboarding, using a TV remote, telephone or environmental controls, painting or for performing many of the personal hygiene tasks. The ability to hold the arm in a given position reduces fatigue in still-functioning muscles, controls shakiness, allows pages to be held down and permits two-handed actions if only one side is affected.

Respondents were also asked to rate the importance of various criteria towards making the orthosis acceptable. The list was derived from Batavia and Hammer's compilation of consumer-based criteria [6]. Cosmesis was identified as a very important factor towards the acceptance of the orthosis since the respondents did not wish to look disabled or attract attention. Others, however, indicated that the importance of regaining the function was greater than the importance of cosmesis ("they already stare anyway").

Affordability was considered critical to the acceptance of the orthosis. The price people are willing to pay is largely dependent on the independence that would be gained, although no dollar figures were given. Robustness and portability were also considered essential. The importance of water-resistance was noted by several of the respondents to allow for washing, spilling drinks and possibly for bathing and showering. They also emphasized that the orthosis must be designed to avoid fatiguing the shoulder. There was some concern before the interviews that potential users may be uneasy with technology; based on the results of the interviews, this concern was not warranted.

While the initial impetus for performing the interviews was to establish a set of task priorities for use in design and development, a useful outcome was the personal contact with people having severe disabilities. Further association will be ongoing during the design phase and through clinical trials of the prototype orthosis.

CHAPTER 4: MOTION ANALYSIS

4.1 Introduction

Functional arm movements have rarely been studied, as shown in the literature review, yet they are the most relevant for clinical applications. The analysis of functional arm movement achieved two goals: 1) it provided insight and data on how the arm moves while performing functional tasks, beyond what other researchers have provided and 2) it provided data with which to evaluate whether a simulated powered orthosis with limited degrees of freedom could perform the functional tasks chosen. The selection of tasks was based on the priorities defined from the interviews with potential users. The data from the motion analysis was essential for the orthosis simulations, to provide the desired positions, orientations and intial estimates of joint angles.

4.2 Method

The natural motions of able-bodied subjects performing specific functional tasks were recorded with two video cameras. The two sets of images were analysed with customized marker tracking software to determine the joint angle rotations and marker paths. Details are provided below.

4.2.1 Test Setup

Wearing a dark turtleneck and thin gloves, the subject was positioned in an armless chair at a specified location, with the distance from the table determined by placing the subject's elbow comfortably at the edge. The subject was then strapped to a post behind the shoulders such that the trunk would not move forward while performing the tasks (see Figure 4-1). This was necessary as the expected orthosis user is not able to bend forward.

In order to follow the joint locations and to define rotations, five markers were attached to the right arm of the subject: one at the shoulder, one at the elbow, one at the wrist, another on an extension from the wrist, and one on the hand at the second knuckle, MCP 3, as shown in Figure 4-1. The markers, 25 mm diameter white styrofoam spheres, were attached with double-sided adhesive. The backdrop and all of the objects used in the tasks were covered in black in order to increase the contrast of the markers.


Figure 4-1: Subject Performing Task

Two video cameras mounted on tripods approximately 50 degrees apart, as shown in Figure 4-2, were used to record each task. Appendix D lists the hardware used. The cameras were calibrated using a rigid three-dimensional frame with ten markers positioned at known coordinates (see Figure 4-3). The frame provides a reference for the two-dimensional image planes of both cameras to be correlated to three-dimensional space coordinates. A square white reference marker was included within the image field to adjust for movements of the camera image. Using the ten calibration markers (only six are needed) to produce 20 linear equations, the eleven calibration parameters are solved for using a least-squares fit. The known image coordinates from each camera together with the calibration parameters can then be used to solve for the unknown three-dimensional coordinates. Known as the Direct Linear Transformation method, developed by Abdel-Aziz and Karara [1], the details of the calibration and three-dimensional coordinate calculations are given in Appendix E.

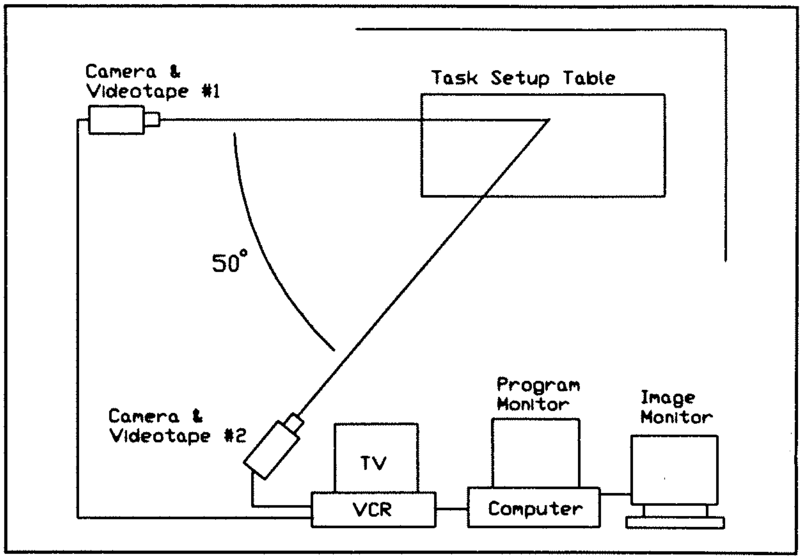

Figure 4-2: Test Setup

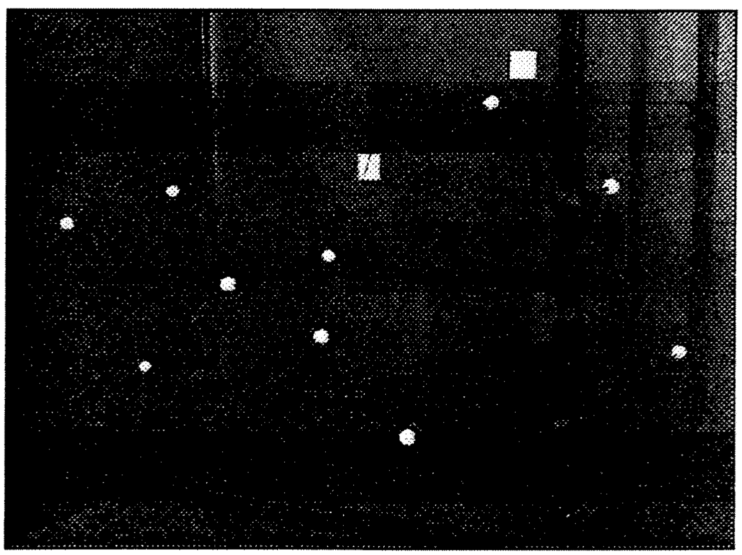
Figure 4-3: Calibration Frame

4.2.2 Subjects

In total six able-bodied subjects, ranging in age from 22 to 44 and in height from 5'-2" to 6'-1/2" participated in the study. Three were female, three male. All were right-hand dominant.

4.2.3 Procedure

Before beginning the tasks, the subject assumed a "standard position" with all joint angles at zero degrees except the elbow, which is bent at 90 degrees, i.e. with the upper arm straight down, the elbow flexed to 90 degrees and the hand flat with the thumb up. Safaee-Rad [102] and Maulucci [67] used this position to correct the calculated joint angle values. This was not done in this research because it was determined that the inaccuracy of positioning the subject in the standard position was greater than the inaccuracy of positioning the markers (elevation in the standard position was as much as 13° due to body geometry, whereas marker position accuracy is within 4°). It was useful however to have one known position when examining the results of the tests.

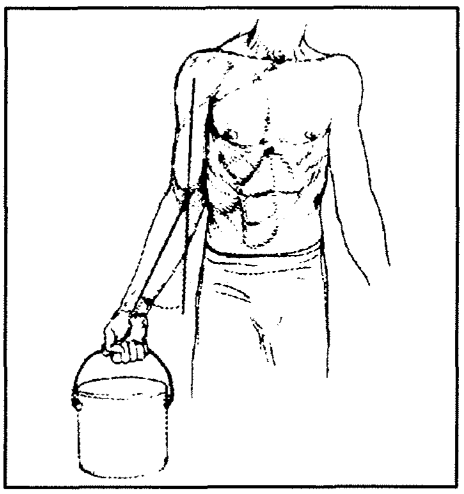

Figure 4-4: Carrying Angle (After [47])

The distance between the marker centroid and the joint centre was measured for each joint. This was used later to translate the markers from the outside of the arm to the joint centres. See Section 4.3.2 for further details. The carrying angle, shown in Figure 4-4, was also measured for each subject. The value of the carrying angle is used in the joint angle calculations (see Section 4.3.2).

4.2.4 Tasks

Twenty-two standardized daily-living tasks were performed. Before each trial the subject activated a camera flash in order to synchronize the two camera images to the same frame during analysis. A starting position was defined for all of the tasks; starting from this position the subject completed a single task, then returned to the starting position. All but one subject executed each task four times with only one trial chosen for analysis. Normally the last trial was chosen for analysis, since unfamiliar tasks became more natural, but another trial was selected if the camera flash occurred on a frame boundary or the trial was performed incorrectly. One subject performed each task eight times, with four trials being analysed to examine the variability for a single individual.

The 22 tasks were classified into several categories:

Eating and Drinking:

1. Eating with the Hands
2. Eating with a Fork
3. Eating with a Spoon
4. Drinking from a Cup

Reaching:

5. Reaching to Position 1, Cylinder Vertical
6. Reaching to Position 2, Cylinder Vertical
7. Reaching to Position 3, Cylinder Vertical
8. Reaching to Position 1, Cylinder Horizontal
9. Reaching to Position 2, Cylinder Horizontal
10. Reaching to Position 3, Cylinder Horizontal

Daily-Living:

11. Pouring from a Pitcher
12. Reaching for and Rotating a Door Lever
13. Reaching for and Rotating a Door Knob
14. Turning a Tap Lever
15. Flipping a Light Switch

16. Pointing to a Button
17. Turning a Page
18. Lifting a Phone Receiver
19. Reaching to the Lap

Personal Hygiene:

20. Washing the Face
21. Brushing the Teeth
22. Combing the Hair

Since it would be impractical to design more than one grasp type into the orthosis (Figure 4-5 shows various possibilities), the tasks were always performed using the overhand cylindrical or palmar grasp. The palmar grasp is normally used about 50% of the time for picking objects up and about 88% of the time when holding objects for use [114] and is therefore the most likely to be designed into an orthosis. The cylindrical grasp accommodates holding utensils with a cylindrical handle or in a palm cuff. This grasp contrasts with other motion analysis researchers who have used the more traditional 'web of thumb' grasp for eating tasks (see Figure 4-5b).

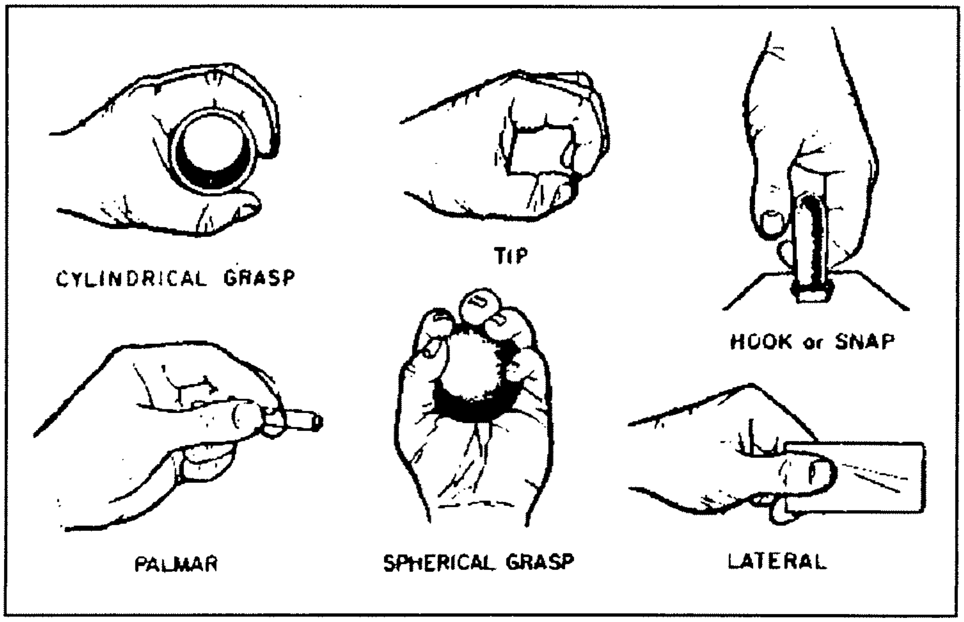

Figure 4-5a: Hand Positions (After [66])

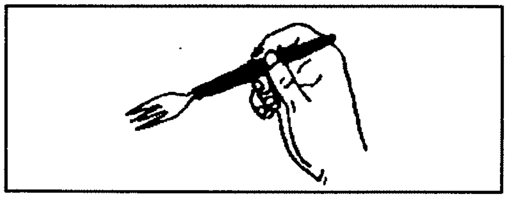

Figure 4-5b: Web-of-Thumb Grasp
(After [112])

During the tests, the utensils were covered with a cylindrical foam handle (a commonly-used daily-living aid) and a stopper piece to keep the fingers in the proper grasp. In all other ways the subject was instructed to perform the tasks as naturally as possible. Muffin pieces or raisins were used for eating with the hands and with a fork, yoghurt was used for eating with a spoon, and water was used for drinking from a cup. A daily-living-aid cup having a lid and spout but no handle was used in the testing. For the reaching tasks, the subject began at the starting position with a 37 mm diameter by 90 mm long foam cylinder at a defined orientation (vertical or horizontal), carried the cylinder to the desired position and then returned to the initial position. Position 1 was at the far right of a normal working area, based on the average for men and women as reported by Pheasant [91] (see Figure 4-6 for the tabletop positions); position 2 was directly in front of the right shoulder for an average person; and position 3 was directly in front of the left shoulder for an average person. The second set of reaching tasks was to the same positions, but with the hand in the second orientation. These positions incorporate the area that would be needed when using a keyboard.

A gardening pitcher was used to study pouring since many of those surveyed expressed an interest in gardening. This is comparable, however, to pouring from either a kettle or a pitcher used for refreshments.

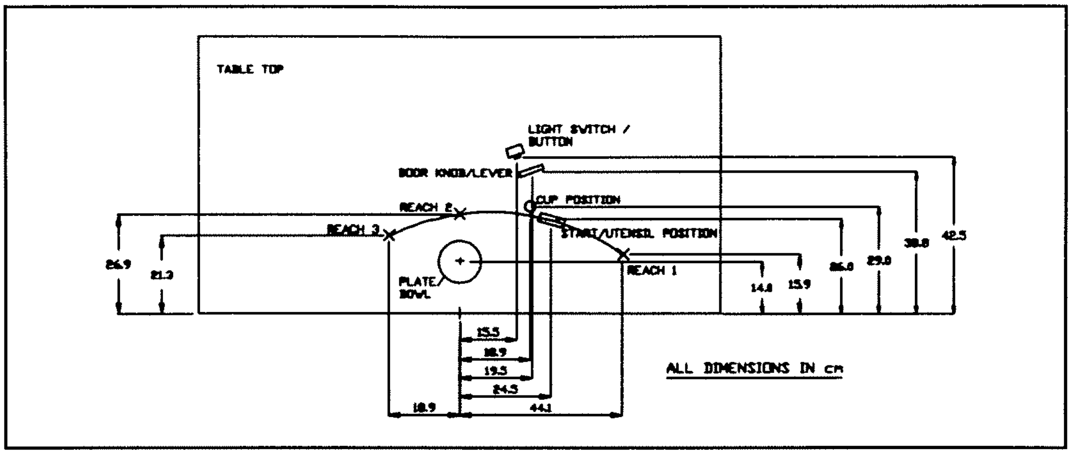

Figure 4-6: Test Setup Dimensions

The door knob and door lever tasks used a mockup door resting on the table, with the height of the handles from the ground being equivalent to that of a full-sized door (96 cm). Similarly, the light switch was set at the same height as a normal light switch (134 cm); it was flipped using the left side of the index finger. The "button" task involved pointing to the light switch, making it identical to the light switch task except for the hand being rotated downwards (pronated). The tap lever was pulled towards the subject.

A rubber page turner was fixed to the end of a straight handle for the page turning task. This is the most likely way a person wearing an orthosis would perform this task, and it is a simple daily-living aid to construct.

To 'wash' the face, a washcloth was passed over the left cheek, the right cheek and then returned to the starting position. To 'brush' the teeth, a toothbrush was held at the front teeth, the left teeth and then the right teeth. Since it was assumed that the orthosis user would use an electric toothbrush, the up and down motions were not required. To comb the hair, each subject performed his or her choice of five strokes.

For reaching into the lap, a television remote control was placed on the legs, just in front of the knees. Starting with the hand relaxed on the leg, the subject reached forward to the remote then returned to a relaxed position. The inclusion of this task allows the user to reach objects in the lap (a common place to put things), scratch a knee (a common aggravation) and have a more relaxed, less obtrusive arm position. All other tasks were performed on the tabletop.

4.3 Motion Analysis Software

In order to analyse the tasks, software was developed [99] to:

1. Control the VCR,
2. Load and manipulate the video image,
3. Track the markers,
4. Solve for the three-dimensional coordinates of each marker,
5. Display stick figure diagrams of the movement and,
6. Calculate the joint angles.

Although software was originally obtained from the University of Manitoba to perform these functions [64, 102], the incompatibilities between frame grabbers and VCRs, as well as discrepancies in the choice of marker positions and method of calculating the joint angles necessitated developing a completely new program. The hardware used in the system is listed in Appendix D.

4.3.1 Joint Angle Definitions

Shoulder Definitions

The human arm can be approximated by seven degrees of freedom modelled as sequence-dependent rotations. In anatomy, "abduction" describes lifting the arm up to the side while "flexion" describes lifting the arm forward. There is no definition for any position between these two. If abduction follows flexion, however, the axis of abduction changes. Abduction followed by flexion is therefore different from flexion followed by abduction. Both Safaee-Rad [102] and Lipitkas [62] used "flexion", "abduction" and "inward/outward rotation" to describe the shoulder joint. This is a common definition for other joints as well, such as the hip and wrist [38,110]. Another approach, by An *et al.* [2], was to use "latitude", "longitude", and "axial rotation" to define the motions. This research instead defines the shoulder rotations as "azimuth", "elevation" and "roll", definitions that have only been used recently, by From [32] and Maulucci [67]. These rotations are defined in Section 4.3.2.

There are two major advantages to using azimuth, elevation and roll. The first is that the orthosis design and control is more likely to correspond to this coordinate system. The second is that, since both azimuth and elevation occur about fixed axes, the coordinates are easier to visualize.

Eulerian vs. Direct Calculations

The analysis performed here differs from previous studies in that joint angles are solved for directly, based on a model of the human arm. Although not as general as the Eulerian approach, the results are more consistent. In the Eulerian method used by Safaee-Rad [102], Langrana [54] and Lipitkas [62], marker locations are used to define a set of axes at each joint. A transformation matrix is then determined between each set of axes. The numerical values of this matrix are equated with the theoretical Euler matrix of three successive rotations to determine the joint rotations. (See Appendix F for a sample calculation.) Because of inaccuracies in the definition of the axes based on the marker locations, the solution for the three rotations can be inconsistent. Since the calculation of the endpoint position using the resulting joint angle values is therefore also inconsistent, it was decided to calculate the joint angles directly.

Carrying Angle

A necessary assumption of the direct method was to define how the carrying angle affects the plane of elbow flexion. The carrying angle is defined with the arm fully extended as the angle between the forearm and the extension of the upper arm. The angle results from the geometry of the bones at the elbow joint, as shown in Figure 4-7. There are variations, however, in the reported values. While Berme reports that men typically have a carrying angle from 10 to 15 degrees and women have a carrying angle from 20 to 25 degrees [7], Hoppenfield reports that 5 degrees is normal for males and that women normally vary between 10 to 15 degrees [47]. The carrying angle measured for the three males in this study were 10, 13 and 14 while the females had carrying angles of 10, 14 and 19.

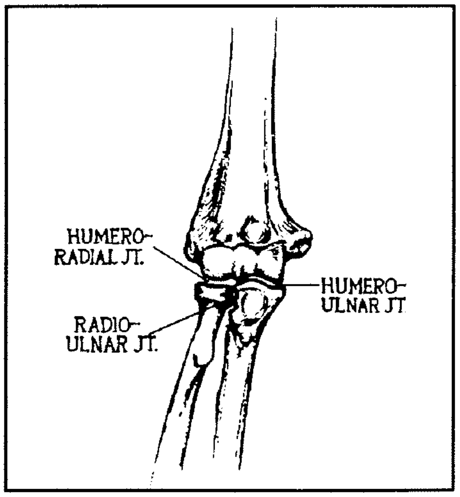

Figure 4-7: Carrying Angle Bone Configuration (After [47])

For the purposes of this research the carrying angle is considered constant, describing a constant tilt in the plane of elbow flexion. This is supported by Chao and Morrey [15,74] and Youm *et al.* [118] in their studies of elbow motions (although the defined order of rotations is switched). Both studies demonstrated that forearm rotation does not significantly affect the carrying angle. Chao and Morrey recorded a constant carrying angle throughout elbow flexion while Youm *et al.* recorded deviations in the carrying angle and a zero degree carrying angle past 90 degrees of elbow flexion. Because of the discrepancy, because the difference does not have a large effect, and for the sake of simplicity, a constant carrying angle was used in this research.

In summary, there are three ways in which this analysis differs from previous work:

1. A clearer definition of shoulder joint rotations is used, which is more suited to orthosis design.
2. Each joint angle is calculated directly, based on a model of the arm, instead of solving for the three Euler rotations simultaneously at each joint.
3. A passive carrying angle is defined which rotates the plane of elbow flexion.

4.3.2 Joint Angle Calculations

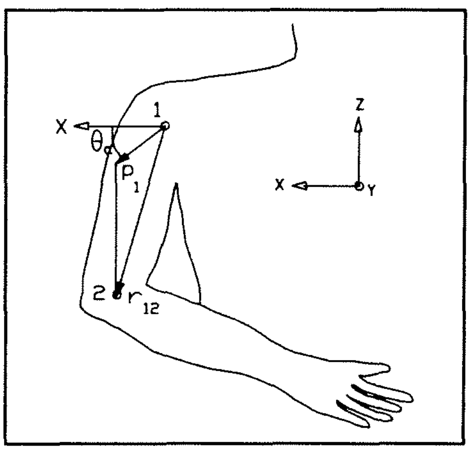

Figure 4-8: Azimuth Angle Definition

The azimuth angle is the rotation about a vertical axis through the shoulder joint (see Figure 4-8). Zero degrees is defined as the upper arm directed towards the side. The following calculations are valid for the right arm only.

Let $\mathbf{p}_1$ be the projection of $\mathbf{r}_{12}$ onto the horizontal plane XY (defined by the normal vector Z), where the vector $\mathbf{r}_{12}$ is defined as the vector from marker 1 to marker 2. This convention is used throughout the calculations.

Then,

$$p_1 = r_{12} - \left(\frac{r_{12} \cdot Z}{|Z|^2}\right) Z \qquad \textbf{(4-1)}$$

and,

$$\theta_a = \textit{azimuth} = \arccos\left(\frac{p_1 \cdot X}{|p_1|}\right) \qquad \textbf{(4-2)}$$

Elevation is the angle of rotation up from a vertical position, about a horizontal axis through the shoulder joint (see Figure 4-9). Zero degrees of elevation is defined as the upper arm pointed straight down.

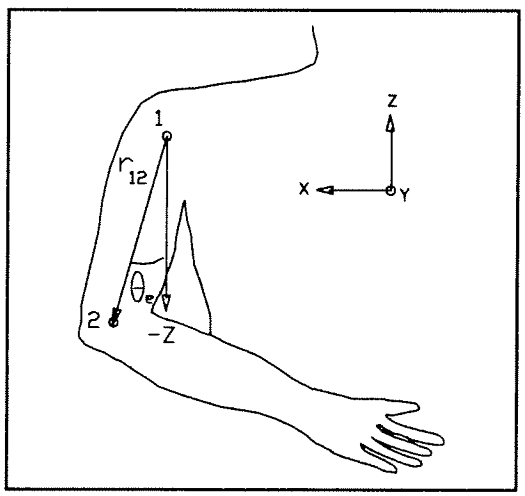

Figure 4-9: Elevation Angle Definition

Thus,

$$\theta_e = \textit{elevation} = \arccos\left(\frac{r_{12} \cdot (-Z)}{|r_{12}|}\right) \qquad (4\text{-}3)$$

Although carrying angle and roll are sequence independent, the coordinates are dependent and are not uniquely determined by the positions of the markers. The subject's measured carrying angle is therefore input into the program in order to calculate a value for roll. For the purposes of the following calculations, let the

$$\textit{carrying angle} = \theta_c \quad \textit{(measured)} \qquad (4\text{-}4)$$

Roll occurs about the axis of the upper arm (see Figure 4-10a,b). Elbow flexion is defined to be zero with the arm fully extended (see Figure 4-11).

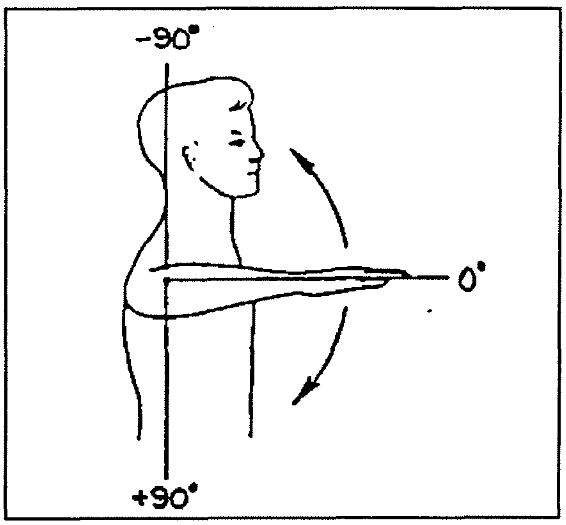

Figure 4-10a: Roll Anatomical Definition, Upper Arm Horizontal (After [102])

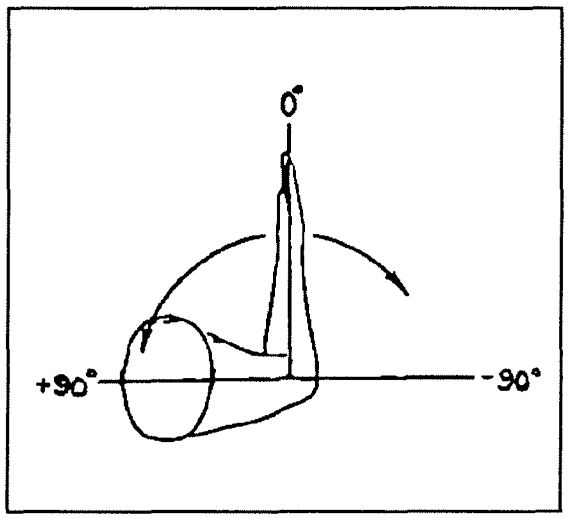

Figure 4-10b: Roll Anatomical Definition, Upper Arm Vertical (After [102])

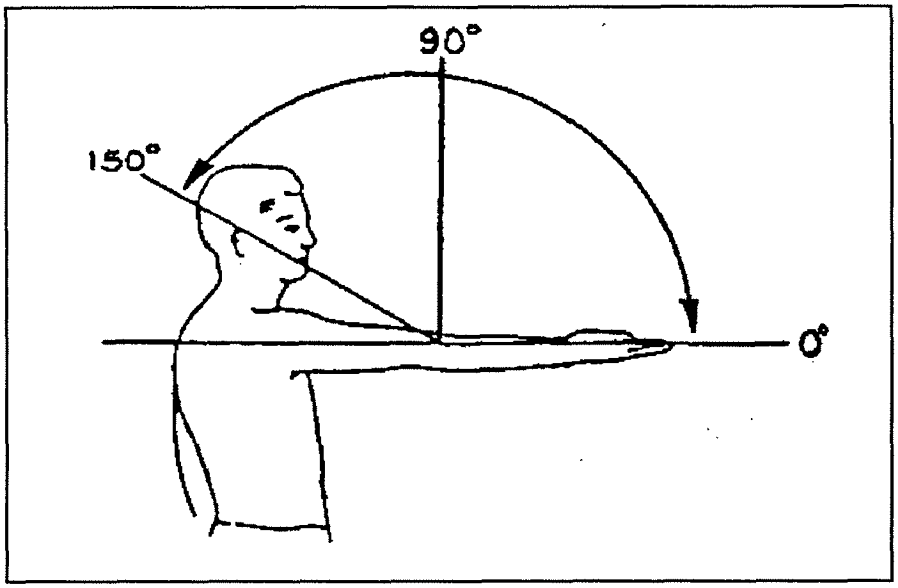

Figure 4-11: Elbow Flexion Anatomical Definition (After [102])

Vector $\mathbf{n}_1$ in Figure 4-12 is normal to the upper arm, facing forward when the azimuth is zero. Plane A in Figure 4-12 is defined by the upper arm and by the forearm with the elbow flexed at 90 degrees. That is, plane A consists of the upper arm and the vector $\mathbf{n}_2$, which is rotated from $\mathbf{n}_1$ by the upper arm roll. Plane B is the plane in which the forearm moves. Plane B is rotated from plane A by the carrying angle, θ_c.

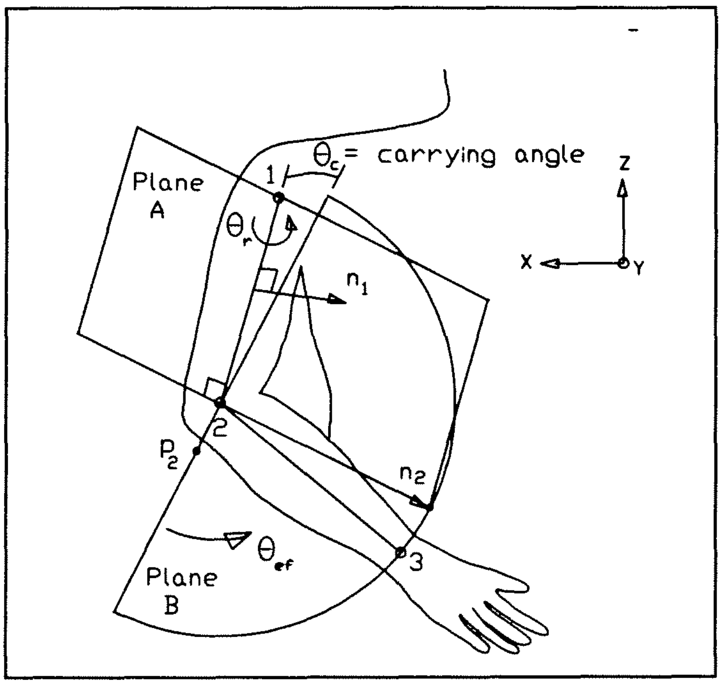

Figure 4-12: Roll and Elbow Flexion Angle Definitions

Thus,

$$n_1 = Z \times r_{12} \qquad (4\text{-}5)$$
$$n_2 = r_{21} \times r_{2p2} \qquad (4\text{-}6)$$

$$\theta_r = roll = \begin{cases} +\arccos\left(\dfrac{n_1 \cdot n_2}{|n_1||n_2|}\right) & \text{if } (n_1 \times n_2) \cdot r_{21} \le 0 \quad (\textit{inward rotation}) \\ -\arccos\left(\dfrac{n_1 \cdot n_2}{|n_1||n_2|}\right) & \text{if } (n_1 \times n_2) \cdot r_{21} > 0 \quad (\textit{outward rotation}) \end{cases} \qquad (4\text{-}7)$$

$$\theta_{ef} = elbow\ flexion = \begin{cases} \arccos\left(\dfrac{r_{23} \cdot r_{2p_2}}{|r_{23}||r_{2p_2}|}\right) & \text{if } (r_{2p_2} \cdot r_{12}) \ge 0 \quad (\textit{flexion} < \frac{\Pi}{2}) \\ \pi - \arccos\left(\dfrac{r_{23} \cdot r_{2p_2}}{|r_{23}||r_{2p_2}|}\right) & \text{if } (r_{2p_2} \cdot r_{12}) < 0 \quad (\textit{flexion} > \frac{\Pi}{2}) \end{cases} \qquad (4\text{-}8)$$

The position of point p_2, the projection of point 3 (the wrist) onto the line of the forearm in full extension, is derived in Appendix G.

Forearm rotation is defined as rotation about the axis of the forearm. At zero degrees, the wrist extension is perpendicular to plane B, the plane of forearm movement. Zero rotation has conventionally been defined as the thumb facing up when the elbow is flexed by 90 degrees (see Figure 4-13). There is no definition at any other position. In this study, the neutral position is rotated inward by the carrying angle because of the tilt in the plane of elbow flexion. Pronation, or inward rotation, is defined here as positive while supination, or outward rotation, is defined here as negative.

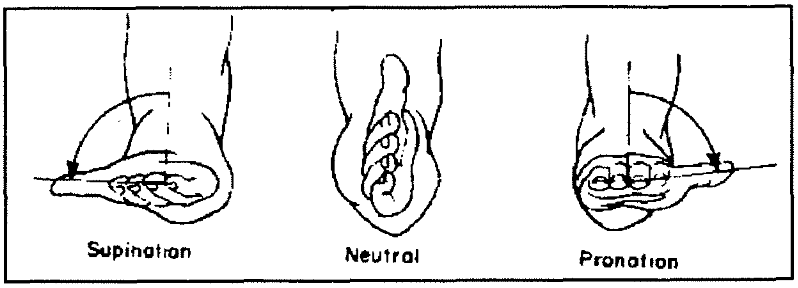

Figure 4-13: Traditional Forearm Rotation Anatomical Definition (After [16])

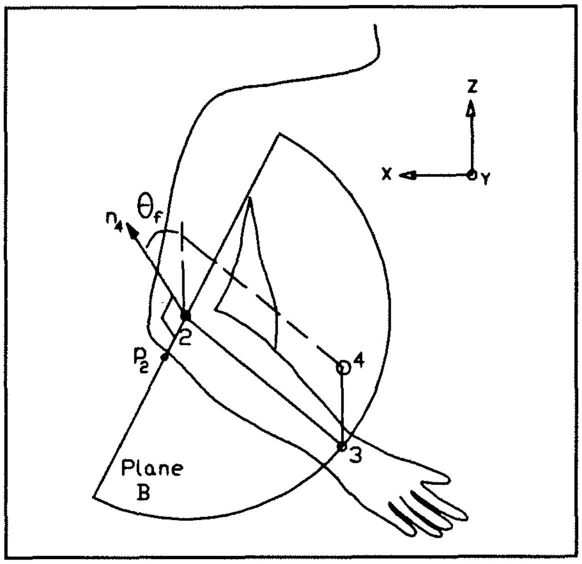

Figure 4-14: Forearm Rotation Angle Definition

The calculation of forearm rotation assumes that the wrist extension is perpendicular to the forearm axis. To ensure that this is the case, $\mathbf{r}_{34}$ is projected onto the plane defined by $\mathbf{r}_{23}$. This projection is referred to as $\mathbf{r}_{34}'$.

$$r_{34}' = r_{34} - \left(\frac{r_{34} \cdot r_{23}}{|r_{23}|^2}\right) r_{23} \tag{4-9}$$

Let $\mathbf{n}_4$ be the vector normal to plane B, as shown in Figure 4-14:

$$n_4 = r_{2p_2} \times r_{23} \qquad \textbf{(4-10)}$$

Then,

$$\theta_f = \textit{forearm rotation} = \arccos\left(\frac{r'_{34} \cdot n_4}{|r'_{34}||n_4|}\right) \qquad \textbf{(4-11)}$$

For wrist flexion, a positive angle refers to bending the hand down (flexion), a negative angle to bending the hand up (extension), as shown in Figure 4-15. Referring to Figure 4-16, let $\mathbf{p}_4$ be the projection of $\mathbf{r}_{35}$ onto the plane of the forearm defined by $\mathbf{n}_5$, where:

$$n_5 = r'_{34} \times r_{32} \qquad \textbf{(4-12)}$$

$$p_4 = r_{35} - \left(\frac{r_{35} \cdot n_5}{|n_5|^2}\right) n_5 \qquad \textbf{(4-13)}$$

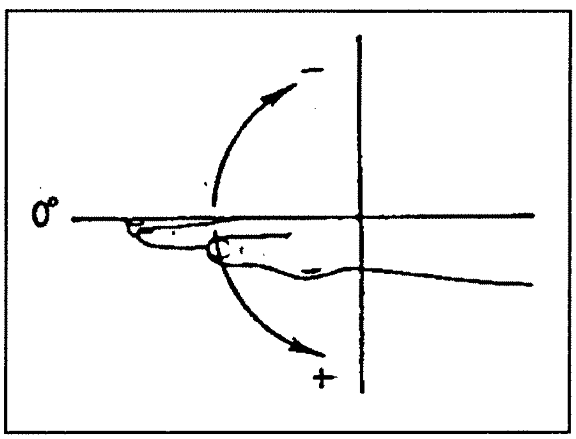

Figure 4-15: Wrist Flexion Anatomical Definition (After [102])

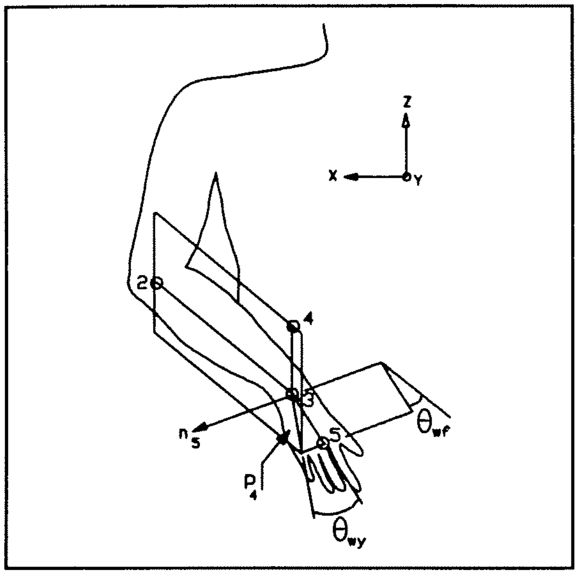

Figure 4-16: Wrist Flexion and Wrist Yaw Angle Definitions

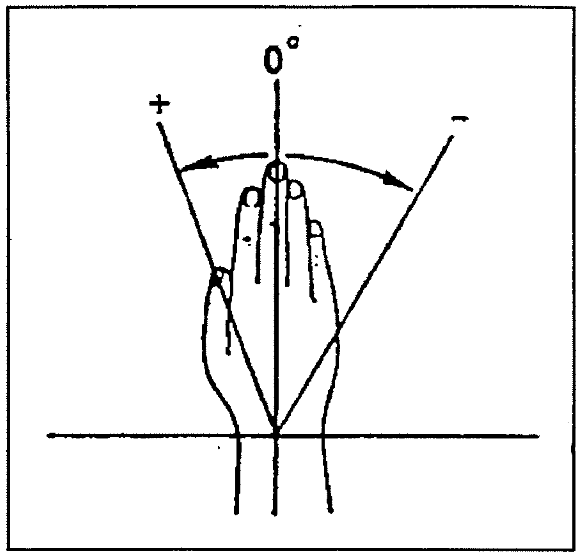

Figure 4-17: Wrist Yaw Anatomical Definition (After [102])

So that,

$$\theta_{wf} = \textit{wrist flexion} = \begin{cases} +\arccos\left(\dfrac{p_4 \cdot r_{23}}{|p_4||r_{23}|}\right) & \textit{if } p_4 \cdot r_{34} \le 0 \quad \textit{(flexion)} \\ -\arccos\left(\dfrac{p_4 \cdot r_{23}}{|p_4||r_{23}|}\right) & \textit{if } p_4 \cdot r_{34} > 0 \quad \textit{(extension)} \end{cases} \tag{4-14}$$

Positive wrist yaw refers to moving the right hand to the left (radial deviation) while negative wrist yaw refers to moving the hand to the right (ulnar deviation), as shown in Figure 4-17.

$$\theta_{wy} = \textit{wrist yaw} = \begin{cases} +\arccos\left(\dfrac{r_{35} \cdot p_4}{|r_{35}||p_4|}\right) & \textit{if } r_{35} \cdot n_5 \le 0 \quad \textit{(radial deviation)} \\ -\arccos\left(\dfrac{r_{35} \cdot p_4}{|r_{35}||p_4|}\right) & \textit{if } r_{35} \cdot n_5 > 0 \quad \textit{(ulnar deviation)} \end{cases} \tag{4-15}$$

The above equations provide the initial calculations for the joint angles. Adjustments are made to consider quadrant indeterminacy and to move the markers to the joint centres. Due to the quadrant indeterminacy of arccosine, the solution for azimuth is in the first quadrant when the arm is in the fourth. Also, occasionally when the arm is close to vertical, the markers will indicate that the arm is in the third quadrant (behind the back) when in fact it is in the first. The following corrections are therefore included:

if $(p_1 \cdot Y) < 0$ **(4-16)**
  if $(p_1 \cdot X) < 0$
    azimuth $= \pi -$ ***azimuth***
    elevation $= -$ ***elevation***
    roll $= \pi -$ ***roll***
    forearm rotation: choose the alternate $\vec{p}_2$ ***& recalculate***
  if $(p_1 \cdot X) > 0$
    azimuth $= -$ ***azimuth***

Another consideration is that an error is introduced into the above joint angle calculations because the markers are on the outside of the arm. Past studies have accepted this approximation. In this study the distance between the marker centroid and the joint centre was measured for each joint. The markers are then translated mathematically to the joint centres for a better estimate of the joint angles. The greatest difference in joint angle values occurs because of the apparent movement of the wrist when the forearm rotates. For example, the wrist marker rotates at a radius of 35 mm, on average, from the centre of the wrist. Both elbow flexion and roll then appear to change by approximately 8 degrees, whereas at most the inaccuracy of defining the distance between the centres would lead to an error of 2 degrees.

The vectors are first calculated as described above. The markers are then translated along the appropriate vector, from the marker to the joint centre, by the distance measured on the subject.

i) The shoulder marker (marker 1) is moved along vector $\mathbf{r}_{21}$ x $\mathbf{n}_2$ (refer to Figure 4-12).
ii) The elbow marker (marker 2) is also moved along vector $\mathbf{r}_{21}$ x $\mathbf{n}_2$ (refer to Figure 4-12).
iii) The wrist marker (marker 3) is moved along vector $\mathbf{r}_{43}'$, down the adjusted wrist extension (see Figure 4-14). The adjusted marker 4 remains in the same position.
iv) The hand marker (marker 5) is moved along vector $\mathbf{r}_{35}$ x $\mathbf{p}_4$ if $(\mathbf{r}_{35} \text{ x } \mathbf{p}_4) \bullet \mathbf{r}_{34}' < 0$ (i.e. the vector is pointing into the knuckle) and in the opposite direction otherwise (see Figure 4-16).

The joint angle results shown below are based on the adjusted marker positions.

4.4 Accuracy of the System

The static accuracy of the system was tested using stationary markers with known positions. Errors in the static accuracy may be due to inaccuracies in the camera calibrations, nonuniform lighting causing noncircular images of the spheres, noise in the image analysis system or lens distortion. The static accuracy of this system was found to be ± 1 pixel = ± 3 mm ≈ ± 0.3% based on the field of view. This is an improvement over that of the University of Manitoba system (0.8%) [102] and the Langrana system (1.8%) [54] due to differences in the size of the field of view, and significantly better than the 4% in Shapiro's system [107].

For dynamic accuracy, the known distance between the wrist marker and its extension was tracked as the arm moved. This gave a dynamic accuracy of ± 4 mm. The possible causes of dynamic inaccuracies are changes in the illumination of the markers, elongation of the marker images during quick movements and the inexact synchronization between cameras.

Inaccuracies in the joint angle values due to the imaging system inaccuracy are greatest at the wrist (± 3 degrees) because the markers are closest together in this region. In addition, although the marker positions are well defined at the wrist and on the hand, the short distance between markers causes joint angle inaccuracies of ± 3 degrees related to errors in positioning the markers. Positioning of the shoulder marker has the most variability but the length of the upper arm limits the region of error to only ± 2 degrees in the resulting joint angles.

Overall, the coordinates accuracy is ± 5 mm and the joint angles accuracy is ± 4 degrees, which is sufficient for the purposes of this study.

4.5 Results

4.5.1 Single Subject/ Single Trial

Each of the 22 tasks is distinctive, both in terms of the range of motion required for each joint and in terms of the path taken to perform the task. It is clear, for example, that Eating with the Hands and Brushing the Teeth involve quite different motions despite both bringing the hand to the mouth. Figures 4-18 and 4-19 show the raw data angle-time graphs for the two tasks, with each line representing a different joint angle. Representative angle-time graphs for all of the tasks are included in Appendix H.

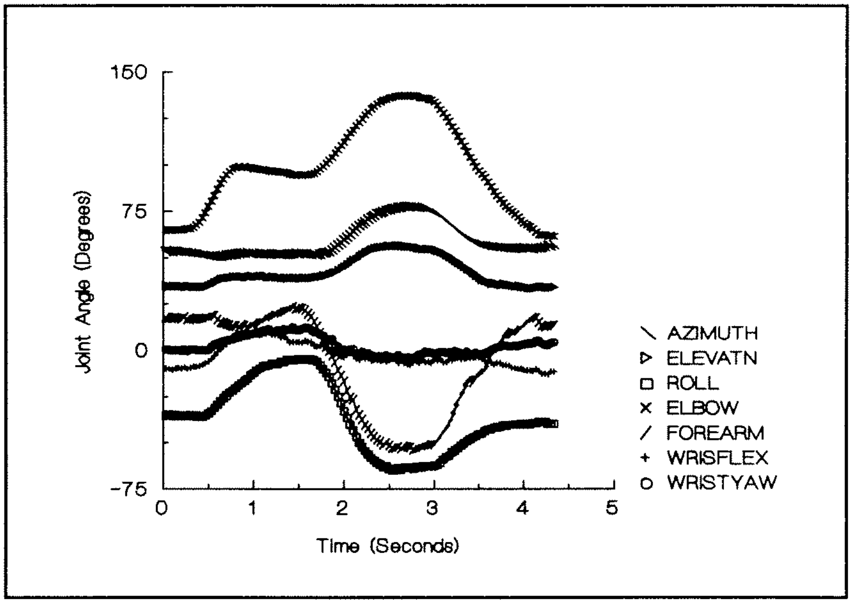

Figure 4-18: Angle-Time Graph for Eating with the Hands

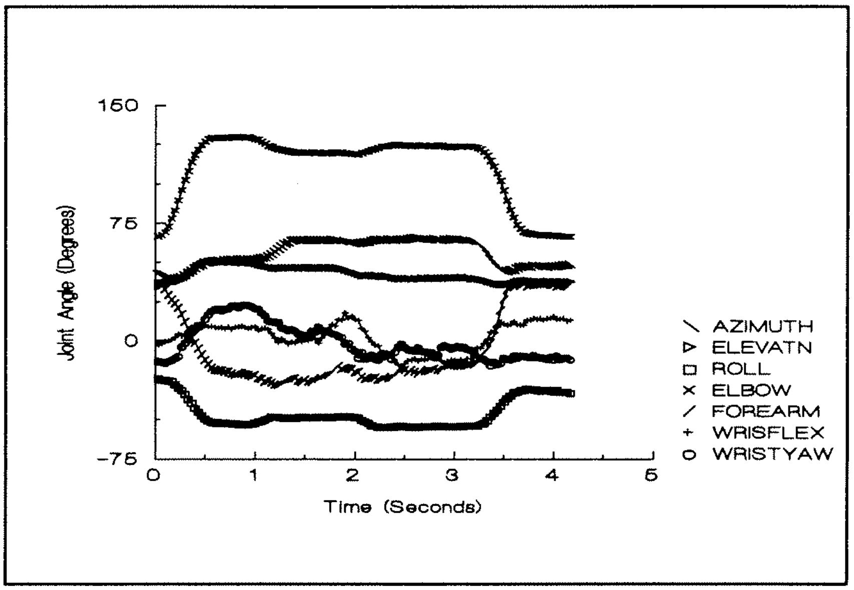

Figure 4-19: Angle-Time Graph for Brushing the Teeth

The tasks can be roughly linked together in terms of the path taken by the endpoint (although the orientations may be different) as follows:

1. The 6 Reaching tasks (Across the table, parallel to the body)
   Page Turning

2. Eating with the Hands (Towards the face or head, from below)
   Eating with a Fork
   Drinking from a Cup
   Lifting a Phone Receiver
   Washing the Face
   Brushing the Teeth

3. Flipping the Light Switch (Up and out)
   Pointing to the Button

4. Door Lever (Out, perpendicular to the body)
   Door Knob
   Turning the Tap

The remaining tasks, Eating with a Spoon, Combing the Hair, Pouring from a Pitcher and Reaching to the Lap, have distinct paths and endpoints. Eating with a spoon differs significantly from either of the other two eating tasks because of the need to keep the spoon level, needing greater elevation, roll and wrist flexion. The results show that eating with a spoon and combing the hair place complex demands on the orthosis design.

Before this motion analysis study, one possibility for orthosis control was to program "component movements" into the orthosis. Upon examining the results, however, there are not sufficient similarities between tasks, in both position and orientation, to support this approach.

The flexibility of the subjects' fingers added movement beyond the basic seven degrees of freedom. While lifting the cup to the lips, for instance, the thumb often rotated down to cause the cup to rotate. Not having this flexibility, the orthosis would have to compensate with greater forearm rotation.

4.5.2 Single Subject/ Multiple Trials

For one subject, four trials of each task were analysed to quantify the variability for a single individual. Table 4-1 tabulates the results. The sample standard deviation is used because of the low number of samples.

The table shows that the results are repeatable with elevation being the most consistent and wrist flexion the least. Based on these tests, the average joint angle standard deviation was found to be 3.0 degrees. Washing the Face, Combing the Hair and the starting position of Reaching to the Lap were the most variable.

4.5.3 All Subjects / Single Trial Comparisons

The average minimums and maximums for each joint angle were calculated for each task for the six subjects. Table 4-2 summarizes the results; the full table is included in Appendix I.

	AZIMUTH				ELEVATION				ROLL				E-FLEX				F-ROTN				W-FLEX				W-YAW			
	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev
HANDS	33	2.5	60	3.8	30	1.4	49	5.3	-53	7.1	-2	7.2	68	1.9	134	4.9	-54	8.2	52	0.9	-16	2.9	21	7.1	-15	6.1	10	3.0
FORK	23	-2.	39	3.0	34	0.3	61	2.0	-28	3.3	10	2.9	80	0.8	136	3.3	-32	3.0	75	4.7	3	5.5	47	13.	-21	8.4	12	3.4
SPOON	20	1.1	44	2.2	31	0.3	74	5.6	-60	5.5	5	2.9	84	1.4	132	8.8	-9	6.6	77	5.8	-2	2.9	41	4.1	-16	6.2	18	2.2
CUP	22	1.3	45	3.9	29	1.7	68	2.6	-65	2.4	-12	2.2	75	1.1	142	2.4	8	2.5	51	2.5	-31	4.7	21	4.6	-19	2.9	4	3.4
RCH1A	13	2.5	47	3.6	30	1.3	35	1.5	-50	3.5	-31	3.3	69	1.3	85	3.0	-16	3.8	2	2.0	-30	2.6	-5	2.8	-16	3.9	2	3.5
RCH2A	40	1.6	76	11.	31	2.5	43	2.9	-37	1.5	-23	5.3	64	3.5	80	2.4	-19	6.4	-2	2.1	-31	6.3	-16	5.1	-10	4.3	-2	1.5
RCH3A	38	1.0	111	0.9	32	0.4	44	0.9	-40	3.0	-22	1.6	54	1.5	82	1.5	-18	3.2	-2	3.4	-31	1.7	-9	4.5	-10	3.9	-0	1.2
RCH1B	11	0.6	43	1.1	35	0.3	40	1.3	-32	0.6	-18	1.0	68	1.2	79	1.4	48	3.4	58	2.2	-19	0.3	-6	1.0	-7	3.2	3	3.2
RCH2B	39	2.1	79	1.7	35	1.1	44	1.8	-31	1.7	-20	1.5	60	1.4	77	1.6	47	2.1	57	0.9	-17	2.1	-6	3.5	-8	0.6	1	2.0
RCH3B	41	0.7	109	1.1	34	0.9	46	1.2	-32	3.2	-19	3.0	51	1.3	78	1.3	45	3.2	59	2.6	-18	2.4	-7	4.3	-7	2.0	2	1.5
POUR	34	2.7	73	3.4	33	1.3	87	4.4	-45	5.4	-17	4.2	57	3.5	84	4.2	-46	4.6	47	2.7	-31	6.5	-1	6.4	-18	2.8	-2	3.0
DOOR	39	1.8	71	0.5	34	1.1	57	2.4	-47	1.0	-18	1.3	58	3.4	84	1.9	4	11.	59	1.3	-26	2.8	-2	1.3	-9	1.5	6	1.9
KNOB	36	2.6	64	1.5	38	1.1	65	0.9	-38	3.3	-10	1.4	42	1.7	81	1.9	11	7.6	62	3.0	-40	5.1	-6	4.7	-13	4.0	3	2.6
TAP	37	3.3	66	2.4	34	1.2	63	2.3	-52	6.0	-24	3.2	59	2.2	74	1.5	25	12.	61	1.2	-15	2.1	26	1.1	-39	2.5	6	2.6
LIGHT	40	3.8	73	1.8	33	1.0	94	3.2	-64	6.3	-27	3.6	43	1.7	85	10.	-40	6.4	56	4.3	-21	0.8	6	5.5	-26	4.4	-5	2.2
BTTN	44	2.7	68	2.5	33	1.4	85	2.6	-63	1.8	-27	5.1	56	1.4	85	6.6	24	4.5	53	1.8	-22	5.0	5	7.0	-13	3.9	-3	2.3
PAGE	6	1.4	66	3.9	27	1.5	43	3.4	-24	1.7	-5	2.9	84	1.7	97	1.7	53	2.7	70	1.7	-21	3.4	21	1.4	-20	3.5	10	2.1
PHONE	36	1.7	71	4.3	36	0.8	65	3.1	-87	4.8	-29	2.1	74	0.7	153	1.1	-20	3.4	57	1.2	-28	6.3	2	4.6	-20	2.4	8	1.6
LAP	4	8.6	83	1.9	9	0.2	32	0.7	-33	1.4	30	6.8	56	2.0	84	1.5	52	2.5	66	2.9	-28	5.3	23	2.2	-13	3.3	4	1.2
WASH	30	5.6	99	3.0	21	1.5	55	0.9	-87	3.4	-23	3.4	76	1.5	150	2.2	-93	2.3	56	2.5	-43	5.1	10	4.8	-28	0.4	4	2.0
BRUSH	28	1.0	59	2.9	35	1.1	86	2.8	-83	4.1	-20	2.9	76	1.1	143	4.8	-30	8.1	48	3.1	-19	5.2	41	13.	-23	4.8	15	3.6
COMB	29	2.3	97	2.4	32	1.2	82	1.0	-103	5.9	-26	2.6	75	1.4	156	1.7	-26	2.5	55	1.0	-40	4.4	27	7.9	-22	5.2	20	1.7
EXTREM.	*4*		*111*		*9*		*94*		*-103*		*10*		*42*		*156*		*-93*		*77*		*-43*		*47*		*-39*		*20*	
AVG SD		*2.2*		*2.8*		*1.0*		*2.4*		*3.5*		*3.0*		*1.7*		*3.2*		*5.0*		*2.4*		*3.8*		*5.0*		*3.6*		*2.4*

Table 4-1: Motion Analysis Results, Single Subject

	Least Avg. Min. (degrees)	Task Where L.A.M. Occurs	Greatest Avg. Max. (degrees)	Task Where G.A.M. Occurs	Average Range (degrees)
Azimuth	7	Page (sd 6) Reach1A (10) Reach1B (7) Lap (23)	108	Reach3A (sd 5) Reach3B (sd 7)	40
Elevation	15	Lap (sd 3)	96	Light (sd 6)	26
Roll	-85	Comb (sd 12)	20	Lap (sd 25)	34
E-Flex	42	Knob (sd 4)	151	Phone (sd 15)	39
F-Rotn	-86	Wash (sd 18)	61	Page (sd 6)	52
W-Flex	-42	Wash (sd 10)	53	Spoon (sd 16)	33
W-Yaw	-39	Tap (sd 6)	24	Comb (sd 10)	21

Table 4-2: Summary of Motion Analysis Results, All Subjects

The standard deviation for the average minimum and maximum joint angles for these tests was found to be 8.0 degrees.

A comparison of the plots for the path of the hand for each task showed that the personal hygiene tasks, Washing the Face, Brushing the Teeth and Combing the Hair were the most variable from person to person. All of the others were quite similar, although the head position varied between individuals for the eating tasks.

There were no identifiable differences between the male and female subjects except with elbow flexion in which subjects with longer arms did not have to extend the arm as much to reach the same position.

4.5.4 Comparisons with Previous Work

Figures 4-20 to 4-26 compare the results from this study to previous ones with each joint being compared individually. The abscissa range shows the approximate joint limits for each joint angle [11]. Since more researchers have studied elbow and wrist motion than shoulder motion, these will be discussed first. In each case, the leftmost end of each horizontal line represents the average minimum for that task, the rightmost end the average maximum. When the standard deviation for the average maximum or minimum was given, vertical lines were included to indicate ± one standard deviation about the minimum or maximum, thus 68% of the population would fall within these limits.

Two previous researchers have quantified elbow flexion and forearm rotation for functional tasks: Safaee-Rad *et al.* [103] and Morrey, Chao *et al.* [15,74]. The former used a video-based motion analysis system to examine the whole-arm movement in performing Eating with a Fork, Eating with a Spoon and Drinking from a Cup; the latter used a triaxial electrogoniometer to study elbow motion exclusively. The Safaee-Rad study included ten male subjects while the Morrey study included 15 male and 18 female subjects. No significant difference was found between the male and female subjects.

In general, the results of the present study (marked UBC) shown in Figures 4-20 and 4-21 compare well with the previous studies. The layout of the objects on the table, which was different between studies, affects how far the subject must reach and thus the minimum elbow extension. Also, trunk movement was not restricted in the other studies. Differences in the amount of elbow flexion are therefore to be expected.

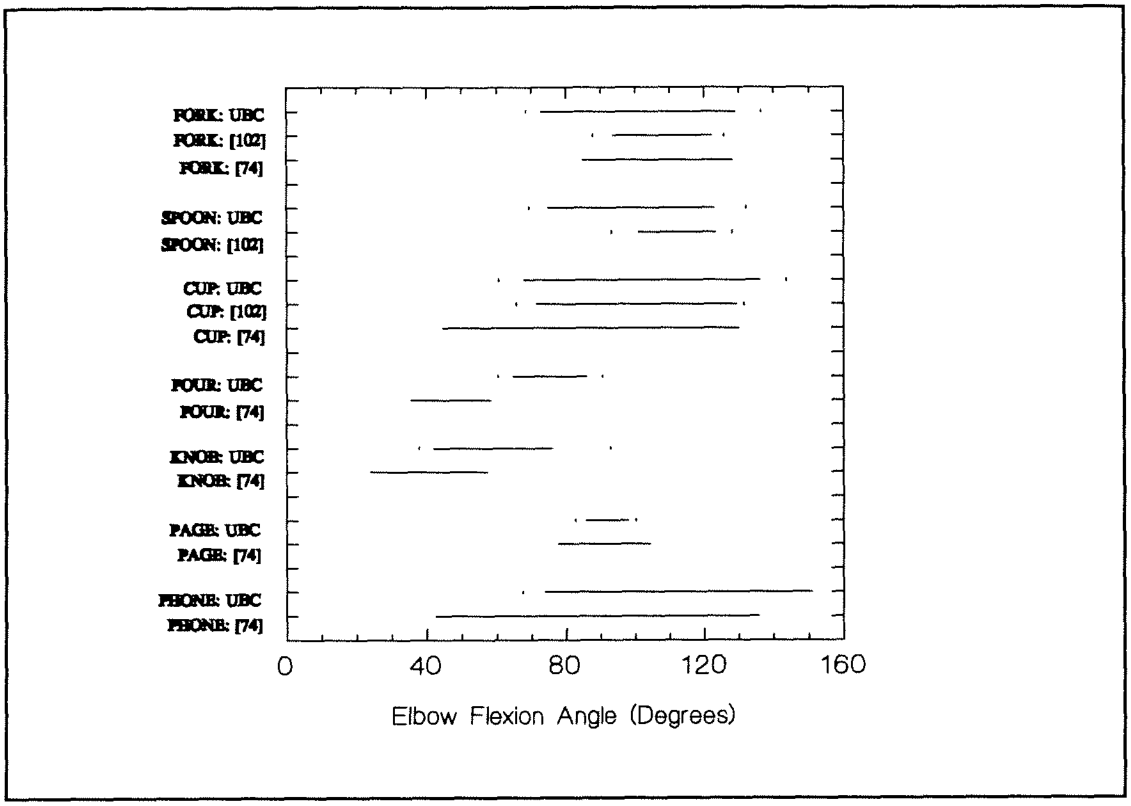

Figure 4-20: Comparison of Motion Studies for Elbow Flexion

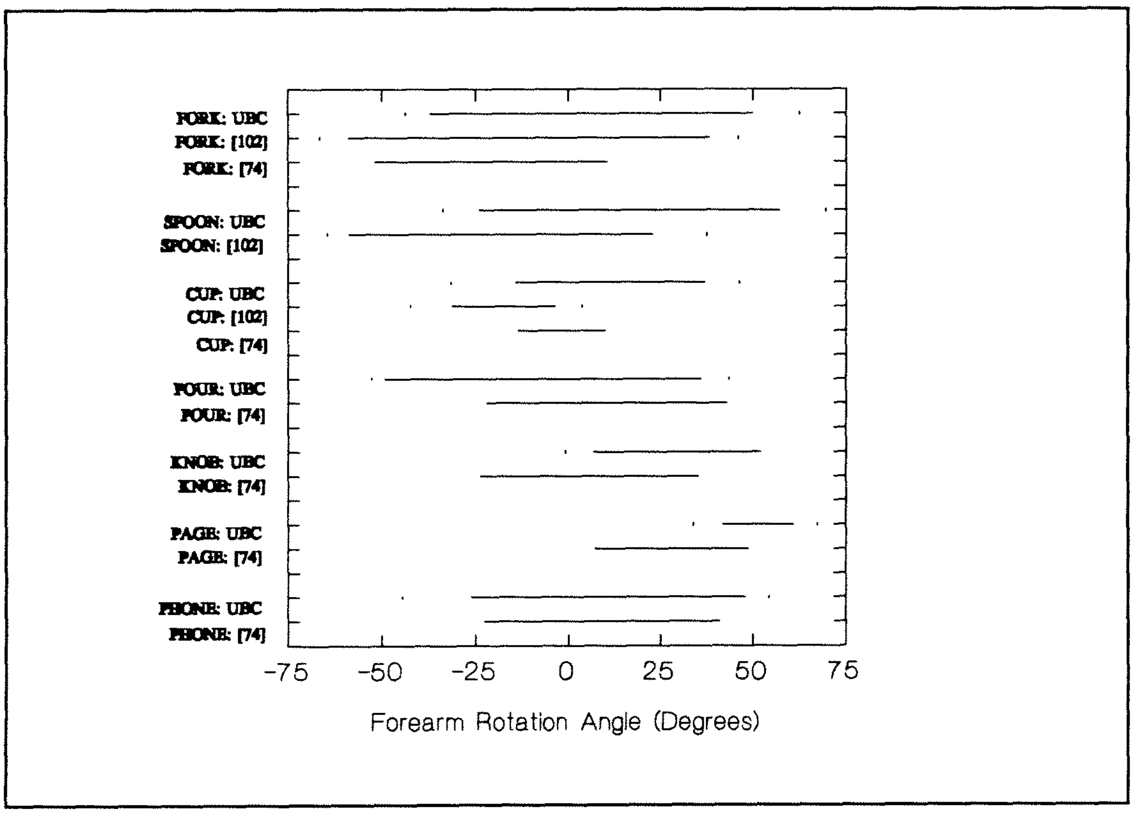

Figure 4-21: Comparison of Motion Studies for Forearm Rotation

There are several explanations for the differences in forearm rotation. The subjects in this study used an overhand cylindrical grasp to hold onto the fork and spoon whereas subjects in the other studies used the more traditional underhand web-of-thumb grasp. While more practical for an orthosis, the overhand grasp requires more pronation (positive forearm rotation). The type of pitcher used, a gardening pitcher for this study, a beverage jug for the Morrey study, may account for the differences in pouring. In the "Knob" task, "Opening a Door" [74] was compared to "Turning a Door Knob while seated at a table" (UBC): the seated subjects reached for the doorknob in a more pronated orientation whereas those who were standing chose a more supinated orientation; opening the door itself would also require more supination. Similarly "Page Turning" for the UBC study used a handled page turner, causing the hand to be more pronated than for "Reading a Newspaper" in the Morrey study. The definitions of forearm rotation also vary, as outlined in Section 4.3.2 and Appendix F.

Three researchers have studied functional wrist motion: Safaee-Rad *et al.*, as mentioned above, Ryu *et al.* [101] and Brumfield & Champoux [13]. Ryu studied 40 subjects (20 women, 20 men) with a biaxial wrist electrogoniometer while Brumfield and Champoux used a uniaxial electrogoniometer to examine just the wrist flexion of 19 subjects (7 women, 12 men). Palmer *et al.* [86] studied functional wrist motion, but only reported the centroid of each joint angle rather than the extremes so the results are not shown here.

The graph comparing wrist flexion (Figure 4-22) shows the effect of the overhand grasp on eating with a fork, eating with a spoon and page turning even more dramatically than for forearm rotation. It was clearly more awkward for the subjects to get the food onto the fork or spoon and to keep the spoon level as it was raised. The wrist flexion used to "Turn a Tap"

(UBC) versus "Opening and Closing a Faucet Handle" [101] depends both on the shape and the height of the tap, which was not documented. All of the other task motions are quite similar. The comparisons of wrist yaw (Figure 4-23) show similar results to those for wrist flexion.

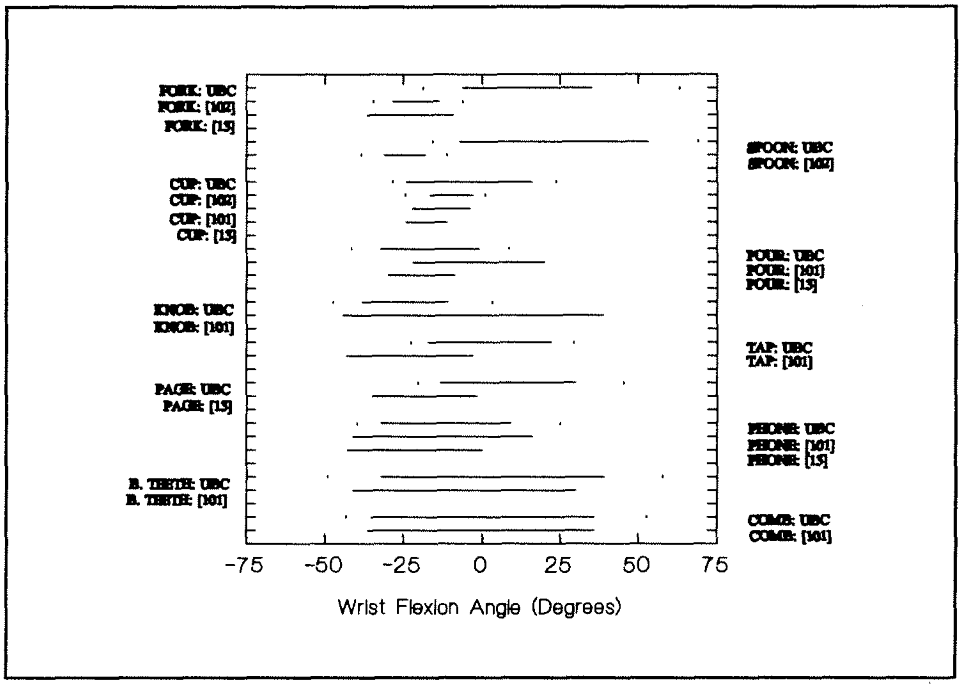

Figure 4-22: Comparison of Motion Studies for Wrist Flexion

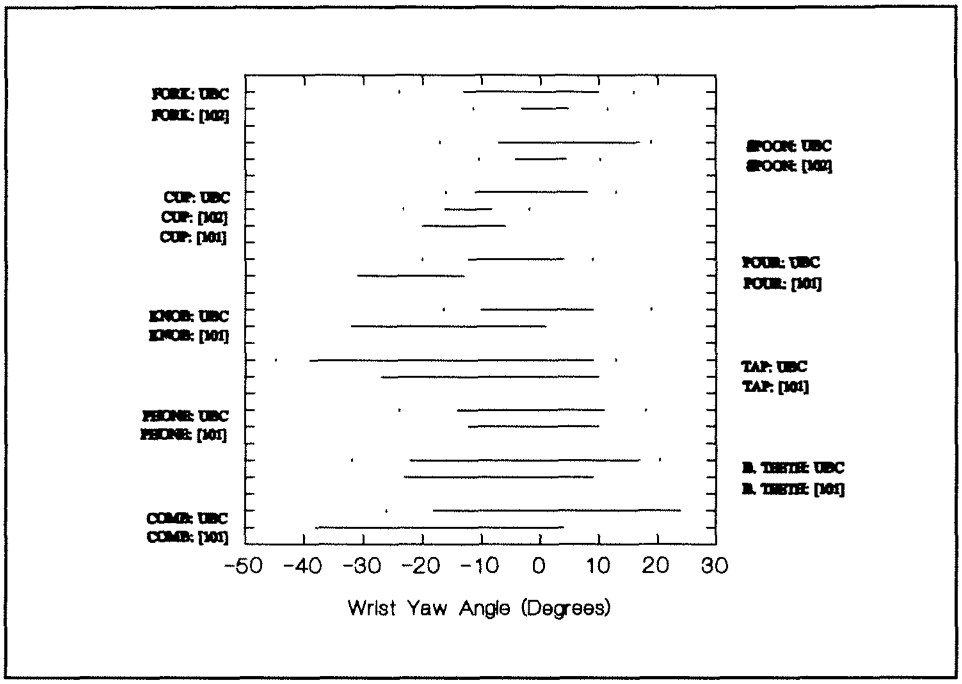

Figure 4-23: Comparison of Motion Studies for Wrist Yaw

Only one researcher, Safaee-Rad, has documented shoulder motion while performing functional tasks, although others, such as Lipitkas [62] and Maulucci [67], have studied reaching to specific locations. The rotation axes chosen were "flexion" followed by "abduction" followed by inward/outward "rotation". The results were translated to azimuth, elevation and roll for comparison with this study. Appendix J gives the details of this translation.

Safaee-Rad reported two sets of results: the original, or initial, joint angles calculated (I) and the joint angles shifted by an initial deviation (D), based on the subject's standard position. However, the standard position was established only by visual inspection, which Safaee-Rad noted to be inaccurate. Both results are presented here.

Figures 4-24 to 4-26 show a wide variation between Safaee-Rad's original results and the results with the initial deviation taken into account. In general, the original calculations are in better agreement with the current study. The ranges of roll and azimuth are greater because the current study includes picking up the fork and spoon as part of the task; the Safaee-Rad study only considers the task between the point of loading the food to unloading it into the mouth. In addition, eating with a spoon requires both greater elevation and greater roll because of the grasp type used in the current study, as mentioned previously. Eating with a fork shows greater roll in the UBC study because of the grasp position. Drinking from a cup required more roll, the amount of roll being largely dependent on the amount of liquid in the cup, which was two-thirds full in this study; the spouted no-spill cup also required the cup to be rotated slightly more. The wide variation in azimuth demonstrates the variety of techniques used by the individual subjects to drink.

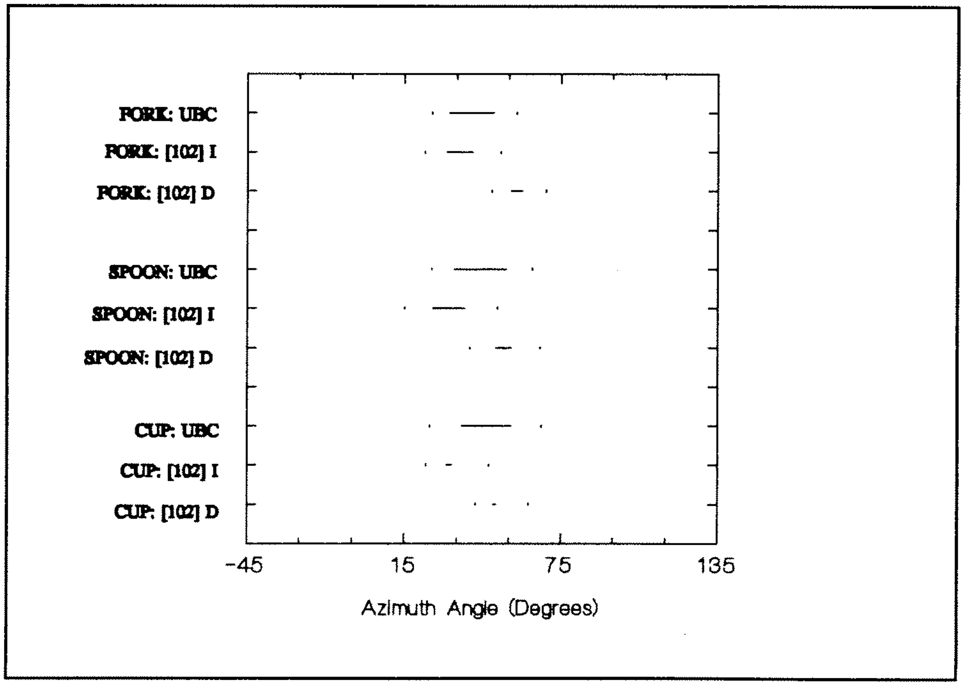

Figure 4-24: Comparison of Motion Studies for Azimuth

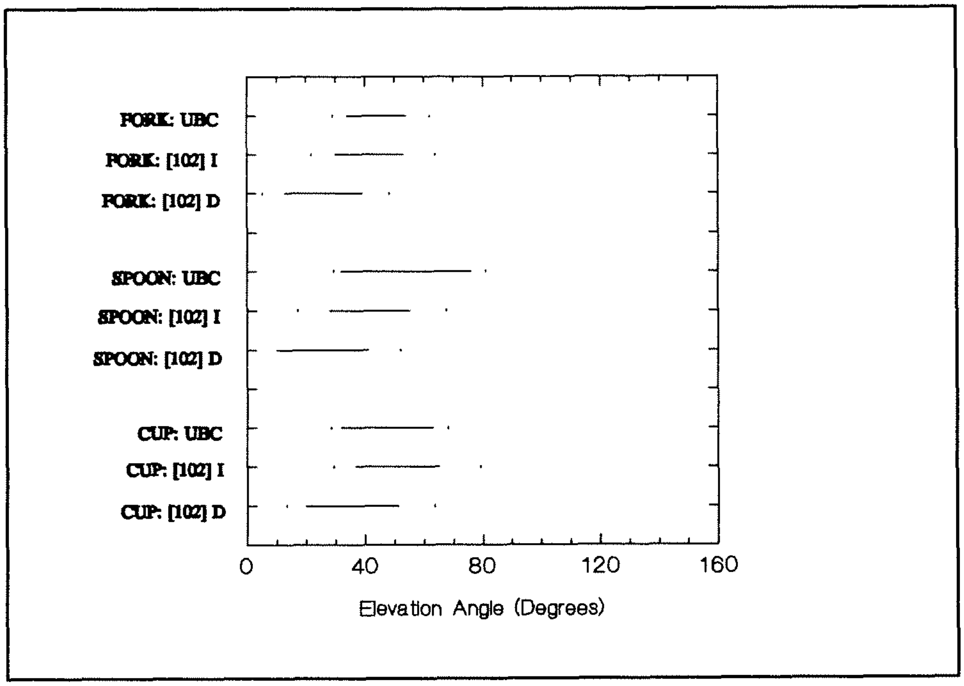

Figure 4-25: Comparison of Motion Studies for Elevation

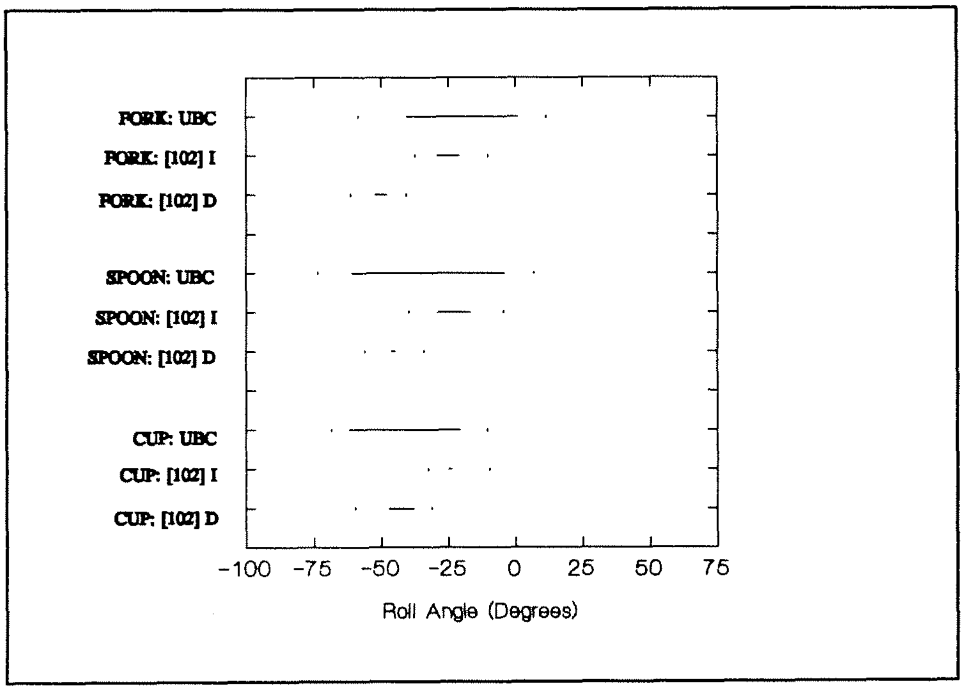

Figure 4-26: Comparison of Motion Studies for Roll

4.5.5 Implications for Orthosis Design

For each joint, the average minimums, average maximums and extremes of all subjects were plotted for each task. This gave insight into the possibilities for fixing or otherwise simplifying each joint. The rightmost point of each solid line is the average maximum for that task, while the leftmost point is the average minimum for that task. The dashes are the highest and lowest individual joint angle values for that task. As with the graphs comparing motion studies, the abscissa axis represents the approximate joint limits.

Two ways to simplify the degrees of freedom are to:

1) fix a joint rotation, or
2) couple two or more joint rotations together.

One other possibility is to fix a joint rotation but have more than one predetermined position such that an attendant could change the orthosis from one mode to another. This was considered but was not found to be desirable because there was no clear division of tasks, such as eating, when an attendant would be present to change the mode.

Shoulder Motion - Azimuth, Elevation and Roll

Figures 4-27 to 4-29 show that all three joint rotations of the shoulder vary considerably from task to task. A wide range of azimuth and roll is required in order to reach the various positions on the table. A low elevation is required to reach to the lap, a high elevation to reach the light switch and so on. It is therefore not immediately obvious which one(s) can be fixed or should be fixed. Specific tasks would be sacrificed if any of the shoulder rotations were entirely fixed. The decision concerning which to fix and which to power will be based on the results of the simulations and the priority of the tasks as identified in the interviews.

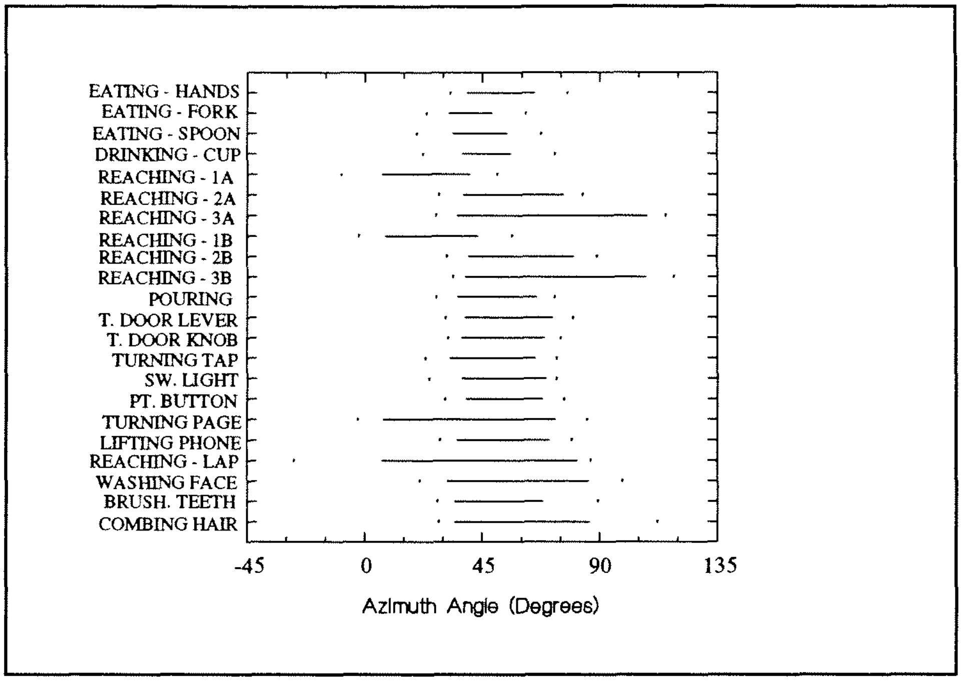

Figure 4-27: Azimuth: Average Min/Max & Extremes for All Subjects

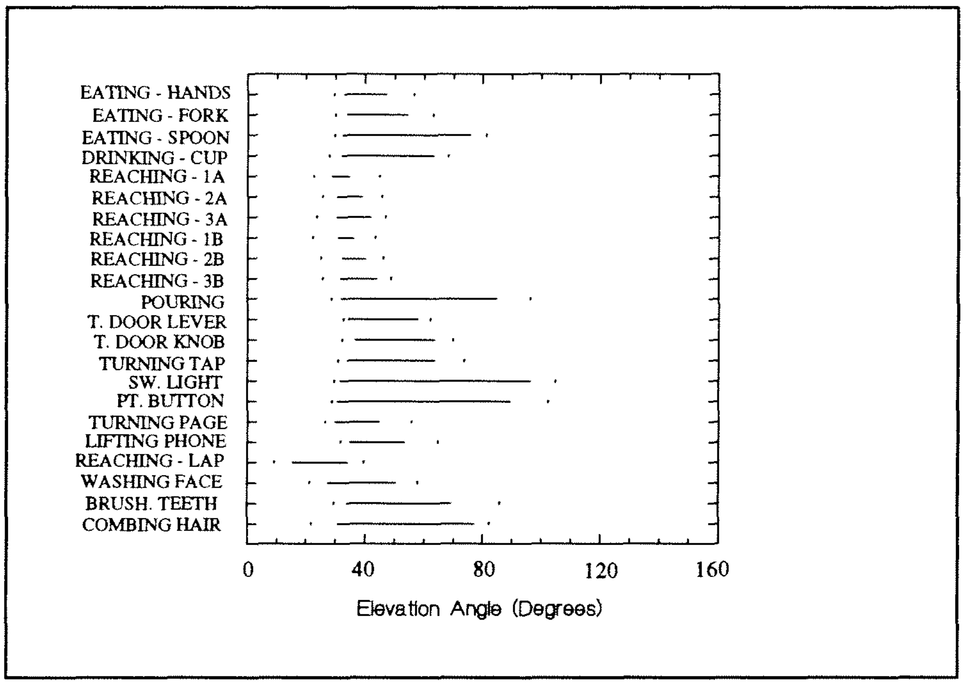

Figure 4-28: Elevation: Average Min/Max & Extremes for All Subjects

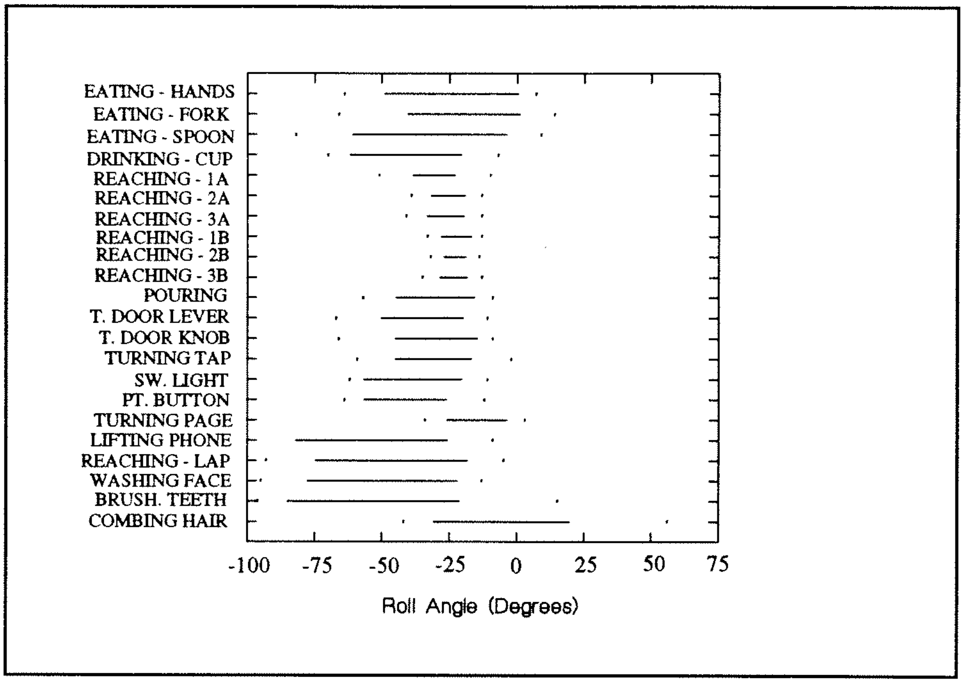

Figure 4-29: Roll: Average Min/Max & Extremes for All Subjects

Elbow Flexion and Forearm Rotation

Elbow flexion must be powered because elbow flexion alone defines the distance from the shoulder to the wrist. Figure 4-30 shows the range of elbow flexion from the average minimum to the average maximum for each task. All of the tasks, except the reach tasks, vary considerably in forearm rotation, as shown in Figure 4-31. In addition, most involve both pronation and supination (positive and negative forearm rotation), especially the eating and personal hygiene tasks since a utensil must first be picked up and then pointed towards the face. Forearm rotation must therefore either be powered independently or coupled with elbow flexion.

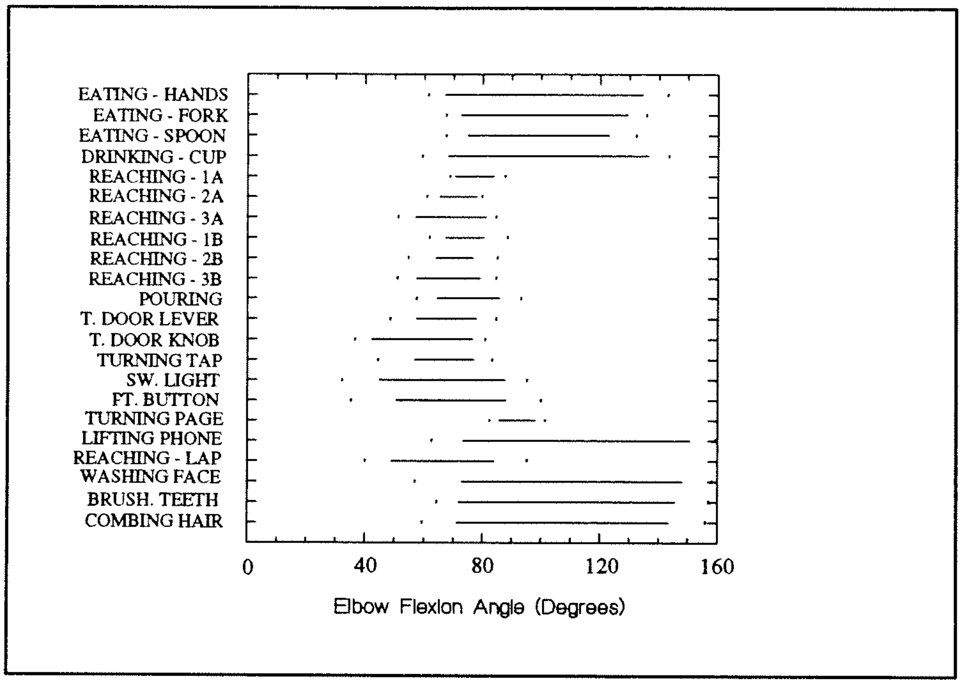

Figure 4-30: Elbow Flexion: Average Min/Max & Extremes for All Subjects

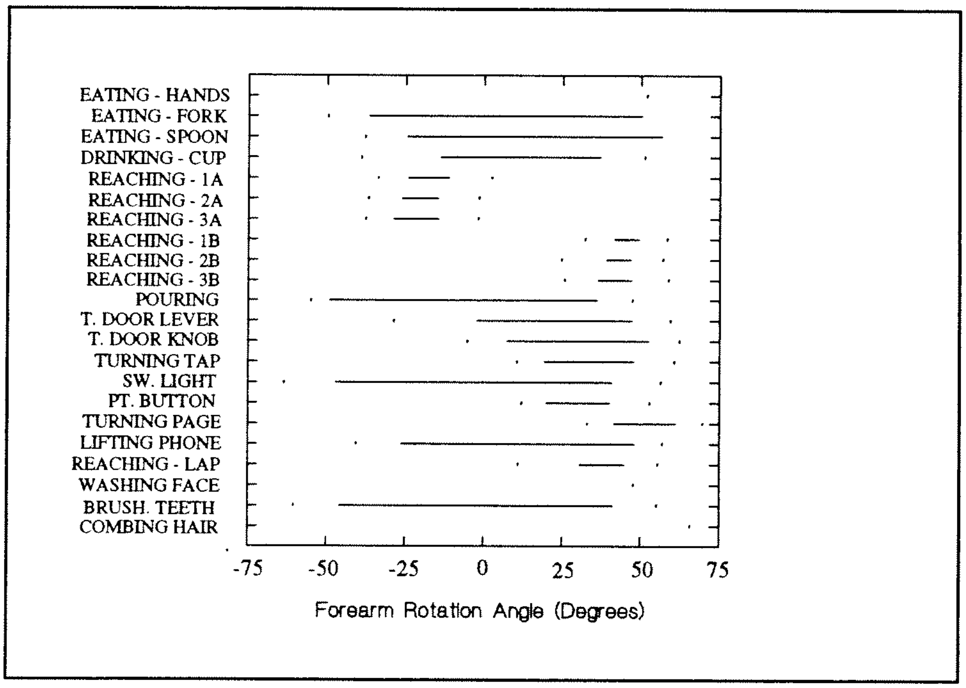

Figure 4-31: Forearm Rotation: Average Min/Max & Extremes for All Subjects

The Hugh MacMillan orthosis uses the second option, coupling forearm rotation and roll to elbow flexion, but this makes the orthosis extremely limited. Because of the defined forearm rotation, the user cannot drink from a cup or reach for any object with the hand upright. The user also cannot eat with a spoon, brush the teeth, comb the hair, wash the face, pour from a pitcher or switch a light, which are most of the tasks under consideration. In fact, other researchers studying functional arm movement have mentioned the priority of forearm rotation [27,50,103]. The motion analysis results therefore indicate that forearm rotation should be independently powered.

Wrist Flexion and Wrist Yaw

Figure 4-32 shows that the required wrist flexion covers a smaller percentage of the total joint limit range than for most of the other joints. It is also quite variable between individuals, indicating that more options are possible. If wrist flexion is fixed, the ability to precisely orient the hand will be lost. However, orientation is not critical for most of the tasks, allowing them to be done differently by an orthosis wearer than by an able-bodied person. Problems with keeping a spoon level, brushing the teeth or combing the hair may be overcome using special handles. Therefore, there is a potential for reducing orthosis complexity without a major sacrifice in task performance by fixing wrist flexion.

The total joint limit range of yaw motion is quite small, as shown in Figure 4-33. Furthermore, both wrist flexion and wrist yaw are at the end of the kinematic chain so that no further joints are affected. Consequently, there is also potential for reducing orthosis complexity without significantly reducing functionality by fixing wrist yaw.

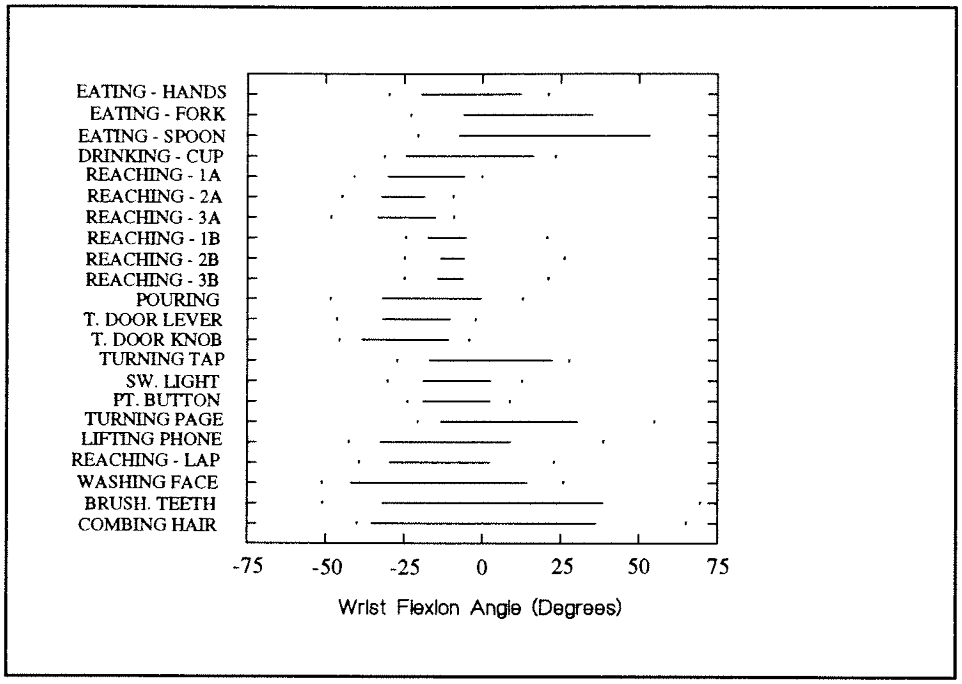

Figure 4-32: Wrist Flexion: Average Min/Max & Extremes for All Subjects

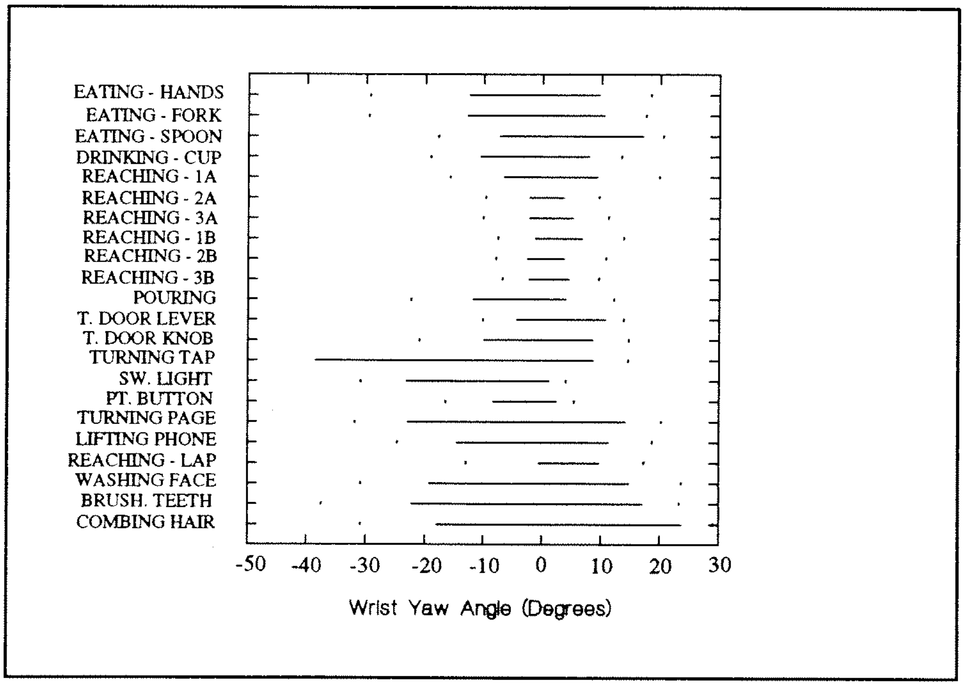

Figure 4-33: Wrist Yaw: Average Min/Max & Extremes for All Subjects

Fixing both wrist rotations hampers the flexibility of orientation, forcing tasks to be done differently or to use the head or trunk to compensate. The simulation results will demonstrate whether the ability to orient the hand without the wrist rotations is sufficient for these tasks.

Summary

Based on the results of the motion analysis, the following design should be investigated with the simulation program:

Power:	Two of the three shoulder degrees of freedom Elbow Flexion Forearm Rotation
Fix:	One shoulder degree of freedom Wrist Flexion Wrist Yaw

Performing this motion analysis provided data concerning how the arm moves while performing daily-living tasks. This allowed some hypotheses to be developed concerning the design of a powered upper-limb orthosis. The simulation program described in the next chapter uses the data to test these hypotheses.

CHAPTER 5: ORTHOSIS SIMULATION

5.1 Introduction

The final two research objectives are to develop a kinematic simulation program to test possible configurations of a powered upper-limb orthosis and to use this simulation program to determine the simplest orthosis configuration that is still capable of performing the highest priority tasks. Although other researchers have studied the problem qualitatively, an examination of required degrees of freedom has never been quantified before. The quantitative evaluation allowed design options to be examined for a wide variety of tasks and individuals before building a prototype.

The kinematic simulation algorithm determines whether a possible orthosis configuration can achieve a given position and orientation. For example, if a degree of freedom is fixed the algorithm determines whether the remaining degrees of freedom are able to compensate in order to still achieve the functional points required for the task. The functional points, i.e. the critical positions and orientations, are derived from the motion analysis results. The number of achievable and unachievable tasks is determined for each alternative configuration. This chapter discusses the calculation procedures employed in the simulation program and the results of the simulations. In the end, two orthosis configurations are recommended.

5.2 Kinematic Formulation

The developed software minimizes a cost function to bring a simulated orthosis as close as possible to a desired position and orientation while remaining within anatomical joint limits. It employs a forward kinematic solution procedure, calculating the endpoint position from given rotations and link lengths.

In robotic analysis, the more common method for finding the joint angles corresponding to a desired position and orientation is the pseudoinverse or generalized least-squares method [79]. While the author was not aware of this method until after development of the optimization approach, further study in this area should consider this approach as it may be more efficient. The method iteratively calculates the pseudoinverse of the Jacobian of the position function to determine the direction and magnitude of each step to be taken towards the target position. Weighting constants can be incorporated. Singularities (where no solution exists) present the greatest difficulty; however several techniques have been developed to deal with this problem [17][78][115]. There is no provision for requiring that the solution fall within joint limits. The method used in this research handles singularities, weightings and joint limit penalties simply.

The software examines the ability to reach particular points rather than follow paths for several reasons. First, by dealing with just the functional points, such as loading the food onto a fork and unloading it into the mouth, the orthosis is not constrained to follow the path taken by the able-bodied subjects. Second, it is more straightforward to define a point than a path and consequently it is easier to define whether a simulated orthosis can match a point rather than match a path. Since a path is a sequence of points, it is possible, in practice, to evaluate a path by evaluating a finite sequence of points. Up to eight functional points were tested for each task. Most importantly, given two achievable points, some path can be found between them unless a constraint is imposed, such as keeping a cup level.

In this formulation, the arm is modelled by a sequence of one-dimensional rotations connected by rigid link segments. Multi-dimensional joints such as the shoulder are created by joining one-dimensional rotations with zero-length links. The sequence of rotations, in order of effect on the end position, is: azimuth, elevation, roll, carrying angle, elbow flexion, forearm rotation, wrist flexion and wrist yaw. There are three rotations at the shoulder, three at the elbow and two at the wrist. The formulation uses the Denavit-Hartenberg (D-H) method, commonly used in the robotics field, for setting up the axes and calculating the transformation matrices [33]. Figure 5-1 shows the axis definitions.

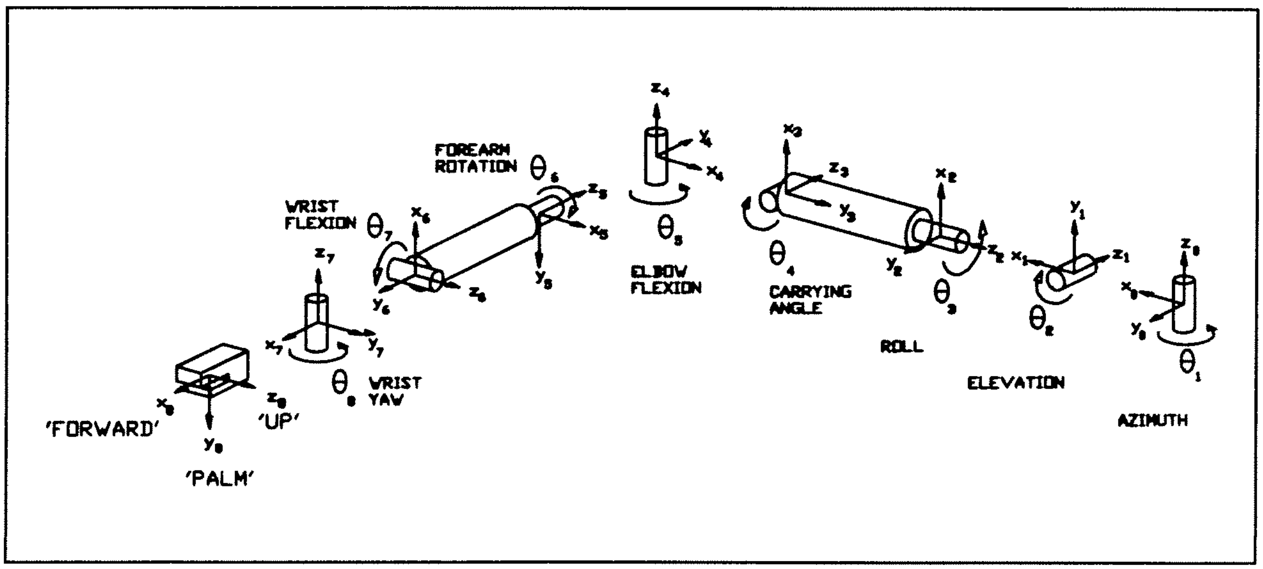

Figure 5-1: Kinematic Formulation Axis Definitions

The Denavit-Hartenberg parameters are given in Table 5-1.

Joint	Name	θ_i	α_i	a_i	d_i
1	Azimuth	0	90	0	0
2	Elevation	90	-90	0	0
3	Roll	0	90	0	- upperarm
4	Carrying Angle	90	90	0	0
5	Elbow Flexion	0	-90	0	0
6	Forearm Rotation	-90	-90	0	- forearm
7	Wrist Flexion	90	90	0	0
8	Wrist Yaw	0	-90	hand	0

Table 5-1: Denavit-Hartenberg Parameters

where,

θ_i = the joint angle from the x_{i-1} axis to the x_i axis about the z_{i-1} axis using the right-hand rule;

α_i = the offset angle from the z_{i-1} axis to the z_i axis about the x_i axis using the right-hand rule;

a_i = the offset distance from the intersection of the z_{i-1} axis with the x_i axis to the origin of the i^{th} frame along the x_i axis (or the shortest distance between the z_{i-1} and z_i axes); and,

d_i = the distance from the origin of the $(i-1)^{th}$ coordinate frame to the intersection of the z_{i-1} axis with the x_i axis, along the z_{i-1} axis.

The general D-H homogeneous transformation matrix for adjacent coordinate frames *i* and *i-1* is given by:

$$\begin{bmatrix} p_u \\ p_v \\ p_w \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix} \qquad (5-1)$$

where $\{p_x, p_y, p_z\}$ is an arbitrary point in the (i-1)th frame and $\{p_u, p_v, p_z\}$ is the corresponding point in the ith coordinate frame. In reduced form this gives:

$$\hat{p}_{uvw} = [H_{(i-1,i)}]\,\hat{p}_{xyz} \qquad (5-2)$$

The top left 3x3 gives the rotation matrix from one frame of reference to the next; the right 3x1 gives the translation vector. The columns of the rotation matrix define the x, y and z unit vectors of the ith set of axes, expressed in the coordinates of the (i-1)th set of axes. The fixed frame of reference (subscript 0) is defined by the identity matrix. The transformation matrices for each joint, with $C_i = \cos\theta_i$ and $S_i = \sin\theta_i$, are as follows:

$$\textit{Azimuth:}\quad H_{01} = \begin{bmatrix} C_1 & 0 & S_1 & 0 \\ S_1 & 0 & -C_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5-3)$$

$$\textit{Elevation:}\quad H_{12} = \begin{bmatrix} C_2 & 0 & -S_2 & 0 \\ S_2 & 0 & C_2 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5-4)$$

$$\textit{Roll:}\quad H_{23} = \begin{bmatrix} C_3 & 0 & S_3 & 0 \\ S_3 & 0 & -C_3 & 0 \\ 0 & 1 & 0 & -\textit{upperarm} \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5\text{-}5)$$

$$\textit{Carrying Angle:}\quad H_{34} = \begin{bmatrix} C_4 & 0 & S_4 & 0 \\ S_4 & 0 & -C_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5\text{-}6)$$

$$\textit{Elbow Flexion:}\ H_{45} = \begin{bmatrix} C_5 & 0 & -S_5 & 0 \\ S_5 & 0 & C_5 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5\text{-}7)$$

$$\textit{Forearm Rotation:}\ H_{56} = \begin{bmatrix} C_6 & 0 & -S_6 & 0 \\ S_6 & 0 & C_6 & 0 \\ 0 & -1 & 0 & -\textit{forearm} \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5\text{-}8)$$

$$\textit{Wrist Flexion:}\ H_{67} = \begin{bmatrix} C_7 & 0 & S_7 & 0 \\ S_7 & 0 & -C_7 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5\text{-}9)$$

$$\textit{Wrist Yaw: } H_{78} = \begin{bmatrix} C_8 & 0 & -S_8 & hand \cdot C_8 \\ S_8 & 0 & C_8 & hand \cdot S_8 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5\text{-}10)$$

The position of the hand relative to the shoulder is defined by the fourth column of H_{08}, where $H_{08} = H_{01}H_{12} \bullet\bullet\bullet H_{78}$. The 'forward' orientation of the hand, corresponding to $\mathbf{r}_{35}$ as defined in Chapter 4 for the motion analysis, is defined by $\mathbf{x}_8$, the first column of H_{08}. (Refer to Figure 5-1 for the orientation axes.) The 'palm' orientation, corresponding to $\mathbf{r}_{43}$ is defined by $\mathbf{y}_8$, the second column of H_{08}. The 'up' orientation, corresponding to $\mathbf{r}_{34}$ x $\mathbf{r}_{35}$ in the motion analysis, is defined by $\mathbf{z}_8$, the third column of H_{08}.

5.3 Cost Function

The cost function upon which the optimization is evaluated involves five components:

1) the squared distance between the actual and desired endpoint positions,
2) the squared angle between the actual and desired 'forward' orientation vectors times a weighting factor,
3) the squared angle between the actual and desired 'palm' orientation vectors times a weighting factor,
4) the squared angle between the actual and desired 'up' orientation vectors times a weighting factor and
5) a penalty function for approaching or exceeding a joint limit.

The components are effectively normalized by a proper choice of the weighting factors.

Orientation is included in the cost function for two reasons. The first is to ensure that the endpoint orientation is correct in order for the task function to be achieved. For example, the direction of the fork during an eating task should be similar to that used by the able-bodied subjects since it is not only important that the hand reach the destination but also that the fork is facing in the proper direction. The secondary reason is that without the constraint of orientation the solution, if found, will not be unique; the arm could be rotated at any angle about the line connecting the shoulder and wrist, as long as it is within the joint limits. Constraining the orientation to be close to that of the able-bodied subjects produces a result that is more natural. The weighting factor defines the relative importance of each orientation. In general, for a particular task, one orientation is most important and is therefore more heavily weighted.

The penalty function, based on the penalty function proposed by Buchal and Cherchas [14], keeps the simulated arm within the natural limits of the arm. It is defined as:

$$\textit{penalty function} = \sum \textit{penalty}_i \cdot (\theta_i - \theta_{lim})^2 \qquad (5\text{-}11)$$

where,

$$\textit{penalty}_i = \begin{cases} 0 & \textit{if} \ \ (\theta_i)_{min} + \theta_{tol} \le \theta_i \le (\theta_i)_{max} - \theta_{tol} \\ k & \textit{otherwise} \end{cases} \qquad (5\text{-}12)$$

and,

$$\theta_{lim} = \begin{cases} (\theta_i)_{min} + \theta_{tol} & \textit{if} \ \ \theta_i \le (\theta_i)_{min} + \theta_{tol} \\ (\theta_i)_{max} - \theta_{tol} & \textit{if} \ \ \theta_i \ge (\theta_i)_{max} - \theta_{tol} \end{cases} \qquad (5\text{-}13)$$

The constant k is made large enough to produce a cost function value that indicates an unsuccessful configuration even if the desired position and orientation are achieved since the configuration cannot be accepted with joint limits exceeded. Instead, the minimization routine continues to search for solutions within the joint limits. While an exponential function would produce a more realistic representation, the step function is reasonable because the arm is comfortable throughout the joint range, until very close to the joint limit.

The cost function is therefore:

$$\Phi(\theta_i) = \begin{bmatrix} (|r_{act} - r_{des}|)^2 + \\ wt_{forw} \cdot (forw_{act} - forw_{des})^2 + \\ wt_{palm} \cdot (palm_{act} - palm_{des})^2 + \\ wt_{up} \cdot (up_{act} - up_{des})^2 + \\ \sum [penalty_i \cdot (\theta_i - \theta_{lim})^2] \end{bmatrix} \qquad (5\text{-}14)$$

where the 'act' and 'des' subscripts refer to the actual and desired values respectively, 'r' is the vector to the endpoint, 'forw', 'palm' and 'up' refer to the orientation angles and 'wt' is the weighting given to each orientation.

The weighting values were typically 0.10 for the most important orientation vector (such as in the 'up' direction - along the fork - for eating with a fork) and 0.05 for the others (since, for example, rotation about the fork is less important). The rationale for these numbers is given in Section 5.4. The value for θ_{tol} was set to one degree. For the penalty function, k was set to 0.5 so that the function tolerance of 6.0 was exceeded even if the position and orientation criteria were met. A maximum number of iterations of 10 was enough to find the minimal solution in almost all cases yet halted the search for configurations that could not achieve the desired position and orientation. Appendix K gives the desired positions, orientations and initial joint angle estimates used in the simulations.

5.4 Minimization Procedure & Program Design

The minimization procedure was adopted from Numerical Recipes in C, Chapter 10 [93]. As explained below, a one-dimensional line minimization is imbedded into the multi-dimensional minimization. Brent's method with the use of first derivatives was chosen as an efficient but robust method. For the multi-dimensional minimization the conjugate (or noninterfering) gradient method was used. The Polak-Ribiere variant was selected because of its smoother transition to further iterations. In both the multi-dimensional method and the imbedded one-dimensional method the Jacobian is calculated analytically to improve the computational efficiency.

In the simulation program, the following steps are taken to minimize the cost function:

1) A scalar function f(c) is constructed having the value of the cost function along the line passing through the current point and in the direction of the gradient of Φ.

$$f(c) = \Phi\left(\theta_1 + c\frac{\partial\Phi}{\partial\theta_1},\ \theta_2 + c\frac{\partial\Phi}{\partial\theta_2},\ \cdots,\ \theta_8 + c\frac{\partial\Phi}{\partial\theta_8}\right) \qquad (5\text{-}15)$$

2) Three points are found which bracket the minimum of f(c) to ensure that a minimum exists. The direction of search depends on the function values at two given abscissa; the third point is then chosen by taking steps until the function value increases again.

3) A parabola is fit to the three points and the minimum of the parabola is found by formula. If the parabolic step falls within the bounding interval (a,b) found in step #2, and implies a movement from the best current value that is less than half the movement of the step before last then this minimum point is exchanged with the point having the greatest function value. Otherwise the interval is bisected, with the segment chosen by the sign of the derivative. This procedure is repeated until the value of c is not changing by greater than a tolerance, the minimum step in the downhill direction takes the function value uphill, or the maximum number of iterations is exceeded.

4) The new point of interest is then

$$\theta_i' = \theta_i + c\frac{\partial\Phi}{\partial\theta_i} \qquad (5\text{-}16).$$

New gradients are calculated and the procedure is repeated from step #2.

5) The procedure is stopped when either the cost function value is less than a tolerance or the maximum number of iterations is exceeded.

This routine finds only a local minimum. The original estimate of the joint angles must therefore be reasonable for the global minimum to be found. The motion analysis results provided this initial estimate.

Upon completion of the minimization procedure the results are classified as successful, close-to-successful or unsuccessful. The criteria, based on the distance between the actual and desired endpoint positions and the angles between the desired and actual orientations, are given in Table 5-2.

	Distance	'Up' Angle	'Forward' Angle	'Palm' Angle	Within Joint Limits
Successful	< 3.0 cm	< 10°	< 10°	< 10°	Yes
Close	< 3.0 cm	< 20°	< 20°	< 20°	Yes
Unsuccessful	> 3.0 cm or	> 20° or	> 20° or	> 20° or	No

Table 5-2: Success Criteria

The criteria for success are approximately equal to the position and orientation standard deviations for all of the tasks and all of the subjects. The close-to-successful category was included because often the orientation is not as critical for performing the tasks as distance. In some cases a task may even be adequately achieved while differing from the average able-bodied orientation by more than 20 degrees, but these need closer examination.

Given the criteria for success, the rationale for the weighting values can now be given. If the solution is within the joint limits and matches the success criteria, the value of the cost function is:

$$\begin{aligned} \Phi(\theta_i) &= (3)^2 + 0.10\,(10)^2 + 0.05\,(10)^2 + 0.05\,(10)^2 \\ &= 9 + 10 + 5 + 5 \end{aligned}$$

Thus, the contribution of distance to the cost function value is comparable to the contribution of the most important orientation. Although the two orientations of lesser importance are weighted half as much, they contribute the same amount to the cost function at 14 degrees as the first orientation does for ten degrees. They, too, must therefore be matched closely.

5.5 Comparison of Simulated Fixed Elbow to Braced Elbow

The human arm has not previously been simulated with variable reduced degrees of freedom. Motion analyses have been performed, however, with the subject's elbow physically braced at a specific angle. Maulucci [67] studied subjects performing reaching tasks with and without a braced elbow, but the results have not yet been analysed. Cooper *et al.* [20] studied eating with a fork, eating with a spoon, and drinking from a cup with and without a braced elbow, however these results cannot be used for comparison for several reasons. First, although the elbow was braced, there was still movement of up to 15 degrees. This is not comparable to the rigidly fixed degree of freedom employed in the simulation. Secondly, the subjects were able to move their trunks to compensate for the fixed elbow, a movement not accounted for or permitted in the simulation. Thirdly, different hand grasps were used for the eating tasks, as explained in Chapter 4.

5.6 Results

5.6.1 Preliminary Evaluation

For an initial evaluation, the positions and orientations at the extremes of each task were analysed. The desired positions and orientations, provided in Appendix K, were determined by averaging the data for each subject from the motion analysis. Table 5-3 lists the 34 initial positions chosen.

Position #	Abbreviation	Task	Position
1	H1	Eating with the Hands	Picking up the Food
2	H2		At the Mouth
3	F1	Eating with a Fork	Picking up the Food
4	F2		At the Mouth
5	S1	Eating with a Spoon	Picking up the Food
6	S2		At the Mouth
7	Cu1	Drinking from a Cup	Before Tilting
8	Cu2		After Tilting
9	R1A	Reaching, Position 1A	Final Position
10	R2A	Reaching, Position 2A	Final Position
11	R3A	Reaching, Position 3A	Final Position
12	R1B	Reaching, Position 1B	Final Position
13	R2B	Reaching, Position 2B	Final Position
14	R3B	Reaching, Position 3B	Final Position
15	Po	Pouring from a Pitcher	Fully Tilted
16	D1	Door Lever	Before Rotating
17	D2		Fully Rotated
18	K1	Door Knob	Before Rotating
19	K2		Fully Rotated
20	T1	Tap Lever	Before Rotating
21	T2		Fully Rotated
22	Li	Light Switch	Highest Point
23	Bu	Button	Highest Point
24	Pa	Page Turning	Farthest Left
25	Ph	Lifting Phone Receiver	At Ear
26	La	Lap	At Knees
27	W1	Washing Face	Left Side
28	W2		Right Side
29	Br1	Brushing Teeth	Centre
30	Br2		Left Side
31	Co1	Combing Hair	Left Side
32	Co2		Right Side
33	St1	Starting Position	Hand Free
34	St2		Holding Utensil

Table 5-3: Initial Test Positions

Coupled Degrees of Freedom

Coupling degrees of freedom may produce a motion that is more suitable for task performance than fixing a degree of freedom. All combinations of degrees of freedom were plotted against one another to investigate potential relationships. The only reasonable relationships observed were to either couple roll with elbow flexion or to couple wrist flexion with elbow flexion (Figures 5.2 and 5.3). In both cases, there is an increase in angle as the elbow flexes initially and then a rapid decrease as the elbow flexion brings the hand to the face. While numerically attractive, the coupling and reversal of motion would lead to a somewhat complicated mechanical design.

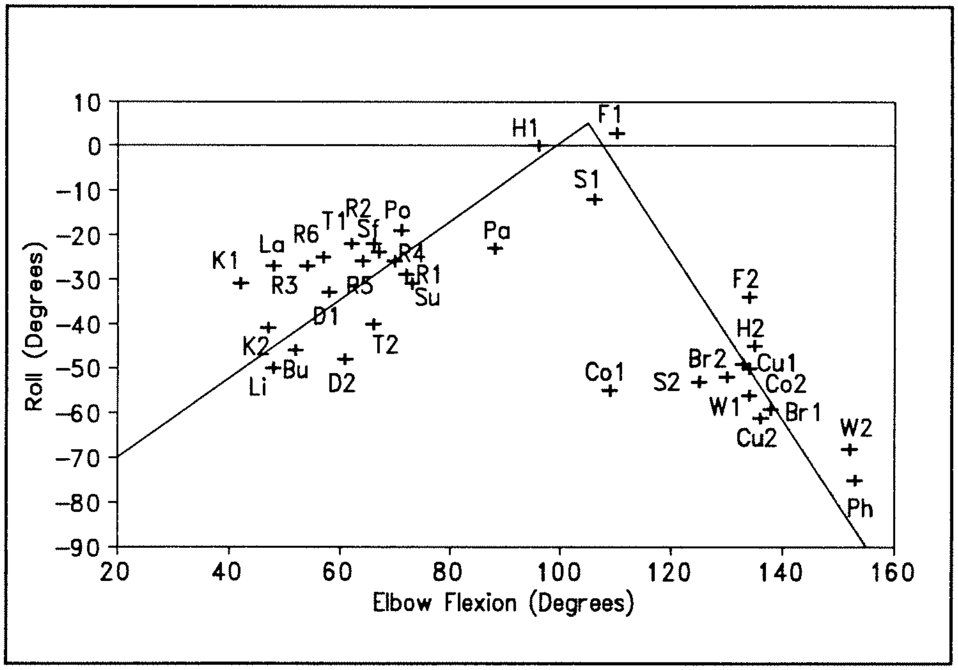

Figure 5-2: Roll vs. Elbow Flexion Coupling Function

To couple roll to elbow flexion, the best linear relationship, shown in Figure 5-2, was:

roll =	0.882 * elbow flexion - 87.6°	if elbow flexion < 105°
=	-1.90 * elbow flexion +204.5°	if elbow flexion >= 105°

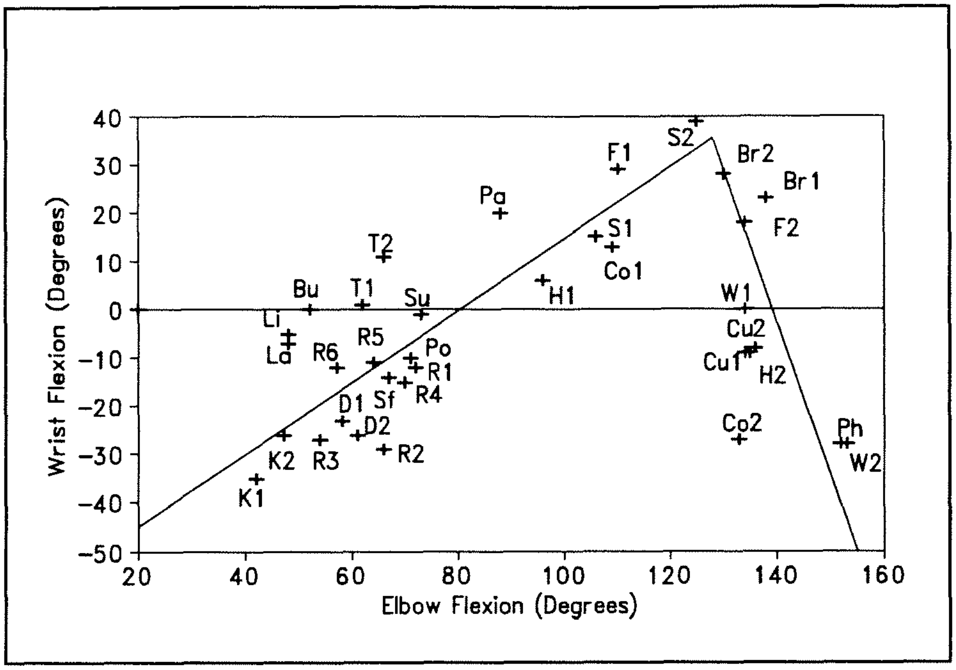

Figure 5-3: Wrist Flexion vs. Elbow Flexion Coupling Function

To couple wrist flexion to elbow flexion, the best linear relationship, shown in Figure 5-3, was:

$$\text{wrist flexion} = 0.75 * \text{elbow flexion} - 60.0^\circ \qquad \text{if elbow flexion} < 128^\circ$$
$$= -3.185 * \text{elbow flexion} + 443.7 \qquad \text{if elbow flexion} >= 128^\circ$$

Table 5-4 gives the results. Detailed results for all of the simulations can be found in reference [3].

	Number of Successful Positions	Number of Close Positions	Number of Unsuccess. Positions	Which Positions Unsuccessful
Roll Coupled with Elbow Flexion	33	0	1	Co1
Wrist Flexion Coupled with Elbow Flexion	28	3	3	Cu1, W1, Co2

Table 5-4: Coupled Degrees of Freedom Results

Single Fixed Degree of Freedom

Each degree-of-freedom was fixed individually. The results, except the elbow, in which almost all of the tasks were unsuccessful, are summarized in Table 5-5.

	Best Angle (degrees)	Number of Successful Positions	Number of Close Positions	Number of Unsuccess. Positions	Which Positions Unsuccessful
Azimuth Fixed	71	27	0	7	F1, S1, R1A, R3A, R1B, R3B, St2
Elevation Fixed	63	31	0	3	Li, Bu, Wl
Roll Fixed	-26	32	0	2	F1, S1
Forearm Rot'n Fixed	5	29	0	5	H2, F2, Wl, Brl, Br2
Wrist Flexion Fixed	-5	32	1	1	K1
Wrist Yaw Fixed	-2	33	0	1	T2

Table 5-5: Single Fixed Degree of Freedom Results

Fixing the wrist degrees of freedom produced the best results, especially since the single unsuccessful task in each case was of a lower priority. Roll had the next fewest unsuccessful tasks when fixed but these were eating tasks whereas elevation affected tasks of lesser importance.

Eating with the hands and with a fork cannot be performed with the forearm rotation fixed in one position. Forearm rotation could be coupled with elbow flexion if the orthosis were only designed for eating. However, a plot of forearm rotation versus elbow flexion showed no relationship if other tasks were included.

The results show that azimuth should not be fixed since, not only were more tasks unsuccessful, but they were the high-priority reach tasks (see Section 3.3 for task priorities).

One Coupled, One Fixed Degree of Freedom

The degrees of freedom that were coupled earlier were analysed together with an additional fixed degree of freedom to further examine the potential for reducing degrees of freedom. The only successful combination, however, was the addition of a fixed wrist yaw to the coupled roll and elbow flexion. The fixing of wrist yaw caused the relationship between wrist and elbow flexion to be more scattered, causing the coupling to be less successful. Also, since elbow flexion is not free to change by very much in approaching a desired position (since it defines the distance between the shoulder and the wrist) it is mostly the wrist flexion that must change to achieve the coupled relationship. However, small changes in elbow flexion caused large changes in wrist flexion, adversely affecting the orientation (refer to Figure 5-3). Thus only the combination of coupled roll and elbow flexion with fixed wrist yaw produced reasonable results, shown in Table 5-6.

	Best Angle (degrees)	Number of Successful Positions	Number of Close Positions	Number of Unsuccess. Positions	Which Positions Unsuccessful
Roll & Elbow Flexion Coupled; Wrist Yaw Fixed	-2	28	3	3	S2,T2,Co2

Table 5-6: Coupled plus Single Fixed DOF Results

Two Fixed Degrees of Freedom

From the single degree of freedom evaluations, only fixing elevation, roll, wrist flexion and wrist yaw were considered further. Table 5-7 shows all combinations of fixing these degrees of freedom (except fixing elevation and roll, which resulted in 22 unsuccessful positions). The best angles are given in the order listed in the row title.

	Best Angles (degrees)	Number of Successful Positions	Number of Close Positions	Number of Unsuccess. Positions	Which Positions Unsuccessful
Elevation & Wrist Flexion Fixed	53 / -5	12	7	15	F1, S2, R1A, R2A, R3A, Po, K1, Li, Bu, Ph, W2 Br1,Br2, Co1, Co2
Elevation & Wrist Yaw Fixed	53 / -2	26	3	5	Po, K1, Li, Bu, Co1
Roll & Wrist Flexion Fixed	-46 / -15	19	4	11	H1, F1, F2, S1, S2, T2, Bu, Pa, Ph, W2, Br2
Roll & Wrist Yaw Fixed	-40 / 4	29	2	3	F1, S1, T2
Wrist Flexion & Wrist Yaw Fixed	-9 / 2	29	1	4	F1, K1, T2, Pa

Table 5-7: Results for Two Fixed Degrees of Freedom

These results show that it is better to fix wrist yaw than wrist flexion if only one is to be fixed. Furthermore, although either fixed roll and wrist yaw or fixed wrist flexion and wrist yaw produced the fewest unsuccessful tasks, they included the higher-priority eating tasks. Fixing elevation and wrist yaw affected relatively less important tasks: pouring from a pitcher, reaching for a doorknob, flipping a light switch (from a seated position), pointing to a 'button' at the light switch height, and combing the hair. Of these, only combing the hair has a higher priority, yet it is sufficiently complex that it would be difficult to perform with any of the orthosis configurations. Also, pouring may still be achieved in specific cases since pouring from the gardening pitcher required a higher elevation than would be needed for pouring from a kettle or beverage pitcher.

One Coupled and Two Fixed Degrees of Freedom

The relationship between roll and elbow flexion has greater scatter when both wrist rotations are fixed. Also, as with the coupled wrist and elbow flexion with fixed wrist yaw, the steepness of the slope (referring to Figure 5-2) creates problems when elbow flexion changes at higher flexion values. There is therefore no benefit in coupling roll to elbow flexion when more degrees of freedom are fixed.

Three Fixed Degrees of Freedom

In an attempt to further reduce the degrees of freedom, two combinations of three fixed degrees of freedom were tested. Table 5-8 gives the results.

	Best Angles (degrees)	Number of Successful Positions	Number of Close Positions	Number of Unsuccess. Positions	Which Positions Unsuccessful
Elevation, Wrist Flexion & Wrist Yaw Fixed	48 / -15 / 3	13	4	17	F1, S1, S2, Po, K1, K2, T1, T2, Li, Bu, Pa, Ph, W1, Br1, Br2, Co1, Co2
Roll, Wrist Flexion & Wrist Yaw Fixed	-46 / -15 / -2	15	8	11	H1, F1, F2, S1, S2, T2, Bu, Pa, Ph, W2, Br2

Table 5-8: Three Fixed Degrees of Freedom Results

Fixing three degrees of freedom produces significantly more unsuccessful tasks than the best alternatives for two fixed degrees of freedom. Furthermore, the high priority eating and personal hygiene tasks are affected in both options. It can therefore be concluded that fixing more than two degrees of freedom produces an unacceptably restricted device.

Torque Considerations

Typically, higher torque requirements necessitate larger motors, increasing both the bulk and the weight of an orthosis. The maximum torques required at each joint for a powered upper-limb orthosis given a one kilogram load were analysed by From [32]. These are listed in Table 5-9.

	Max. Torque (N-m)	Equation	Position of Arm at Maximum Torque
Azimuth	1.5	$T_{az} = [m(d_f + d_u)^2 + M_f(\frac{1}{2}d_f + d_u)^2 + M_o d_u^2 + M_u(\frac{1}{2}d_u)^2] * \alpha$	arm outstretched horizontally
Elevation	21.6	$T_{ev} = g[m(d_f + d_u) + M_f(\frac{1}{2}d_f + d_u) + M_o d_u + \frac{1}{2}M_u d_u]$	arm outstretched horizontally with elbow fully extended
Roll	6.5	$T_r = g[md_f + \frac{1}{2}(M_f+M_{of})d_f]$	elbow bent 90°, forearm and upper arm both lying in horizontal plane
Elbow Flexion	6.5	$T_{eb} = g[md_f + \frac{1}{2}(M_f+M_{of})d_f]$	forearm horizontal, moving upward in vertical plane
Forearm Rotation	0.5	$T_f = gmd_l$	forearm horizontal, load 50mm either side of hand

Table 5-9: Maximum Required Torque for Each Joint

where,

m	= 1 kg	= point mass load
M_f	= 1.5 kg	= mass of forearm
M_u	= 2 kg	= mass of upper arm
M_{of}	= 0.5 kg	= mass of orthotic hardware on forearm
M_o	= 3 kg	= mass of orthotic hardware for whole arm
d_l	= 0.050 m	= maximum eccentricity of load
d_f	= 0.330 m	= length of forearm and hand
d_u	= 0.220 m	= length of upper arm
α	= 2 rad/s^2	= angular acceleration
g	= 9.81 m/s^2	= gravitational acceleration

As shown in the table, the torque required for elevation is more than three times that for any other joint. In fact, the upper arm length is relatively low so maximum torques could be even higher. A spring assist could be used to reduce these torques.

Control Issues

From a user's perspective, endpoint control is more intuitive and easier for device operation than controlling individual degrees of freedom. If the shoulder is free and the wrist fixed then the user simply controls the wrist position in three dimensions, plus forearm rotation and hand grasp. If wrist flexion is powered, then an extra control signal is required to activate the flexion. Powering wrist flexion does, however, provide local movements of the hand. If elevation is fixed there is no redundancy in the joints, which could lead to more unnatural positions. Fixing elevation also leads to a more restricted work envelope.

Conclusions from Preliminary Evaluation

For a more versatile orthosis, only two degrees of freedom should be fixed or coupled. Four alternatives follow from the initial analysis. Table 5-10 summarizes the advantages and disadvantages of these alternatives.

	Advantages	Disadvantages
Elevation & Wrist Yaw Fixed	1) reduces power consumption 2) reduces bulk 3) allows local movements of hand 4) affects only lower-priority tasks	1) restricts work envelope 2) requires control signal for wrist flexion
Roll & Wrist Yaw Fixed	1) reduces bulk 2) reduces power consumption slightly 3) allows local movements of hand	1) same as above 2) affects eating tasks
Wrist Flexion & Wrist Yaw Fixed	1) orthosis as flexible as human arm in positioning wrist 2) fewer control signals needed	1) increases power consumption 2) limits control over orientation 3) affects eating tasks
Roll & Elbow Flexion Coupled; Wrist Yaw Fixed	1) given the correct functional relationship, leads to more successful tasks than with roll and wrist yaw fixed	1) more complex design, bulkier; greater power consumption than for fixed roll

Table 5-10: Advantages and Disadvantages of Preliminary Alternatives

5.6.2 Analysis of Individual Subjects

The four alternatives listed above were tested further using all of the key points plus additional intermediate points for each task. An average of 125 points were tested for each subject. The purpose was both to test more points along the path and to use the individual subject data instead of the averaged data used in the initial evaluation.

There was a range of success among the subjects for each alternative. All of the alternatives had more unsuccessful tasks than appeared in the original evaluation. This was due to the greater variability for a single individual than for the averaged results used above and due to the additional positions tested for the personal hygiene tasks. Page turning was unsuccessful in all cases, but this was primarily due to orientation rather than distance; it may therefore be possible to change the handle to accommodate the orthosis or to turn the pages differently. Page turning is therefore bracketed in the list of unsuccessful tasks below.

The relationship between roll and elbow flexion was more scattered for the individual subjects than in the initial evaluation; in some cases the relationship was lost altogether. Coupling roll and elbow flexion therefore increases the complexity and bulk without producing a significant functional advantage over fixing roll. Table 5-11 summarizes the results, excluding coupled roll and elbow flexion.

In practical application more tasks will be performed than are included here. Many tasks will fall within the same work envelope as one of the included tasks. Also, people will compensate through other motions and means that cannot be simulated.

	Unsuccessful Tasks
Elevation & Wrist Yaw Fixed	Pouring from a Pitcher (at full height), Reaching for a Door Knob, Flipping a Light Switch, Reaching to a High Button, (Turning a Page), Brushing the Teeth (some positions), Combing the Hair (some positions)
Wrist Flexion & Wrist Yaw Fixed	Eating with a Fork, Eating with a Spoon, Reaching for a Door Knob, Turning a Tap Lever, (Turning a Page), Brushing the Teeth (some positions)
Roll & Wrist Yaw Fixed	Eating with a Fork, Eating with a Spoon, Turning a Tap Lever (at extreme), (Turning a Page), Washing the Face (some positions), Combing the Hair (some positions)

Table 5-11: Unsuccessful Tasks for Final Alternatives

5.7 Implications for Orthosis Design

In terms of reducing complexity, fixing roll is equivalent to fixing elevation, but in terms of reducing torque, fixing elevation is significantly more effective than fixing roll. Since the performance of the simulated fixed roll orthosis was not significantly better than the performance of the fixed elevation device, and in fact affects the eating tasks, fixing roll and wrist yaw is not recommended.

The primary advantage of selecting the fixed elevation and wrist yaw alternative is the reduction in maximum torque and therefore the power consumption and bulk. This can be a significant factor in terms of power requirements, battery discharge and speed of activation. The mechanical need for a lever arm from the body to the upper arm to perform elevation increases physical bulk; it is also less aesthetically pleasing because of the lack of streamlining to the arm. From reinforces these arguments, stating that "since the elevator joint consumes the most power during movement and requires the greatest torque, its removal would significantly enhance the size, mass and power consumption of the device" [32]. The primary disadvantage, aside from slightly more unsuccessful tasks, is with respect to control. Choosing to fix elevation as opposed to wrist flexion not only reduces the work envelope and the flexibility of the shoulder but adds the need to control wrist flexion separately. The advantage of controlling wrist flexion is having local control over orientation, thus allowing small adjustments to be made without moving the entire arm.

The primary advantage of fixing both wrist rotations is being able to reach any location that the arm could normally reach. Also, the redundancy of the three shoulder degrees of freedom provides more than one solution for a given position, allowing for more natural arm positions. The disadvantage is that there is no small-scale control of orientation except forearm rotation and the unsuccessful tasks are of a higher priority. A small aesthetic advantage is that the actuation is kept away from the end of the forearm.

Since the importance of the advantages and disadvantages will vary from application to application, both alternatives are recommended. In each case, hand grasp is powered as well.

Although fixed at a particular angle, the fixed angles should be manually adjustable to suit the individual and the individual's circumstances.

5.8 Conclusion

This chapter has outlined the design and use of a simulation program to establish whether a given position and orientation can be achieved with a specified configuration of a simulated orthosis. Based on the results of the simulations, two orthosis designs are recommended. The first is to fix elevation and wrist yaw and power all other rotations. The major advantage is that the power consumption and bulk are reduced. The major disadvantage is that the shoulder, and therefore the position of the hand, is more restricted in its movement. The second design is to fix wrist flexion and wrist yaw. The major advantages and disadvantages for this option are reversed. The major advantage is the greater flexibility of the arm. The major disadvantage is the extra bulk and power requirements needed to operate the shoulder. While the first option affects lower-priority tasks, the second option affects the higher-priority eating tasks. A simpler configuration would be possible if the task requirements were fewer, if the user were able to compensate with the head and trunk, or if the user has residual motion in the arm. In addition, the user may be able to perform the tasks differently or with daily-living aids, such as a fork with an angled handle or a rotating spoon.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The goals of this research are to identify the needs of potential users of a powered upper-limb orthosis and to develop a procedure for determining an optimal configuration. The compromise is between simplicity and functionality. Two alternative configurations are recommended which are more restricted than the motion of the natural arm but provide enough function to perform the majority of the higher-priority daily-living tasks. It was determined that out of the seven degrees of freedom in the human arm, two should be fixed and the rest powered.

These recommendations were arrived at through three stages. The first stage involved interviewing potential users of a powered upper-limb orthosis to determine which tasks they would most like to regain. In stage two, the arm motions of able-bodied subjects performing the high-priority daily-living tasks were profiled. For stage three, alternative orthosis configurations were evaluated using a simulation program.

6.2 Task Definition and Priorities

The objectives pertaining to task priorities were to research the needs and wants of potential users of a powered upper-limb orthosis and to establish the priority of various daily-living tasks. To this end, interviews were conducted with 11 potential users. The interviews covered the top five desired tasks, task abilities, use of daily-living aids, orthosis acceptance criteria and medical details. The conclusions and contributions of this portion of the research are outlined below:

- Interviews were conducted with potential users of a powered upper-limb orthosis rather than a robotic manipulator. Because an orthosis returns function to the user's own arm, there was a greater emphasis on hobbies, crafts, personal hygiene and dressing tasks, tasks that would be less personal and more intimidating if performed by a robotic manipulator.

- Disabled respondents put a greater emphasis than able-bodied respondents on reaching for and picking up objects. All compilations of potential user task priorities have recognized the importance of reaching for and picking up objects.

- The most desired tasks, based on the interviews with 11 potential users conducted for this research, were reaching/picking up objects (9), personal hygiene (7), hobbies/crafts (7), eating/drinking (6), housework (4), dressing (4), strengthening grip (4), cooking (2), toileting/transferring (2), reading (1) and using a computer (1). (The number in brackets shows the number of respondents mentioning the task among their top five choices.)

- Separate from the desire to regain independence was a clear desire to regain creativity, through crafts, hobbies, painting and baking. While these tasks are beyond the capabilities of a practical whole-arm orthosis, mostly due to the dexterity involved, a person with functioning hands but weak arms could use the orthosis to position the hand where needed.

- Affordability and cosmesis are both important factors in user acceptance.

6.3 Motion Analysis

The research objectives for the second phase were to record the motions of able-bodied people performing the top-priority tasks and to analyse these motions in terms of the joint rotations and paths taken during each task. A motion analysis system consisting of two video cameras, an image processing system and customized software was developed and used to profile six subjects, three male, three female performing 22 daily-living tasks. The tasks included eating and drinking tasks, reaching tasks, daily-living activities and personal hygiene tasks. The conclusions and contributions of the developed system and the research performed include the following:

- The literature review and requirements of this research indicated a need for a new motion analysis study of functional tasks. Few whole arm studies have been conducted; only one has data on functional tasks and only for eating and drinking. By contrast, this research profiled 22 functional tasks. The motion analysis provided the desired positions and orientations and initial joint angle estimates for the simulation program.

- Software was developed for this research to control the VCR, load and manipulate the video image, track the joint markers, solve for the three-dimensional coordinates of each marker, display stick figure diagrams of the movements and calculate the joint angles.

- The analysis for this research differed in three ways from previous researchers: a clearer definition of shoulder joint rotations, which is more suited to orthosis design, was used; each joint angle was calculated directly, based on a model of the arm, instead of solving for the three Euler rotations simultaneously at each joint; and a passive carrying angle is defined which rotates the plane of elbow flexion. Although not as general as the Eulerian approach, the method used here produces more consistent results. The displacement of the markers from the joint centres was accounted for as well, improving the accuracy of the results.

- The joint angle results were found to be comparable to previous researchers, except where the hand grasp differed, and repeatable. The average joint angle standard deviation for a single subject was found to be 3.0 degrees; for the six subjects it was found to be 8.0 degrees.

- Previous studies indicated the importance of elbow flexion, forearm rotation and at least one shoulder rotation. The motion analysis results from this study indicated that at least elbow flexion, forearm rotation and two out of the three shoulder rotations should be powered, while possibly one shoulder rotation and both wrist rotations could be fixed. This hypothesis was tested with the simulation program.

6.4 Orthosis Simulation

The objectives for the last phase of the research were to develop a kinematic simulation program to test possible configurations of a powered upper-limb orthosis and to use this simulation program to determine the orthosis configuration with the fewest degrees of freedom that is still capable of performing the highest-priority tasks. The developed program determines how close a simulated orthosis is able to come to a desired position and orientation. It does so by using a cost function and minimization procedure. All reasonable combinations up to three fixed or coupled joint rotations were examined. The conclusions and contributions from this phase of the research are provided below:

- The literature review indicated that, while other researchers have based designs on joint priorities or on tests with mechanical models, an examination of the required degrees of freedom has never been quantified before.

- Preliminary evaluations were conducted with 34 positions, consisting of the critical functional positions for each task. Fixing azimuth (rotation about a vertical axis through the shoulder), elbow flexion or forearm rotation led to a large number of unsuccessful tasks. Therefore, only elevation (rotation about a horizontal axis through the shoulder), roll (rotation about the axis of the upper arm), wrist flexion and wrist yaw were considered further. When two degrees of freedom were fixed, fixing wrist yaw produced better results than fixing wrist flexion. Several joint couplings were evaluated but did not provide a significant advantage over fixing in terms of the number of successful tasks. Fixing three degrees of freedom produced significantly more unsuccessful positions than fixing two degrees of freedom.

- Four potential alternatives emerged from the preliminary evaluation: 1) to fix elevation and wrist yaw, 2) to fix roll and wrist yaw, 3) to fix wrist flexion and wrist yaw and 4) to couple roll and elbow flexion and fix wrist yaw. These were analysed further using up to eight functional points from each task, for each of the six motion analysis subjects.

- The recommended alternatives are to power all but elevation and wrist yaw or to power all but wrist flexion and wrist yaw.

- Both of the final alternatives were unsuccessful in reaching for a doorknob, turning a page and brushing the teeth (some positions). The additional unsuccessful tasks for the first alternative were pouring from a pitcher (at full height), flipping a light switch, reaching to a high button and combing the hair (some positions), all requiring a higher elevation. The additional unsuccessful tasks for the second alternative were eating with a fork, eating with a spoon and turning a tap lever.

6.5 Orthosis Design

As shown in the literature review, a powered upper-limb orthosis that is acceptable to users has yet to be developed. In most cases, they were too complex, bulky and prone to breakdown. The more recent UBC-modified HMRC orthosis is much simpler, but is not sufficiently functional.

- Both recommended options restrict the number of tasks that can be performed; the loss of functionality, however, is offset by the advantages of increased simplicity. A simpler design leads to reduced costs, fewer breakdowns, and is more aesthetically acceptable.

- An even simpler configuration would be possible if the task requirements were fewer, if the user were able to compensate with the head and trunk, or if the user has residual motion in the arm. In addition, the tasks may be able to be performed differently or with daily-living aids.

- Fixing wrist yaw affects the least number of tasks; it therefore appears in both recommended configurations. Fixing elevation significantly reduces power consumption and bulk but restricts the work envelope of the hand. Fixing both wrist rotations expands the work envelope, but increases power consumption and bulk, prevents local movements of the hand and affects higher-priority tasks.

- Although joints are indicated as fixed they should be adjustable to suit the individual. Also, an individual user's remaining function should be utilized rather than restricted.

6.6 Recommendations for Future Work

The following recommendations can be made for future work in the areas of this research:

- A prototype orthosis should be designed and developed based on the recommendations of this thesis, as is planned. The proposed simpler yet versatile design should have a higher probability of user acceptance.

- Throughout the development of the prototype, there should be continued contact with users on design considerations not included here, such as ease of use, appearance etc.. The design process should be iterative to allow for feedback from users.

- Once a prototype orthosis is built, it should be evaluated clinically against the defined high-priority tasks.

- Further motion analyses should be conducted to examine the compensatory movements used by people with upper-limb disabilities in performing tasks.

- Kinematic simulations should be used to improve workspace design for people with upper-limb disabilities.

- Control strategies were not within the scope of this thesis. However, the recommendations on orthosis configuration should be reviewed based on considerations of alternative control strategies.

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APPENDICES

Appendix A: A Brief Medical Description of the Disability Categories

The following provides a brief medical description of each of the disability categories causing upper-limb weakness. The effect on upper-limb weakness is given in Table 3-1.

P (polio): Polio causes muscle weakness due to a viral attack on the muscle nerve root; although eradicated from North America, survivors are now experiencing weakness in muscles previously unaffected [40].

ALS (amyotrophic lateral sclerosis): ALS causes progressive muscle weakness due to a degenerative disease which attacks the motor neurons in the brain and spinal cord; PMA-type primarily affects the arms and legs; bulbar-type primarily affects swallowing and speech [12,111].

MD (muscular dystrophy): MD causes progressive degeneration of the muscle fibres; all three types (Duchenne, limb girdle and facioscapulohumeral) are genetically determined with DMD being the most severe and LGMD and FSH-MD progressing more slowly [12,108].

SCI (spinal cord injury): SCI is caused by a sudden spinal cord injury during e.g. diving or motorcycle accidents; muscles are totally ("complete") or partially ("incomplete") paralyzed below the injury site [65,117].

MS (multiple sclerosis): MS causes demyelination of the central nervous system causing the signal to not be able to reach the muscle (the strength of the muscle before disease is therefore irrelevant) [57].

BPI (brachial plexus injury): BPI is a tearing of the nerve complex at the shoulder (the "brachial plexus") due to a high velocity impact, most commonly from motorcyle accidents; the resulting paralysis depends on which nerves are affected [58].

Str (stroke): Stroke is a sudden disorder leading to a lack of blood with enough oxygen to maintain brain function in a localized area; it usually results in paralysis on a single side; recovery varies from complete (10%) to still needing institutional care (10%) [23,105].

CMT (Charcot-Marie-Tooth): CMT causes progressive muscle weakness with the muscles atrophying in the legs and arms [22].

Appendix B: Task Priority Questionnaire

TASK PRIORITY AND MOTION ABILITY QUESTIONNAIRE
for the design of a
POWERED UPPER EXTREMITY ORTHOSIS

conducted by
CLINICAL RESEARCH AND REHABILITATION ENGINEERING
UNIVERSITY OF BRITISH COLUMBIA

GENERAL DISABILITY INFORMATION

Name: Phone Number:
Diagnosis:

Length of time since first diagnosed:
Lesion level (if applicable): Complete/Incomplete?:

Any other medical illnesses?:

DEGREE OF DISABILITY

	Weakness? (total/partial/none)		**Loss of Sensation?** (total/partial/none)	
Hand	R:	L:	R:	L:
Wrist	R:	L:	R:	L:
Elbow	R:	L:	R:	L:
Arm	R:	L:	R:	L:
Shrug	R:	L:	R:	L:

	Range-of-Motion? (full/limited)	
Grasping	R:	L:
Forearm Rotation	R:	L:
Bending Elbow	R:	L:
Lifting Arm to front	R:	L:
Raising Arm to side	R:	L:
Shrugging Shoulders	R:	L:
Neck Motion - up/down	R:	L:
- left/right	R:	L:
- forward/backward	R:	L:

Daily living aids being used? (list all):

Any involuntary movements?

Any spasms?

Any pain?:

Ambulatory?: If not, what device is used?:

Any eye problems?

Any voice problems?

TASK ABILITY

Which tasks can you *not* do now but would like to be able to do, which involve the hand or arm?

Which of these are most important to you?

Can you perform the following tasks Easily (E)? With difficulty (D)? With an aid (A)? or not at all (N)? If an aid is used, what is the aid? What are the reasons for the difficulties experienced?

Personal Hygiene Tasks

	Ability	Aid	Reason for Difficulty
Brushing teeth			
Washing face			
Combing hair			
Blowing nose			
Shaving			
Applying makeup			
Scratching			
Going to the toilet:			
unrolling paper			
pulling paper off			
wiping			
rearranging clothes			
feminine hygiene			
Turning taps			
Washing hands			
Reaching:			
to top of head			
to mouth			
to waist			
to knees			
to shoes (floor)			

Dressing:
  not able to do: ______________________________
  able to do: ______________________________
Any other personal hygiene tasks?
  (specify) ______________________________
____

Domestic Tasks

	Ability	Aid	Reason for Difficulty
Getting item from fridge			
Using a microwave			
Making a hot drink:			
filling the kettle			
plugging/unplugging			
getting utensils			
pouring water/milk			
adding sugar			
stirring			
Eating:			
loading spoon from plate			
spearing with a fork			
cutting with a knife			
spreading with a knife			
putting food into mouth			
Drinking:			
with a straw			
lifting & tilting the cup			
Using electric can opener			
Opening beverage cans			
Opening beer/pop bottles			
Operating taps			
Using sink plugs			
Turning stove knobs			
Opening/closing doors:			
turning a key			
turning a doorknob			
turning a door lever			
pulling the door			
pushing the door			
Operating light switches			
Reaching, grasping & returning			
Picking item up from floor			
Pushing/pulling drawers			
Opening/closing cupboards			
Turning screwdriver			
Any other domestic tasks?			

(specify) ____

____

Leisure/Recreation Activities

	Ability	Aid	Difficulty	Reason for:
Reading a book:				
holding book				
turning pages				
Reading a newspaper:				
holding newspaper				
turning pages				
Reading a magazine:				
holding magazine				
turning pages				
Playing computer games				
Operating remote control (TV, radio, stereo, VCR)				
Smoking				
Drawing/painting				
Playing board games				
Gardening:				
indoor				
outdoor				
Any other recreational activities? (specify) ______________________				

Work- or School-Related Tasks

	Ability	Aid	Difficulty	Reason for:
Using a computer:				
typing at a keyboard				
using a mouse				
inserting floppy discs				
Writing with pen or pencil				
Picking & placing objects				
Pushing buttons				
Answering the telephone				
Using a touch-tone phone				
Using a stapler				
Using a photocopier				
Using a FAX machine				
Opening a letter				
Sealing an envelope				
Using a calculator				
Filing documents				
Using public transportation				
Riding in a car				
Any other work or school activities? (specify) ______________________				

TASK PRIORITY

What are the top five tasks, in order, that you would most like to do but cannot?

1.
2.
3.
4.
5.

If a device could do some of the above would you consider buying it (Y/N)?

Would you be willing to take part in clinical trials of such a device (Y/N - *note answer for later*)?

CRITERIA FOR ORTHOSIS ACCEPTANCE

If an orthosis were available for grasping, rotating the forearm and bending the elbow, how important would you rate the following criteria (1=very, 5=not at all):

Affordability: ___
Repairability by yourself or an assistant: ___
Having control over all motions vs. preprogrammed motions: ___
Dependability/ Reliability: ___
Durability (expected life): ___
Ease of Donning & Doffing: ___
Ease of Maintenance: ___
Effectiveness of the orthosis in performing tasks: ___
Having choice of grasping/rotation/bending systems: ___
Learnability: ___
Length of time available before recharging: ___
Ease of control: ___
Aesthetics: ___
Acceptability of orthosis when amongst others: ___
Physical Comfort: ___
Physical Safety: ___
Portability (weight & bulk): ___
Speed of operation: ___
Supplier Repairability: ___
Time from purchase to usability: ___

Would anything else be important to you?

PERSONAL INFORMATION

Age:
Age at injury/ onset of disease:
Sex (F/M):

Marital Status:
(Married, Single, Cohabiting, Widow/er, Divorced/Separated)

Accommodation (Home, Hospital, Institution):
If at home, are you Alone, With a partner, With family?
If at home, do you have any home help (Y/N)?

Employment status (FT, PT, occasional, none):
Occupation:
Location (Home-based or Outside the home):
Educational background:

Pasttimes (how do you spend your day?):

Television
Reading
Stereo
Computer Games
Board Games
Visiting
Sleeping
Eating
Other:

THANK YOU!

Confirm (based on answer to question above):

___ You WOULD be willing to be contacted for future practical trials of the device.

OR

___ You would NOT be interested in participating in future practical trials of the device.

NOTES

Appendix C: Subject Task Priorities

The top tasks for each subject, from the interviews conducted with potential users, were:

Subject #1: (post-polio)	1. Dressing self; 2. Eating meal by self; 3. Housework; 4. Cooking, using stove; and, 5. Getting into cupboards.
Subject #2: (kugelberg-welander)	1. Woodwork; 2. Working on cars/machinery; 3. Household renovations; 4. Hobbies, e.g. put together remote control airplanes; and, 5. Strength & stamina.
Subject #3: (C5/6 spinal cord injury)	1. Getting things out of fridge; 2. Stronger grip (opening can, holding knife); 3. Picking up something heavy from the floor; and, 4. Reaching over the head.
Subject #4: (kugelberg-welander)	1. Putting things away overhead; and, 2. Supporting the arm to eat, comb hair etc..
Subject #5: (limb-girdle MD)	1. Eating; 2. Transferring self out of chair, e.g. to bed, toilet; and, 3. Lifting things.
Subject #6: (limb-girdle MD)	1. Reading; 2. Doing hair; 3. Sewing; 4. Painting; and, 5. Cleaning.
Subject #7: (limb-girdle MD)	1. Feeding; 2. Brushing teeth; 3. Putting on lipstick; and, 4. Crocheting.
Subject #8: (limb-girdle MD)	1. Reaching (holding arms up); 2. Dressing; 3. Eating; 4. Using computer; 5. Doing hair; 6. Painting, art & crafts; and, 7. Gardening.

Subject #9:
(limb-girdle MD)

1. Housework;
2. Baking;
3. Opening jars;
4. Lifting and carrying things; and,
5. Travelling.

Subject #10:
(limb-girdle MD)

1. Personal grooming;
2. Feeding;
3. Gardening ("miss terribly!");
4. Toileting;
5. Dressing (esp. nylons);
6. Housework (changing sheets, doing laundry); and,
7. Painting, knitting, crocheting.

Subject #11:
(limb-girdle MD)

1. Strength;
2. Hobby-type work (building, creating);
3. Driving (freedom);
4. Eating;
5. Dressing; and,
6. Brushing hair, washing face, brushing teeth, shaving.

Appendix D: EQUIPMENT SPECIFICATIONS

The following equipment was used to perform the motion analysis:

V.C.R.:	SONY SVO-9500MD S-VHS
Frame grabber board:	Sharp GPB-1 image processing board
TV monitor:	Hitachi Model #CT1397B colour monitor
Computer:	486/50MHz with Windows 3.1
Cameras:	Panasonic PV-S770-K S-VHS camcorders
Tripods:	Manfrotto Art # 075
Tripod Heads:	Manfrotto Art # 136

APPENDIX E: 3D COORDINATE CALCULATIONS

Camera Calibration

Eleven parameters are used to describe the calibration of a single camera [107]. These represent the position and attitude of the camera, the principal distance of the camera and a scaling factor. The method presented here uses a central-projection camera model and assumes no optical distortion in the lens.

Let (x, y, z) be known three-dimensional "object coordinates"; let (u,v) be known two-dmensional "image coordinates". Using homogeneous coordinates [33],

$$\{x\ y\ z\ 1\}\begin{bmatrix} L_1 & L_5 & L_9 \\ L_2 & L_6 & L_{10} \\ L_3 & L_7 & L_{11} \\ L_4 & L_8 & L_{12} \end{bmatrix} = \{tu\ tv\ t\}$$

where L_1 to L_{12} are the elements of the transformation matrix. The system is scaled as necessary to get $L_{12} = 1$. Solving for u, v and t:

$$t = L_9 x + L_{10} y + L_{11} z + L_{12}$$

$$u = \frac{L_1 x + L_2 y + L_3 z + L_4}{t}$$

$$v = \frac{L_5 x + L_6 y + L_7 z + L_8}{t}$$

Hence, two linear equations can be defined for each point:

$$u_i = L_1 x_i + L_2 y_i + L_3 z_i + L_4 - L_9 u_i x_i - L_{10} u_i y_i - L_{11} u_i z_i$$
$$v_i = L_5 x_i + L_6 y_i + L_7 z_i + L_8 - L_9 v_i x_i - L_{10} v_i y_i - L_{11} v_i z_i$$

In matrix form this becomes:

$$\begin{bmatrix} x_1 & y_1 & z_1 & 1 & 0 & 0 & 0 & 0 & -u_1x_1 & -u_1y_1 & -u_1z_1 \\ 0 & 0 & 0 & 0 & x_1 & y_1 & z_1 & 1 & -v_1x_1 & -v_1y_1 & -v_1z_1 \\ x_2 & y_2 & z_2 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ x_n & y_n & z_n & 1 & 0 & 0 & 0 & 0 & -u_nx_n & -u_ny_n & -u_nz_n \\ 0 & 0 & 0 & 0 & x_n & y_n & z_n & 1 & -v_nx_n & -v_ny_n & -v_nz_n \end{bmatrix} \begin{Bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \\ L_5 \\ L_6 \\ L_7 \\ L_8 \\ L_9 \\ L_{10} \\ L_{11} \end{Bmatrix} = \begin{Bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ \cdot \\ \cdot \\ u_n \\ v_n \end{Bmatrix}$$

or, $$[P]_{2n \times 11} \{L\}_{11 \times 1} = \{Q\}_{2n \times 1}$$

At least n = 6 calibration points are required to solve for the unknown calibration parameters, L_1 to L_{11}. In this study 10 were used in order to improve the accuracy. The minimum-squared-error criterion was used to solve the overdetermined system (20 equations for 11 unknowns). Thus,

$$\{L\} = ([P]^T [P])^{-1} [P]^T \{Q\}$$

$$= [P^+]\{Q\}$$

where $[P^+]$ is the pseudo-inverse of P.

3D Coordinate Calculation

Since there are two equations (u, v) for each camera, there are a total of four equations for three unknowns (x, y, z), the coordinates of each marker. Rearranging the earlier equations for u, v and t gives:

$$\begin{bmatrix} L_1-L_9u_1 & L_2-L_{10}u_1 & L_3-L_{11}u_1 \\ L_5-L_9v_1 & L_6-L_{10}v_1 & L_7-L_{11}v_1 \\ L_1'-L_9'u_2 & L_2'-L_{10}'u_2 & L_3'-L_{11}'u_2 \\ L_5'-L_9'v_2 & L_6'-L_{10}'v_2 & L_7'-L_{11}'v_2 \end{bmatrix} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = \begin{Bmatrix} u_1-L_4 \\ v_1-L_8 \\ u_2-L_4' \\ v_2-L_8' \end{Bmatrix}$$

or, $$[A]\ \{x\ y\ z\}^T = \{B\}$$

where L_1 to L_{11} are the calibration parameters for camera 1 and L_1' to L_{11}' are the calibration parameters for camera 2.

For the least-squares fit,

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = ([A]^T[A])^{-1}[A]^T\{B\}$$

The three-dimensional coordinates of any point can therefore be found given the corresponding images of at least two cameras.

The general approach used here is called the Direct Linear Transformation (DLT) method. Without it, the geometric parameters of the camera would have to be known precisely, requiring special cameras. First developed by Abdel-Aziz and Karara [1], the DLT method is now commonly used.

Appendix F: Euler Angle Joint Angle Calculations

The following discussion examines how joint angles are calculated using the Euler angle method as opposed to the direct calculation method used in this study. The Euler method was used by Langrana [54], Lipitkas [62] and Safaee-Rad [102].

Orthogonal axes are defined at each joint based on the marker positions. Each limb segment must have three markers to define a plane. Axes at the elbow reflect rotations at the shoulder, axes at the wrist reflect rotations at the elbow, etc. (Safaee-Rad defines axes such that the carrying angle is ignored, however this affects the values for roll, elbow flexion and forearm rotation.) A stationary body axis is also defined to account for movements of the trunk.

Once the unit vectors (x_i, y_i, z_i) of each set of axes have been found relative to the fixed frame of reference (X, Y, Z) the rotation matrices between each set of axes can be determined.

Given, $[F_i]$ = the unit vectors of the body axes,
$[R_i]$ = the relative rotation matrices and
[FFR] = the unit vectors of the fixed frame of reference,

the stationary body axis is defined by:	$[F_0] = [R_0][FFR]$,
the axis at the elbow is defined by:	$[F_1] = [R_1][FFR]$,
the axis at the wrist is defined by:	$[F_2] = [R_2][FFR]$ and
the axis at the hand is defined by:	$[F_3] = [R_3][FFR]$.

By rearranging the equations, and recognizing that $[R]^{-1} = [R]^T$ for orthonormal axes, the relative joint rotations can be defined as:

$[r_1] = [R_1][R_0]^T$ for the shoulder joint;
$[r_2] = [R_2][R_1]^T$ for the elbow joint; and,
$[r_3] = [R_3][R_2]^T$ for the wrist joint.

Euler angles ϕ, θ, and ψ describe successive rotations about specified axes. For the Euler angles defined as a rotation about the z-axis, followed by a rotation about the x' axis, followed by a rotation about the y" axis, the rotations can be expressed as:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$$

$$\begin{bmatrix} x''' \\ y''' \\ z''' \end{bmatrix} = \begin{bmatrix} \cos\psi & 0 & -\sin\psi \\ 0 & 1 & 0 \\ \sin\psi & 0 & \cos\psi \end{bmatrix} \begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix}$$

Multiplying the three successive rotations together gives:

$$[r] = \begin{bmatrix} \cos\phi\cos\psi - \sin\phi\sin\theta\sin\psi & \sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi & -\cos\theta\sin\psi \\ -\sin\phi\cos\theta & \cos\phi\cos\theta & \sin\theta \\ \cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi - \cos\phi\sin\theta\cos\psi & \cos\theta\cos\psi \end{bmatrix}$$

Matching the corresponding elements of this theoretical matrix with the calculated values of the matrices $[r_1]$, $[r_2]$ and $[r_3]$, each of the three Euler angles can be solved for, for each joint:

$$\phi = \arctan\left[\frac{-r_{13}}{r_{33}}\right]$$

$$\psi = \arctan\left[\frac{-r_{21}}{r_{22}}\right]$$

$$\theta = \arctan\left[\frac{r_{23}\cos\psi}{r_{33}}\right]$$

However, all three angles are being solved for from a single transformation matrix. Given inaccuracies in the axis definitions there will no longer be a consistent solution. The errors are further increased because the relative rotation matrices [r] are based on the multiplication of two absolute rotation matrices [R]. An inconsistent set of angles has a greater effect on the calculation of the endpoint position and orientation than on the angles themselves. Although inconsistencies may be tolerated in the motion analysis results, consistent joint angles were required for the orthosis simulations. A consistent, although less general, approach was used in this study, calculating joint angles directly, based on a developed model of the human arm.

Appendix G: Derivation of Location of P2 for Roll & Elbow Flexion Calculations

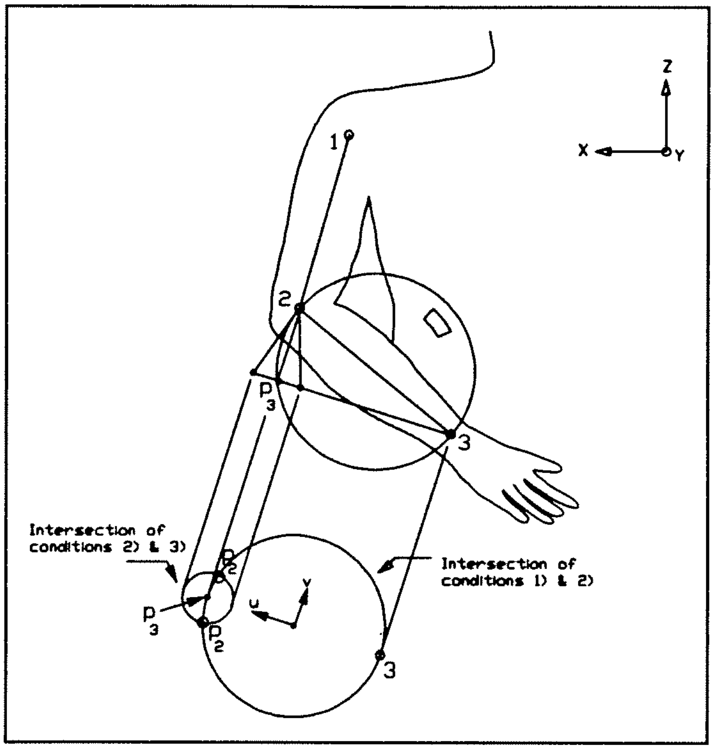

Figure G-1: Diagram for Finding Point p2

Figure G-1 is constructed using three known conditions on point p_2:

1) $\boldsymbol{r}_{2p_2} \perp \boldsymbol{r}_{3p_2}$ ***(by construction)***

Therefore, point p_2 lies on a sphere of radius $\frac{1}{2}|r_{23}|$ (i.e. half the forearm length), centred at $c = \frac{1}{2}(r_{O2} + r_{O3})$, where O is the origin of the coordinate system.

2) $\boldsymbol{r}_{3p_2} \perp \boldsymbol{r}_{12}$ ***(by construction of*** $\boldsymbol{r}_{3p_2} \| \boldsymbol{n}_2$ ***and*** $\boldsymbol{n}_2 \perp \boldsymbol{r}_{12}$***)***

Therefore, point p_2 lies in a plane normal to r_{12} and passing through point 3.

3) ***the angle between r_{2p_2} and r_{12} = θ_c = the carrying angle.***

The intersection of conditions 1 and 2 gives the following four relations:

$$r_{2p_3} = \left(\frac{r_{23} \cdot r_{12}}{|r_{12}|^2}\right) r_{12}$$

$$r_{3p_3} = r_{2p_3} - r_{23}$$

$$radius,\ a = \frac{1}{2}|r_{3p_3}|$$

$$u^2 + v^2 = a^2$$

From the intersection of conditions 2 and 3:

$$radius,\ b = |r_{2p_3}|\ \tan\theta$$

$$(u - a)^2 + v^2 = b^2$$

The intersection of the two circles is then:

$$u = a - \frac{b^2}{2a}$$

$$v = \pm\sqrt{(a^2 - u^2)}$$

The position of p2 is therefore:

$$p_2 = r_3 + \left(\frac{a+u}{|r_{3p_3}|}\right) r_{3p_3} \pm \left(\frac{v}{|r_{3p_3} \times r_{2p_3}|}\right)(r_{3p_3} \times r_{2p_3})$$

where the two solutions correspond to $\pm\ \theta$. The correct solution is that for which

$$n_2 \cdot r_{23} \geq 0.$$

Appendix H: Angle-Time Graphs from the Motion Analysis Study

The graphs below are representative angle-time graphs from the motion analysis study described in Chapter 4. Each line represents the raw data for one joint angle. The data was sampled every 1/30th of a second. Each graph is chosen from one of the six subjects.

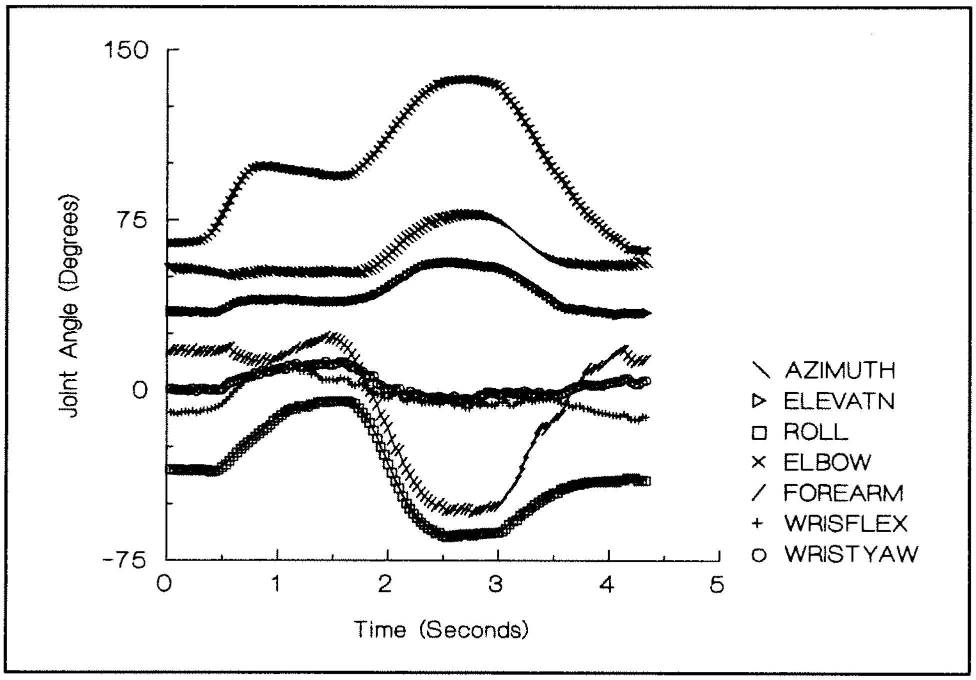

Figure H-1: Eating with the Hands

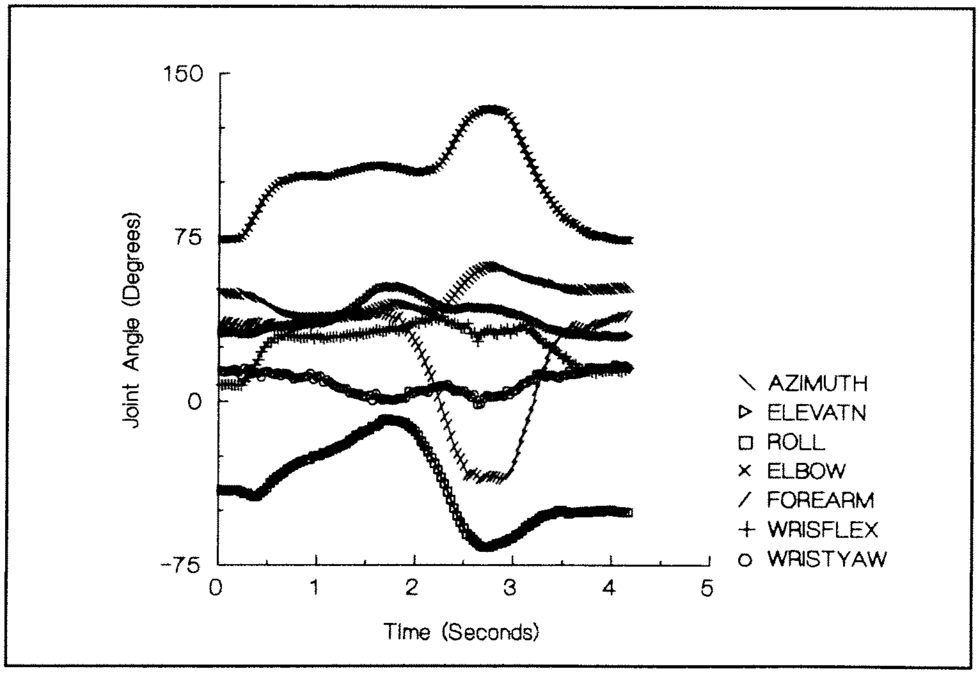

Figure H-2: Eating with a Fork

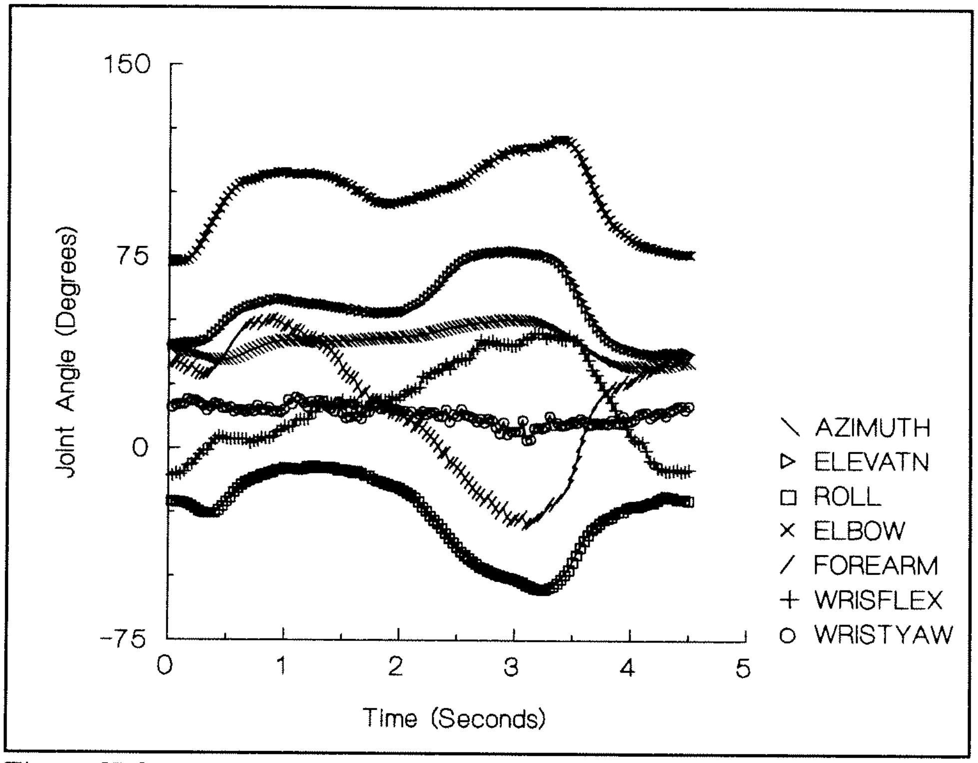

Figure H-3: Eating with a Spoon

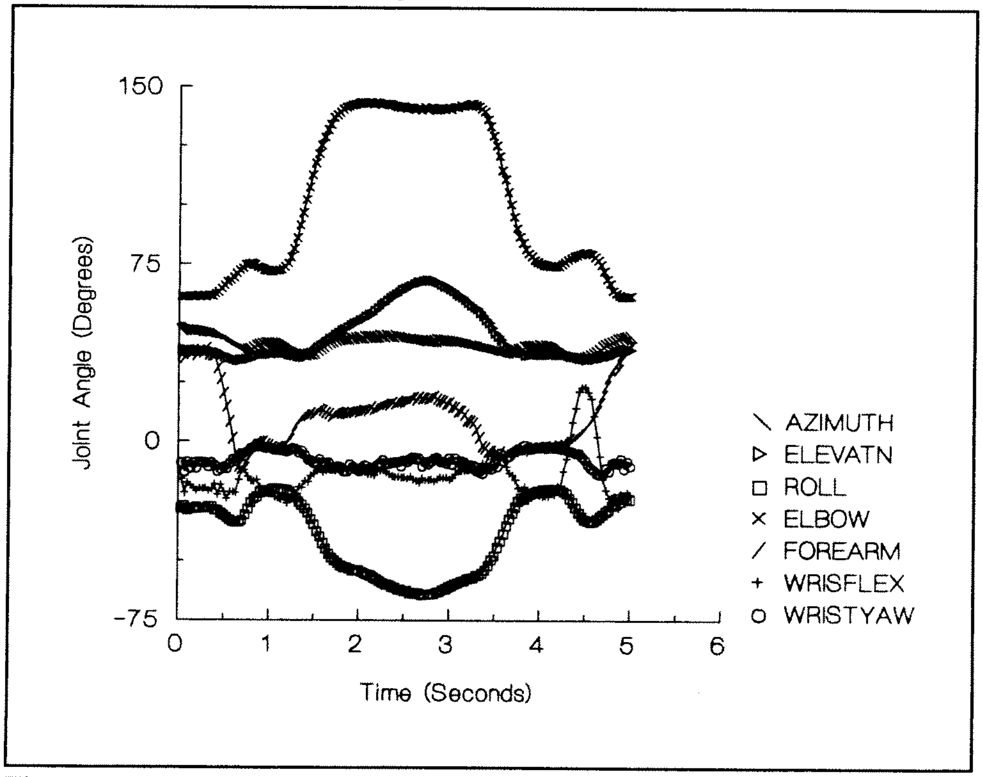

Figure H-4: Drinking from a Cup

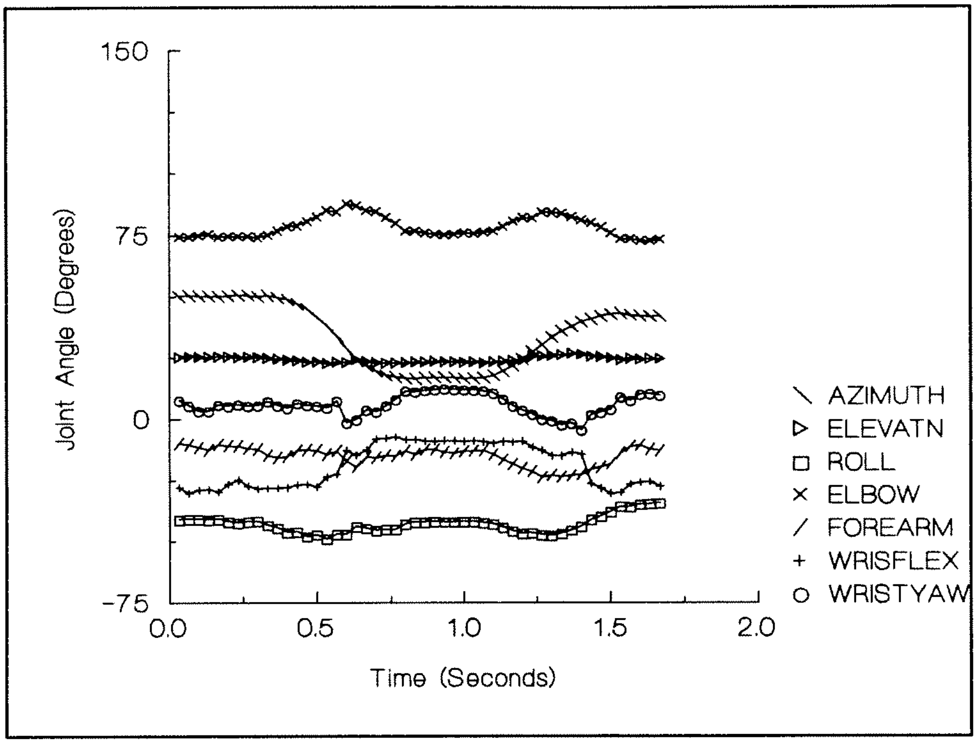

Figure H-5: Reaching to Position 1, Cylinder Vertical

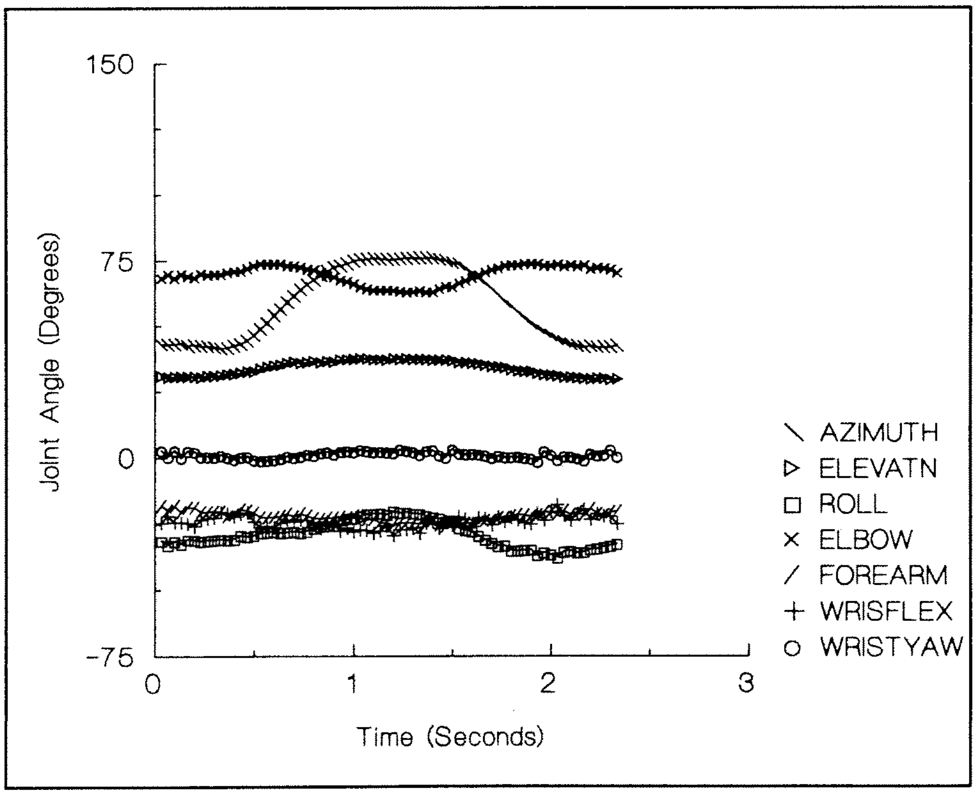

Figure H-6: Reaching to Position 2, Cylinder Vertical

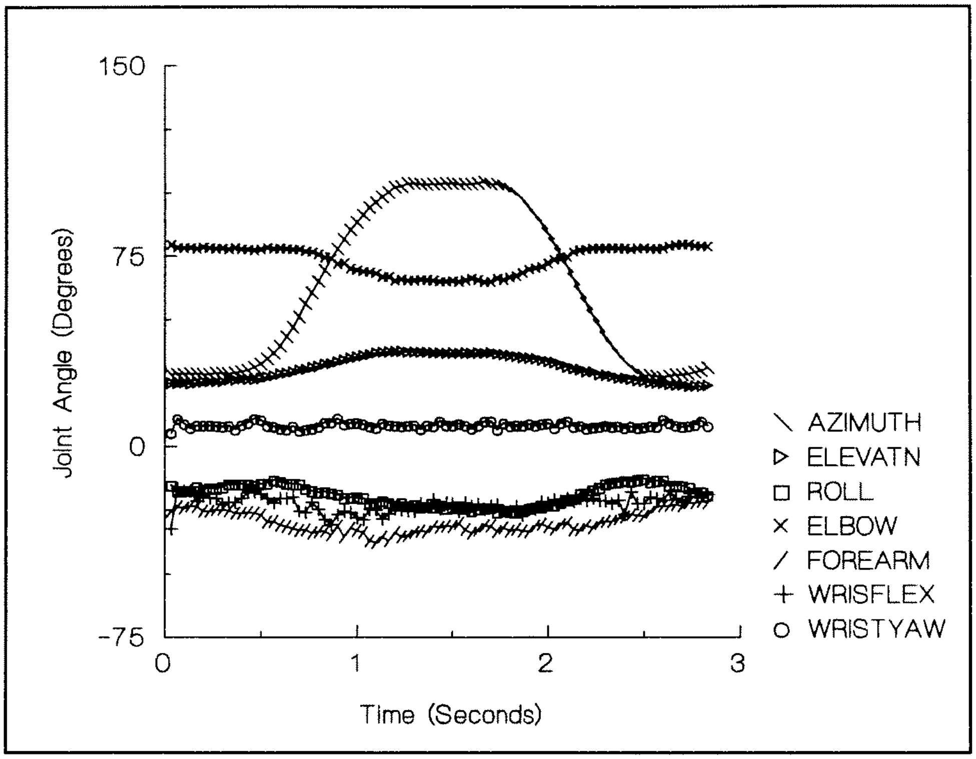

Figure H-7: Reaching to Position 3, Cylinder Vertical

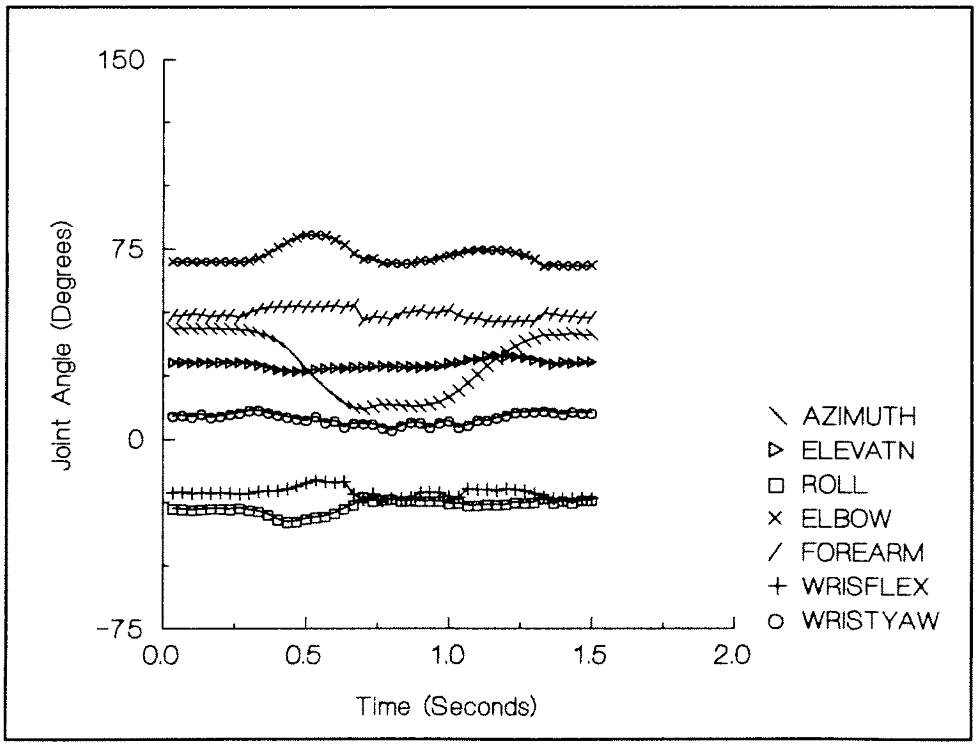

Figure H-8: Reaching to Position 1, Cylinder Horizontal

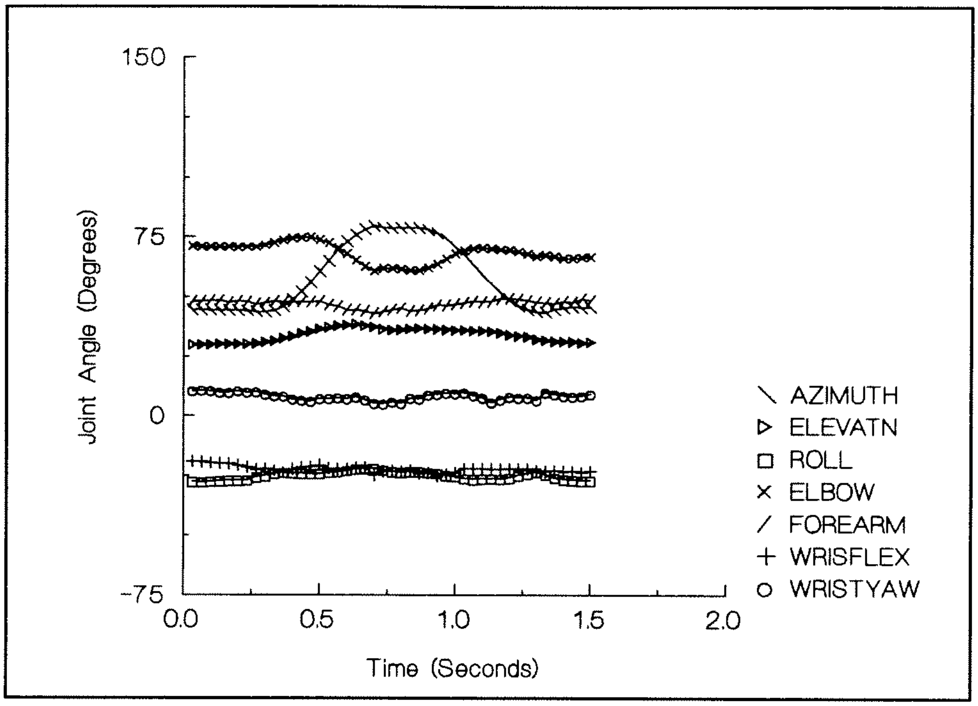

Figure H-9: Reaching to Position 2, Cylinder Horizontal

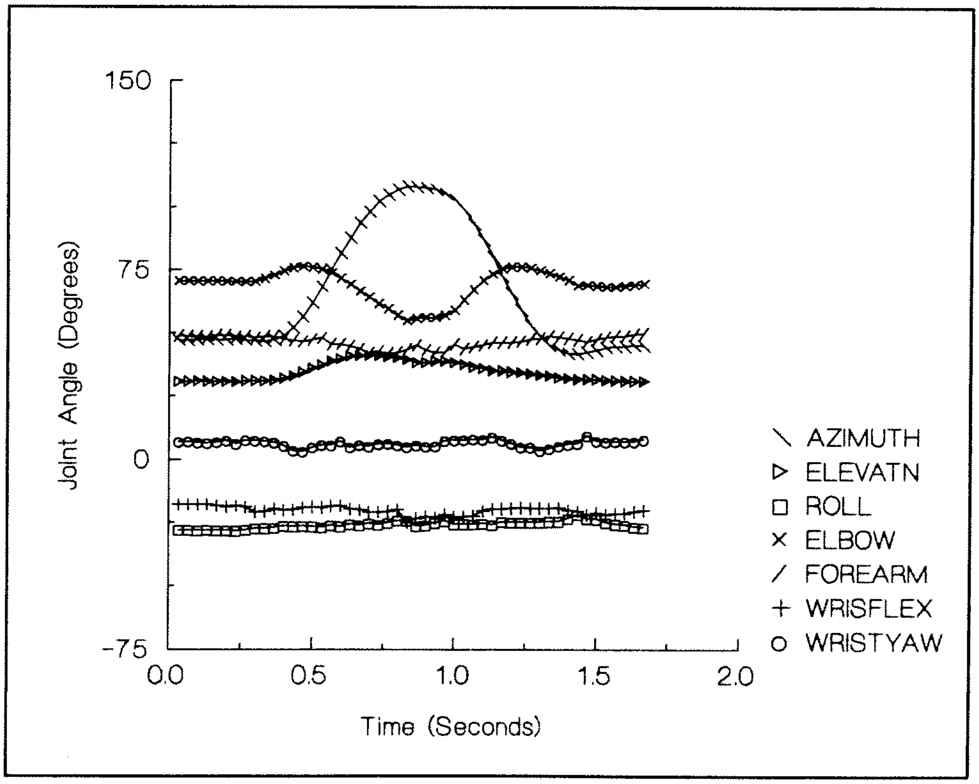

Figure H-10: Reaching to Position 3, Cylinder Horizontal

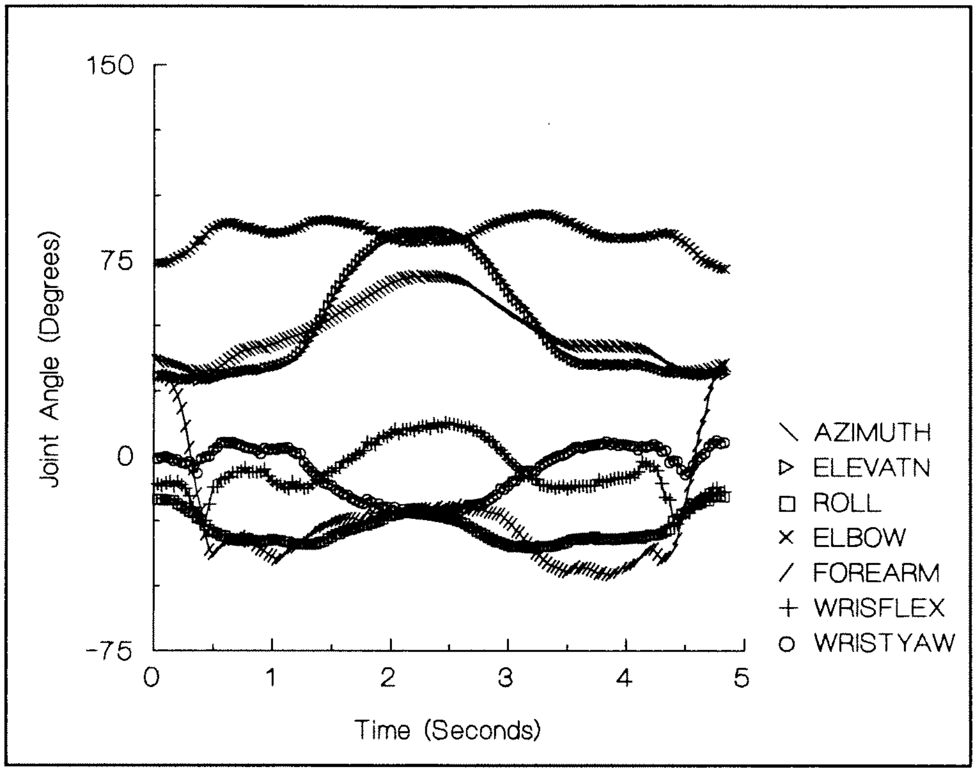

Figure H-11: Pouring from a Pitcher

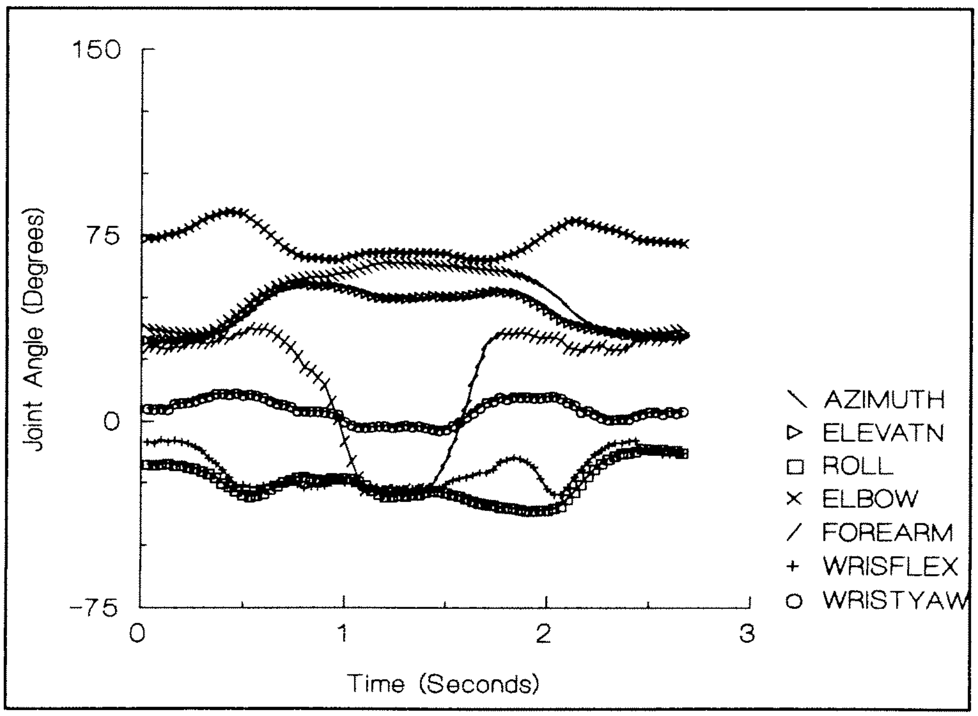

Figure H-12: Reaching for and Rotating a Door Lever

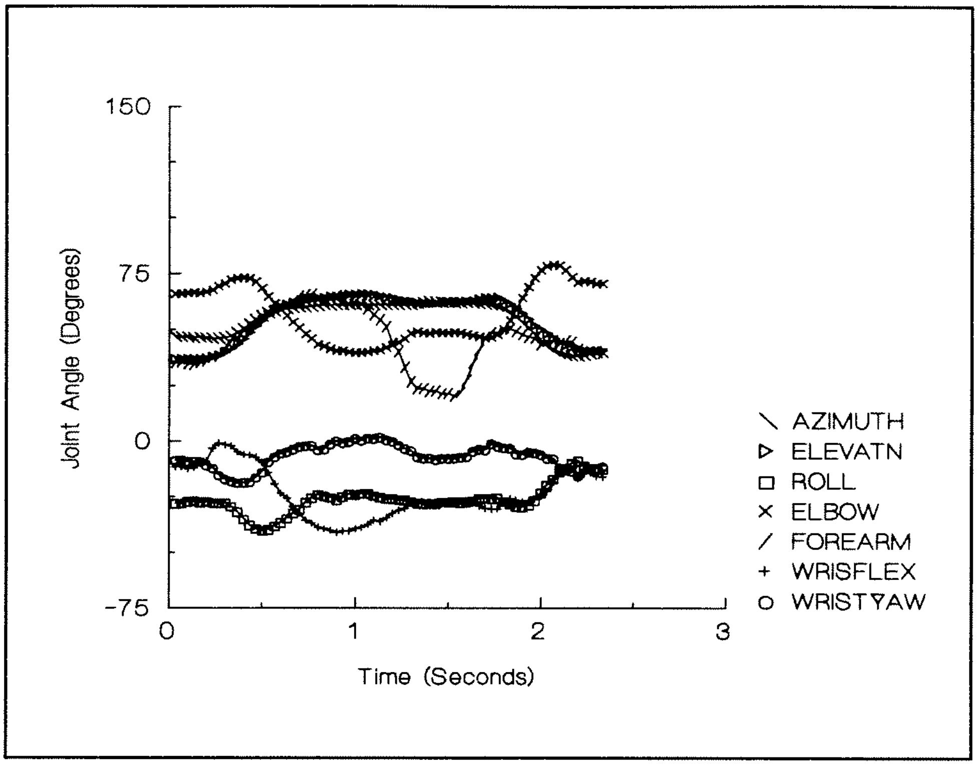

Figure H-13: Reaching for and Rotating a Door Knob

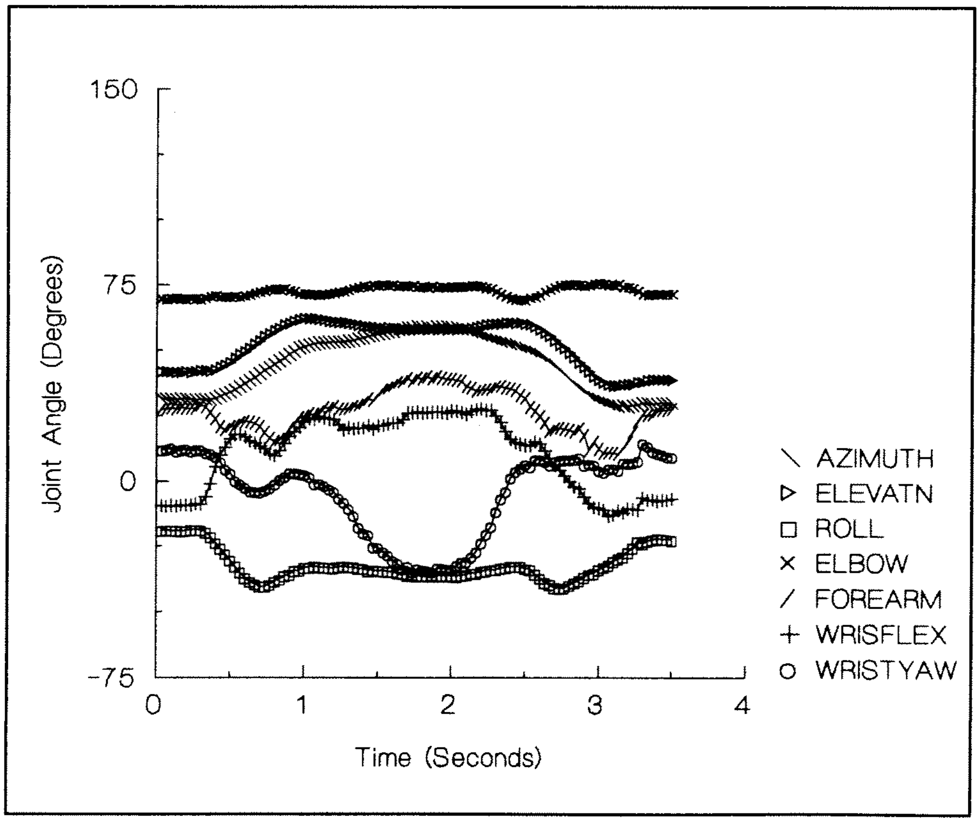

Figure H-14: Turning a Tap Lever

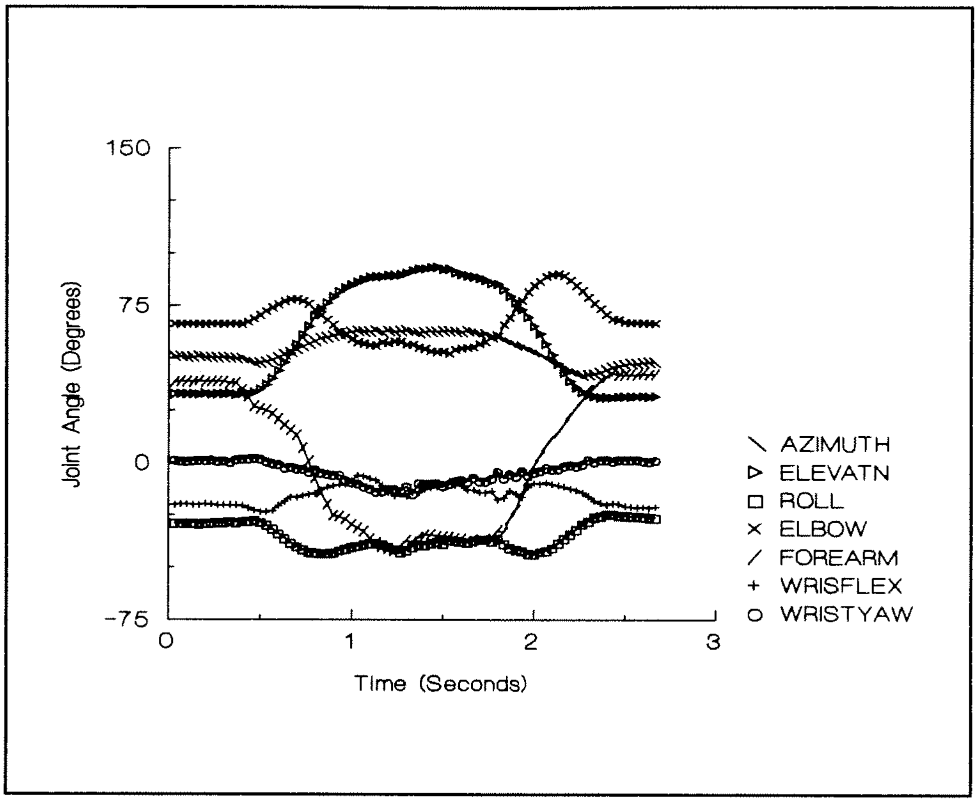

Figure H-15: Flipping a Light Switch

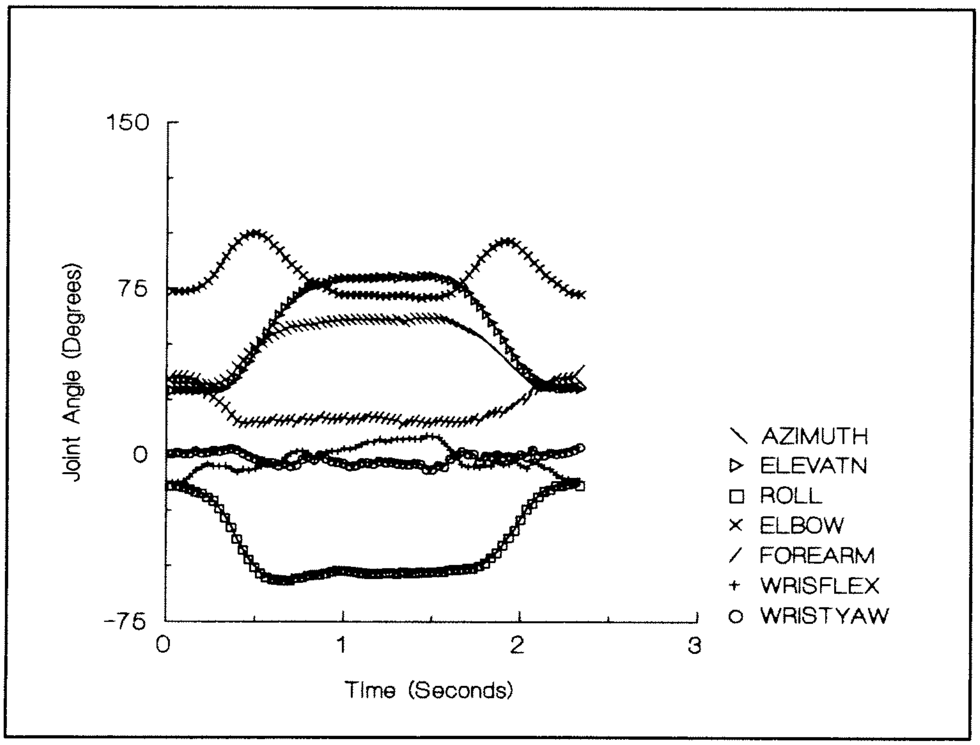

Figure H-16: Pointing to a Button

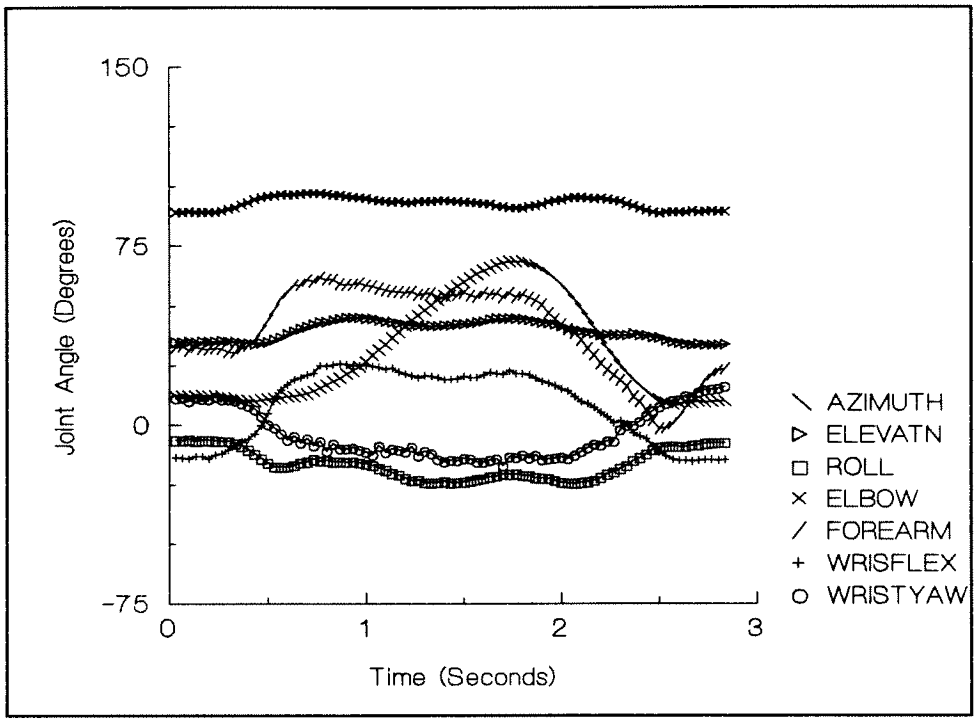

Figure H-17: Turning a Page

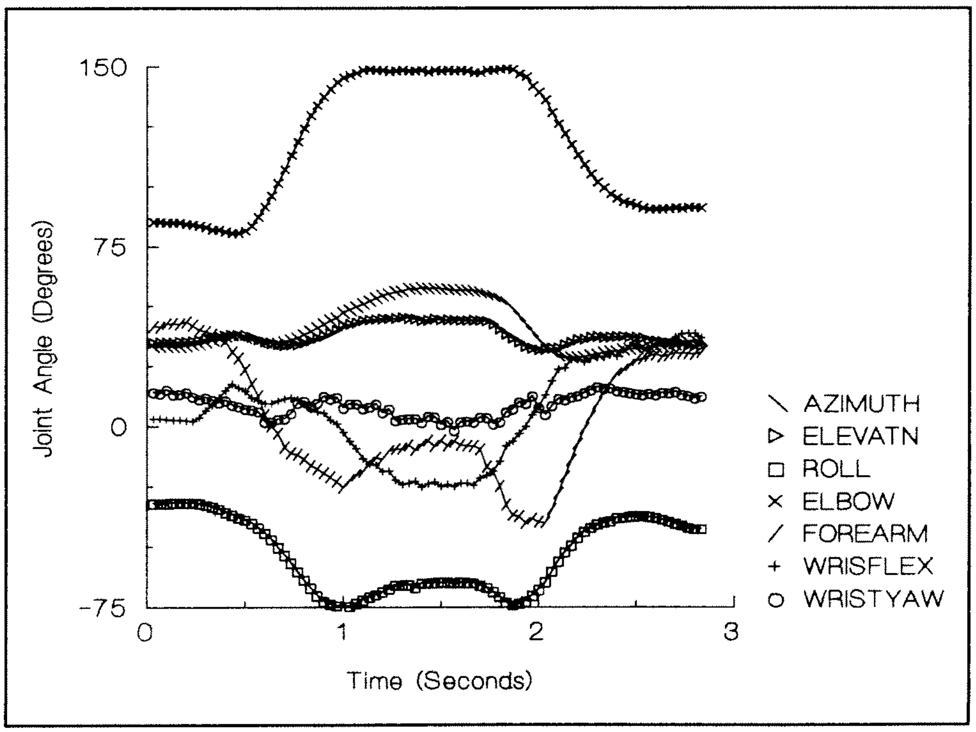

Figure H-18: Lifting a Phone Receiver

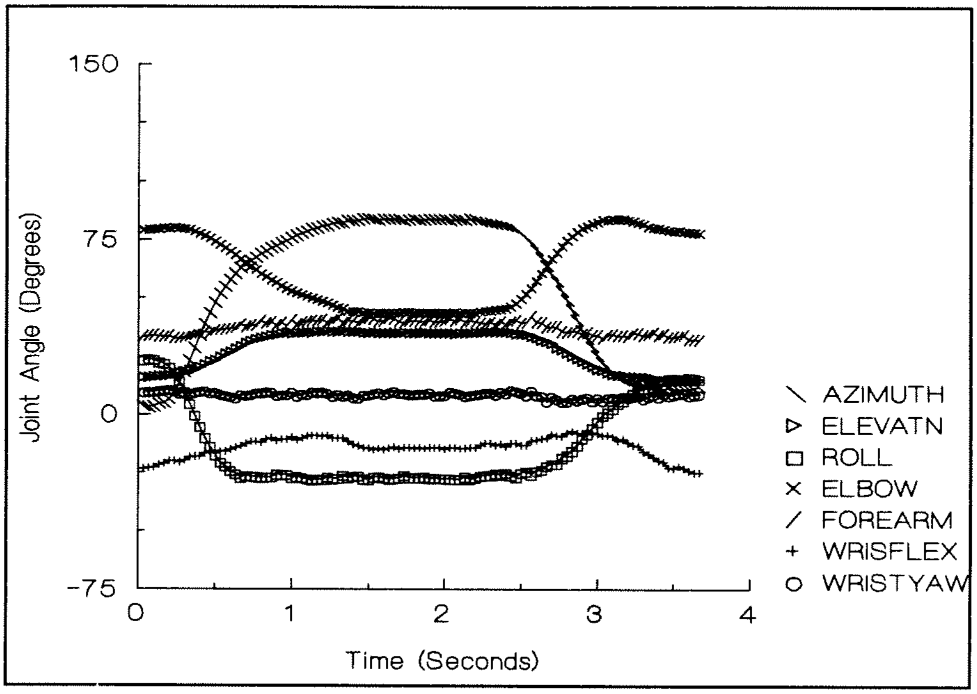

Figure H-19: Reaching to the Lap

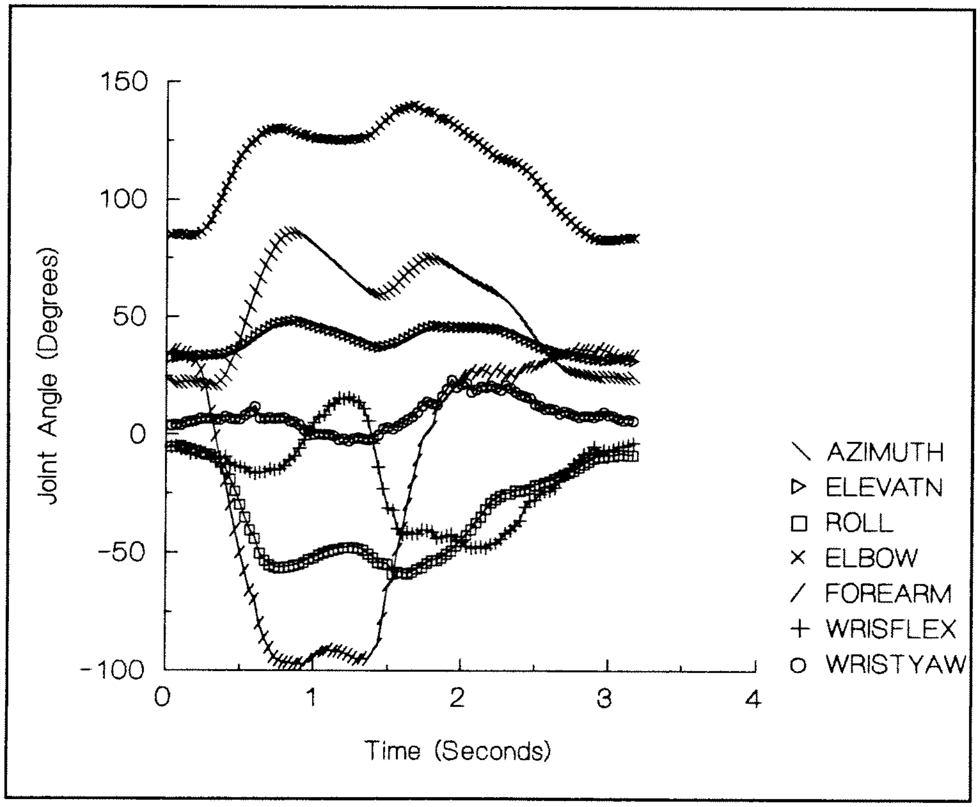

Figure H-20: Washing the Face

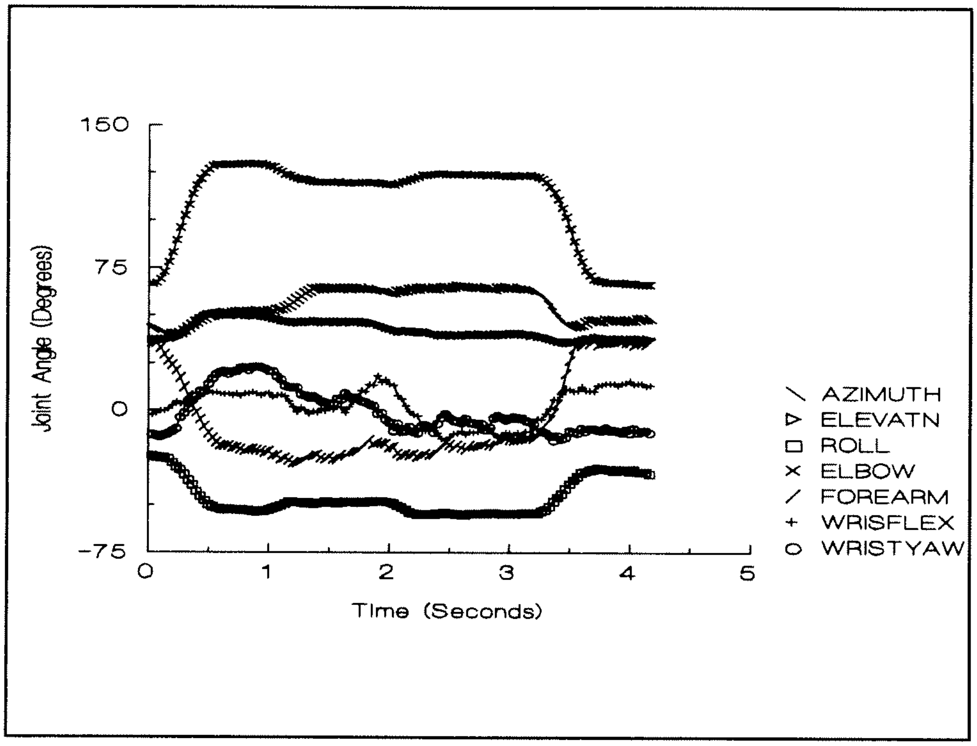

Figure H-21: Brushing the Teeth

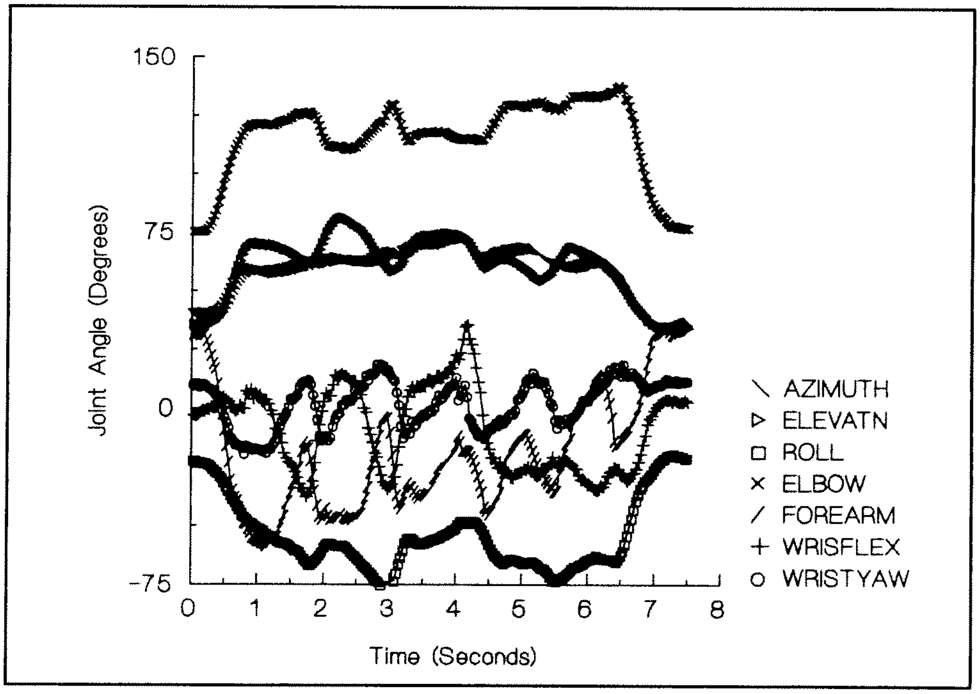

Figure H-22: Combing the Hair

Appendix I: Summary Table of Motion Analysis Results, All Subjects

Table I-1 gives the average minimum and average maximum of each joint angle for each task for all subjects, as found in the motion analysis study performed for this research. The standard deviation of these averages is included. The overall minimum, maximum and average standard deviation for each joint angle is given as well. A summary table is shown in Section 4.5.3.

	AZIMUTH				ELEVATION				ROLL				E-FLEX				F-ROTN				W-FLEX				W-YAW			
	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev	Avg Min	Std dev	Avg Max	Std Dev
HANDS	39	8.0	65	6.5	33	3.1	47	5.6	-49	9.8	0	5.9	67	5.5	134	5.1	-70	16.5	36	9.9	-18	6.3	12	4.9	-12	9.7	10	6.0
FORK	32	6.6	49	8.9	34	4.9	54	8.1	-40	18.2	1	10.4	73	4.3	129	7.4	-37	6.6	50	12.6	-6	12.7	35	28.2	-13	11.6	10	6.6
SPOON	34	8.6	54	10.0	32	2.6	76	4.9	-61	12.6	-4	11.1	75	5.5	123	9.1	-24	9.7	57	12.6	-7	8.6	53	16.0	-7	10.7	17	2.7
CUP	37	12.2	56	11.4	32	3.6	63	5.2	-62	6.6	-21	10.4	68	7.4	136	7.6	-14	17.5	37	9.4	-24	4.4	16	7.9	-11	5.7	8	5.6
RCH1A	7	10.3	40	8.6	29	4.9	35	7.1	-38	12.7	-23	8.9	71	2.4	84	3.1	-24	6.8	-11	8.4	-30	6.0	-6	5.2	-7	6.3	9	6.9
RCH2A	38	6.8	76	4.9	31	4.7	39	5.2	-32	8.1	-19	6.5	66	4.1	78	2.5	-26	8.0	-15	9.7	-32	8.2	-19	6.6	-2	5.6	4	4.8
RCH3A	35	5.9	108	5.1	30	5.1	42	3.8	-33	6.8	-20	5.5	57	4.8	81	2.6	-29	8.2	-15	8.6	-33	8.3	-15	6.2	-2	5.9	5	5.3
RCH1B	8	7.1	43	7.6	31	7.6	36	7.2	-28	4.7	-17	4.2	67	3.8	80	4.4	42	5.6	49	6.7	-17	9.8	-5	13.2	-1	5.6	7	5.1
RCH2B	40	6.1	80	4.7	32	6.4	40	5.4	-27	5.3	-19	3.7	64	7.2	77	4.9	39	8.3	47	7.4	-13	16.6	-6	16.3	-2	5.4	4	4.7
RCH3B	38	4.5	107	7.0	32	5.1	44	3.6	-28	4.1	-19	3.6	58	6.6	79	3.9	37	7.4	47	7.8	-14	14.3	-6	14.0	-2	4.4	5	4.2
POUR	36	7.3	66	7.4	32	4.9	85	9.0	-45	7.8	-16	5.4	65	4.6	86	4.7	-49	3.6	36	7.6	-32	9.5	-1	9.7	-12	8.3	4	5.4
DOOR	39	4.9	72	6.3	34	2.4	58	2.9	-50	10.8	-20	6.5	58	6.7	78	5.5	-2	14.4	47	9.1	-32	8.6	-11	7.3	-4	4.3	11	2.8
KNOB	37	4.0	69	18.8	37	2.9	64	14.7	-45	11.3	-15	6.8	42	4.2	76	16.9	7	7.8	52	27.6	-38	9.3	-11	14.3	-10	6.4	9	10.0
TAP	33	9.9	65	4.9	34	1.9	64	5.2	-45	10.0	-17	9.5	57	9.5	77	4.0	19	6.6	48	9.6	-17	5.6	22	7.3	-39	5.8	9	4.0
LIGHT	37	9.1	69	3.4	32	1.9	96	6.1	-56	6.8	-21	7.1	45	9.9	88	4.6	-47	9.7	41	9.7	-19	7.7	3	6.5	-23	7.3	1	3.2
BTTN	39	4.9	68	5.9	31	7.7	90	1.5	-57	5.5	-27	7.5	51	7.7	88	13.1	20	7.6	40	5.7	-19	5.5	2	4.5	-8	3.5	2	4.5
PAGE	7	6.2	73	7.3	30	2.7	45	6.8	-26	6.4	-4	3.4	86	3.2	98	2.2	42	8.0	61	6.4	-13	7.1	30	15.6	-23	9.3	14	8.1
PHONE	36	6.5	71	7.6	35	2.5	53	6.5	-82	16.1	-26	9.1	74	6.5	151	14.5	-26	18.5	48	6.4	-32	7.8	9	16.1	-14	9.9	11	7.1
LAP	7	23.2	81	5.6	15	3.3	34	3.5	-31	7.3	20	24.8	49	6.6	84	6.5	31	13.3	45	10.6	-30	5.3	2	13.9	-0	6.8	10	5.0
WASH	32	8.3	86	8.2	28	3.6	51	6.6	-75	18.3	-18	7.9	73	10.9	148	12.8	-86	17.7	50	7.0	-42	9.6	14	6.4	-19	10.0	15	8.0
BRUSH	35	5.0	68	11.4	34	3.2	69	11.6	-78	16.0	-22	7.8	72	5.4	146	10.3	-46	13.9	41	5.1	-32	17.2	39	18.7	-22	9.9	17	3.4
COMB	35	5.7	86	16.1	31	4.5	77	8.5	-85	11.9	-13	16.3	71	6.4	143	10.7	-52	25.8	47	9.1	-35	8.2	36	16.6	-18	8.1	24	9.7
EXTREM.	*7*		*108*		*15*		*96*		*-85*		*20*		*42*		*151*		*-86*		*61*		*-42*		*53*		*-39*		*24*	
AVG SD		*7.8*		*8.1*		*4.1*		*6.3*		*9.9*		*8.3*		*6.1*		*7.1*		*11.0*		*9.4*		*8.9*		*11.6*		*7.3*		*5.6*

Table I-1: Motion Analysis Results, All Subjects

Appendix J: Conversion of Shoulder Joint Angles from UM to UBC

The University of Manitoba [102, 103, 104] expressed the three shoulder degrees of freedom as Flexion-Abduction-Rotation whereas the present study at the University of British Columbia uses Azimuth-Elevation-Roll, as explained in Section 4.3.1. This Appendix presents the conversion that was performed to allow the UM results to be compared to the UBC results in Section 4.5.4 of this thesis.

The formulation used for this study (detailed in Section 5.2) was:

$$\begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 \\ \sin\theta_1 & 0 & -\cos\theta_1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \cos\theta_2 & 0 & -\sin\theta_2 \\ \sin\theta_2 & 0 & \cos\theta_2 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \cos\theta_3 & 0 & \sin\theta_3 \\ \sin\theta_3 & 0 & -\cos\theta_3 \\ 0 & 1 & 0 \end{bmatrix}$$

Multiplying this out, it becomes:

$$\begin{bmatrix} \cos\theta_1\cos\theta_2\cos\theta_3 - \sin\theta_1\sin\theta_3 & -\cos\theta_1\sin\theta_2 & \cos\theta_1\cos\theta_2\sin\theta_3 + \sin\theta_1\cos\theta_3 \\ \sin\theta_1\cos\theta_2\cos\theta_3 + \cos\theta_1\sin\theta_3 & -\sin\theta_1\sin\theta_2 & \sin\theta_1\cos\theta_2\sin\theta_3 - \cos\theta_1\cos\theta_3 \\ \sin\theta_2\cos\theta_3 & \cos\theta_2 & \sin\theta_2\sin\theta_3 \end{bmatrix}$$

The University of Manitoba formulation of flexion-abduction-rotation corresponds to the same axis rotations as the above formulation except that the arm is first rotated down by 90 degrees. The first rotation for the present study is about a vertical axis, starting with the arm horizontally out to the side, whereas the first rotation for the UM study was about a horizontal axis, starting with the arm vertically down. The above matrix is therefore premultiplied by the following rotation matrix:

$$\begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix}$$

To give:

$$\begin{bmatrix} \sin\alpha_2\cos\alpha_3 & \cos\alpha_2 & \sin\alpha_2\sin\alpha_3 \\ \sin\alpha_1\cos\alpha_2\cos\alpha_3 + \cos\alpha_1\sin\alpha_3 & -\sin\alpha_1\sin\alpha_2 & \sin\alpha_1\cos\alpha_2\sin\alpha_3 - \cos\alpha_1\cos\alpha_3 \\ -\cos\alpha_1\cos\alpha_2\cos\alpha_3 + \sin\alpha_1\sin\alpha_3 & \cos\alpha_1\sin\alpha_2 & -\cos\alpha_1\cos\alpha_2\sin\alpha_3 - \sin\alpha_1\cos\alpha_3 \end{bmatrix}$$

where α represents the UM angles and θ represents the UBC angles.

Thus, individual elements of the UM matrix and the UBC matrix can be compared.

From the 3rd row, 2nd column:

$$\begin{aligned} \cos\theta_2 &= \cos\alpha_1\sin\alpha_2 \\ \theta_2 &= \arccos(\cos\alpha_1\sin\alpha_2) \\ \textit{elevation} &= \arccos[\cos(\textit{flexion})\cdot\sin(\textit{abduction}+\frac{\pi}{2})] \end{aligned}$$

From the 3rd row, 3rd column:

$$\begin{aligned} \sin\theta_2\sin\theta_3 &= -\cos\alpha_1\cos\alpha_2\sin\alpha_3 - \sin\alpha_1\cos\alpha_3 \\ \theta_3 &= \arcsin\left[\frac{-\cos\alpha_1\cos\alpha_2\sin\alpha_3 - \sin\alpha_1\cos\alpha_3}{\sin\theta_2}\right] \end{aligned}$$

$$\textit{roll} = \arcsin\left[\frac{-\cos(\textit{flexion})\cdot\cos(\textit{abduction}+\frac{\Pi}{2})\cdot\sin(\textit{rotation}) - \sin(\textit{flexion})\cdot\cos(\textit{rotation})}{\sin(\textit{elevation})}\right]$$

And from the 1st row, 2nd column:

$$-\cos\theta_1 \sin\theta_2 = \cos\alpha_2$$

$$\theta_1 = \arccos\left[\frac{-\cos\alpha_2}{\sin\theta_2}\right]$$

$$azimuth = \arccos\left[\frac{-\cos(abduction + \frac{\Pi}{2})}{\sin(elevation)}\right]$$

Appendix K: Simulation Values

The values of the joint limits used in the orthosis simulations are listed in Table K-1. They are approximately equal to the anatomical joint limits compiled by Boone [11].

Degree of Freedom	Minimum Angle	Maximum Angle
Azimuth	-10°	140°
Elevation	0°	120°
Roll	-90°	70°
Elbow Flexion	0°	160°
Forearm Rotation	-85°	75°
Wrist Flexion	-75°	75°
Wrist Yaw	-36°	22°

Table K-1: Joint Limit Values

The value of the minimum and maximum carrying angle is unimportant as long as the minimum value is set equal to the maximum value to indicate that it is fixed at the value of the initial estimate.

The initial joint angle estimates were derived from the motion analysis results as an average of all subjects. If an individual's position or orientation were significantly different from the others, the values were excluded from the average. The initial joint angle estimates that were used in the simulations are given in Table K-2. See Table 5-3 for a description of the task abbreviations.

Task	Azim.	Elev.	Roll	Carry	Elbow	F. Rot'n	W. Flex	W. Yaw
H1	48.0	38.5	-0.4	13.3	96.6	27.7	6.1	4.2
H2	62.8	43.2	-44.9	13.3	134.1	-70.7	-9.6	-12.3
F1	40.7	56.6	2.6	13.3	109.5	50.2	29.4	-4.3
F2	44.4	45.9	-36.4	13.3	133.5	-31.0	16.8	-2.2
S1	46.1	56.6	-12.0	13.3	106.4	47.6	14.8	12.7
S2	47.2	74.3	-51.6	13.3	122.8	-18.3	39.9	7.0
Cu1	51.9	50.7	-49.5	13.3	134.6	0.5	-8.7	-4.8
Cu2	54.8	63.2	-61.6	13.3	133.3	8.7	-7.7	-0.1
R1A	6.8	31.0	-29.0	13.3	73.0	-16.5	-11.8	7.8
R2A	73.0	37.9	-21.9	13.3	66.8	-22.9	-29.1	1.4
R3A	107.8	41.2	-26.3	13.3	57.5	-21.5	-28.7	4.2
R1B	9.4	32.1	-25.7	13.3	70.1	46.1	-15.4	4.0
R2B	80.1	38.1	-25.8	13.3	64.4	43.1	-11.7	-0.6
R3B	107.1	42.3	-24.9	13.3	58.1	39.7	-12.5	0.4
Po	64.7	85.3	-18.4	13.3	71.2	-25.0	-10.0	-10.1
D1	61.9	56.9	-32.7	13.3	59.2	28.8	-23.3	3.4
D2	71.5	48.4	-48.5	13.3	61.5	-2.1	-26.5	-1.0
K1	64.2	63.4	-31.4	13.3	41.6	48.0	-35.5	2.8
K2	68.2	58.8	-41.8	13.3	48.0	10.3	-26.8	-7.1
T1	56.0	62.9	-22.0	13.3	61.9	35.9	1.1	0.4
T2	66.4	54.9	-35.9	13.3	66.9	46.9	14.4	-35.6
Li	67.8	96.4	-50.5	13.3	47.2	-43.6	-5.1	-17.0
Bu	66.9	90.0	-46.0	13.3	51.4	22.9	-0.2	-2.4
Pa	73.1	43.8	-20.7	13.3	87.3	55.5	21.7	-16.3
Ph	69.5	53.4	-77.1	13.3	149.8	-10.6	-30.3	-8.7
La	80.5	33.5	-26.3	13.3	49.3	40.0	-7.3	3.8
W1	84.4	48.9	-60.1	13.3	132.3	-82.6	-1.4	-6.1
W2	72.3	48.9	-73.2	13.3	149.4	-28.0	-31.0	-5.2
Br1	53.4	63.7	-61.1	13.3	135.8	-45.7	21.3	-4.1
Br2	54.2	57.0	-54.2	13.3	129.2	-43.6	22.4	-10.0
Co1	71.6	80.3	-54.4	13.3	108.2	-36.2	13.3	5.7
Co2	62.1	63.9	-63.8	13.3	125.9	-18.0	-25.1	-0.2
St1	43.8	36.6	-24.2	13.3	67.9	29.8	-14.0	-1.0
St2	43.4	35.5	-31.2	13.3	72.7	35.6	-1.3	4.1

Table K-2: Initial Joint Angle Esimates

The limb lengths used in the simulations were also based on the average of all subjects:

Upper arm: 26.9 cm
Forearm: 25.3 cm
'Hand': 7.2 cm (wrist to knuckle)

The desired endpoint positions, relative to the shoulder, are given in Table K-3.

Task	Desired X Coord (+ = to the right)	Desired Y Coord (+ = forward)	Desired Z Coord (+ = up)
H1	-14.2	31.4	-19.9
H2	-11.9	21.7	2.8
F1	-9.4	31.2	-15.0
F2	-7.5	22.1	-0.4
S1	-8.6	32.9	-9.5
S2	-6.4	23.0	11.4
Cu1	-5.1	21.0	6.9
Cu2	-4.3	18.0	12.5
R1A	30.4	28.2	-21.9
R2A	-11.6	43.9	-22.1
R3A	-34.0	36.0	-22.3
R1B	27.6	31.3	-21.4
R2B	-17.9	41.8	-22.0
R3B	-35.2	33.0	-21.9
Po	-8.7	47.5	10.1
D1	2.9	51.1	-5.6
D2	2.5	51.0	-9.2
K1	7.5	52.7	-4.6
K2	8.0	53.6	-6.5
T1	3.4	51.1	-6.6
T2	1.3	51.5	-7.5
Li	7.1	48.7	27.3
Bu	4.6	48.4	23.5
Pa	-18.7	37.4	-13.9
Ph	-2.5	12.4	9.4
La	-13.7	43.5	-31.9
W1	-14.8	18.6	6.6
W2	-3.8	14.6	8.4
Br1	-6.9	17.9	9.7
Br2	-7.8	22.3	7.5
Co1	-14.3	23.0	20.5
Co2	-2.6	21.8	16.9
St1	8.1	43.6	-21.6
St2	8.2	41.9	-19.7

Table K-3: Desired Endpoint Positions

The values for the orientation vectors, relative to the fixed frame of reference, as well as the weightings are given in Table K-4.

Task	'Up' vector	Wt	'Forward' Vector	Wt	'Palm' Vector	Wt
H1	(-0.508, -0.808, 0.170)	.05	(-0.818, 0.540, -0.030)	.05	(-0.068, -0.154, -0.935)	.10
H2	(0.520, -0.316, 0.782)	.05	(-0.705, 0.336, 0.605)	.05	(-0.454, -0.866, -0.048)	.10
F1	(-0.516, -0.688, -0.475)	.10	(-0.641, 0.699, -0.315)	.05	(0.549, 0.142, -0.802)	.05
F2	(0.030, -0.830, 0.487)	.10	(-0.818, 0.256, 0.437)	.05	(-0.487, -0.411, -0.671)	.05
S1	(-0.400, -0.734, -0.550)	.10	(-0.844, 0.514, -0.072)	.05	(0.335, 0.435, -0.824)	.05
S2	(-0.179, -0.945, -0.170)	.10	(-0.963, 0.152, 0.095)	.05	(-0.064, 0.180, -0.937)	.05
Cu1	(-0.389, -0.854, 0.049)	.10	(-0.451, 0.230, 0.853)	.04	(-0.740, 0.310, -0.475)	.04
Cu2	(-0.474, -0.745, -0.334)	.10	(-0.493, -0.077, 0.859)	.04	(-0.665, 0.572, -0.331)	.04
R1A	(-0.390, 0.053, 0.900)	.10	(0.614, 0.740, 0.241)	.05	(-0.653, 0.646, -0.321)	.05
R2A	(-0.330, -0.230, 0.898)	.10	(-0.197, 0.936, 0.197)	.05	(-0.886, -0.111, -0.354)	.05
R3A	(-0.197, -0.385, 0.885)	.10	(-0.607, 0.753, 0.213)	.05	(-0.743, -0.504, -0.389)	.05
R1B	(-0.917, 0.377, 0.045)	.10	(0.371, 0.888, 0.232)	.05	(0.047, 0.229, -0.954)	.05
R2B	(-0.764, -0.632, 0.008)	.10	(-0.618, 0.748, 0.165)	.05	(-0.110, 0.120, -0.961)	.05
R3B	(-0.438, -0.890, 0.003)	.10	(-0.872, 0.431, 0.147)	.05	(-0.132, 0.062, -0.964)	.05
Po	(-0.670, -0.578, 0.417)	.08	(-0.404, 0.785, 0.414)	.07	(-0.566, 0.108, -0.759)	.07
D1	(-0.931, -0.319, 0.081)	.10	(-0.211, 0.783, 0.567)	.05	(-0.244, 0.510, -0.796)	.05
D2	(-0.567, -0.271, 0.760)	.08	(0.174, 0.860, 0.446)	.05	(-0.774, 0.385, -0.441)	.05
K1	(-0.928, -0.086, -0.283)	.05	(-0.245, 0.722, 0.620)	.05	(0.151, 0.644, -0.691)	.10
K2	(-0.825, -0.042, 0.515)	.05	(0.248, 0.832, 0.449)	.05	(-0.447, 0.498, -0.676)	.10
T1	(-0.905, -0.265, -0.222)	.10	(-0.326, 0.919, 0.151)	.05	(0.164, 0.209, -0.981)	.05
T2	(-0.944, 0.281, 0.020)	.10	(0.285, 0.943, 0.144)	.05	(0.022, 0.141, -0.971)	.05
Li	(-0.193, -0.485, 0.808)	.05	(0.028, 0.826, 0.523)	.05	(-0.922, 0.123, -0.145)	.10
Bu	(-0.963, -0.208, 0.056)	.05	(-0.114, 0.721, 0.664)	.10	(-0.179, 0.633, -0.718)	.05
Pa	(-0.797, -0.499, -0.242)	.05	(-0.523, 0.828, -0.031)	.05	(0.215, 0.102, -0.921)	.10
Ph	(-0.145, -0.941, -0.197)	.10	(0.051, -0.201, 0.962)	.05	(-0.945, 0.129, 0.077)	.05
La	(-0.831, -0.521, 0.109)	.05	(-0.535, 0.821, -0.126)	.05	(-0.024, -0.163, -0.961)	.10
W1	(0.671, -0.068, 0.633)	.05	(-0.684, -0.015, 0.705)	.05	(-0.038, -0.906, -0.056)	.10
W2	(0.226, -0.901, -0.013)	.05	(0.007, 0.012, 0.979)	.05	(-0.881, -0.221, 0.009)	.10
Br1	(0.131, -0.897, 0.204)	.10	(-0.840, -0.083, 0.451)	.05	(-0.388, -0.239, -0.764)	.05
Br2	(0.106, -0.874, 0.456)	.10	(-0.848, -0.117, 0.444)	.05	(-0.441, -0.433, -0.729)	.05
Co1	(0.252, -0.954, 0.103)	.10	(-0.754, -0.134, 0.620)	.05	(-0.578, -0.234, -0.753)	.05
Co2	(-0.127, -0.983, -0.033)	.10	(-0.121, -0.009, 0.990)	.05	(-0.973, 0.129, -0.117)	.05
St1	(-0.950, -0.105, 0.237)	.05	(-0.061, 0.965, 0.207)	.05	(-0.250, 0.183, -0.923)	.05
St2	(-0.938, -0.217, 0.197)	.10	(-0.214, 0.940, 0.122)	.05	(-0.197, 0.076, -0.931)	.05

Table K-4: Desired Orientation Vectors and Weighting

The detailed results for the two recommended alternatives are given below. Tables K-5 and K-7 give the distances and angles between the actual and desired endpoint positions and orientations at the final point. Tables K-6 and K-8 give the joint angles at the final position.

If the cost function value had a value less than 6.0 or ten iterations had been exceeded, the search was terminated.

Task	Successful?	Distance (cm)	Up Angle (Degrees)	Forward Angle (Degrees)	Palm Angle (Degrees)	Cost Function Value (cm^2)
H1	Y	1.3	3	5	5	5.31
H2	Y	1.1	2	2	2	1.47
F1	Y	1.0	2	1	2	1.19
F2	Y	1.2	5	4	6	5.42
S1	C	2.8	11	11	3	23.43
S2	Y	2.5	7	5	6	12.87
Cu1	Y	1.2	5	5	6	5.32
Cu2	Y	1.2	5	5	5	5.45
R1A	Y	2.8	10	10	6	21.88
R2A	Y	1.8	7	7	5	9.99
R3A	Y	2.4	8	8	5	15.97
R1B	Y	1.7	6	6	3	8.19
R2B	Y	1.6	4	3	4	5.14
R3B	Y	0.9	1	5	6	3.32
Po	N	5.7	2	3	4	34.39
D1	Y	2.1	6	5	3	8.61
D2	Y	1.8	3	2	3	4.01
K1	N	3.4	9	8	4	18.61
K2	Y	1.9	2	2	3	4.69
T1	Y	2.6	7	8	2	13.30
T2	C	2.4	13	12	4	30.07
Li	N	19.3	20	20	6	415.04
Bu	N	16.1	3	3	2	265.20
Pa	C	2.9	16	16	4	33.98
Ph	Y	0.3	2	3	4	1.28
La	Y	1.1	4	3	3	2.43
W1	Y	0.9	5	2	6	5.13
W2	Y	1.2	6	3	6	6.08
Br1	Y	0.9	5	3	7	5.65
Br2	Y	0.5	6	9	4	7.48
Co1	N	6.6	2	7	7	50.40
Co2	Y	1.8	3	3	3	4.59
St1	Y	1.7	4	2	4	4.08
St2	Y	1.2	4	6	7	5.84

Table K-5: Actual vs. Desired Values for Fixed Elevation and Wrist Yaw

Task	Azim.	Elev.	Roll	Carry	Elbow	F. Rotn	W. Flex	W. Yaw
H1	48	53	9	13	98	13	1	-2
H2	54	53	-30	13	133	-73	-14	-2
F1	40	53	1	13	109	51	29	-2
F2	32	53	-27	13	137	-39	10	-2
S1	41	53	-4	13	113	53	14	-2
S2	80	53	-89	13	132	-9	74	-2
Cu1	37	53	-41	13	138	-6	-12	-2
Cu2	55	53	-63	13	141	12	-8	-2
R1A	-5	53	8	13	83	-43	-39	-2
R2A	68	53	3	13	68	-45	-42	-2
R3A	106	53	-6	13	54	-40	-37	-2
R1B	3	53	9	13	67	17	-30	-2
R2B	77	53	3	13	55	16	-24	-2
R3B	108	53	-1	13	46	18	-20	-2
Po	95	53	-84	13	85	33	23	-2
D1	65	53	-40	13	62	35	-20	-2
D2	72	53	-46	13	55	-3	-25	-2
K1	67	53	-50	13	55	64	-27	-2
K2	79	53	-70	13	49	34	-18	-2
T1	61	53	-38	13	68	50	7	-2
T2	87	53	-80	13	51	71	6	-2
Li	82	53	-91	13	92	-6	4	-2
Bu	79	53	-83	13	96	56	15	-2
Pa	69	53	-15	13	83	42	16	-2
Ph	48	53	-56	13	151	-10	-42	-2
La	84	53	30	13	30	-15	-28	-2
W1	71	53	-45	13	134	-85	-3	-2
W2	53	53	-52	13	151	-28	-45	-2
Br1	54	53	-65	13	139	-43	32	-2
Br2	52	53	-52	13	130	-43	29	-2
Co1	106	53	-92	13	122	-12	39	-2
Co2	64	53	-42	13	128	5	-40	-2
St1	39	53	5	13	62	3	-29	-2
St2	31	53	4	13	73	7	-13	-2

Table K-6: Resulting Joint Angles for Fixed Elevation and Wrist Yaw

Task	Successful ?	Distance (cm)	Up Angle (Degrees)	Forward Angle (Degrees)	Palm Angle (Degrees)	Cost Function Value (cm^2)
H1	Y	1.4	4	6	4	5.83
H2	Y	0.8	5	5	2	3.32
F1	N	4.1	10	21	19	63.37
F2	Y	1.0	5	5	6	5.77
S1	Y	1.2	3	7	6	5.93
S2	Y	2.3	7	8	5	12.61
Cu1	Y	1.1	5	3	5	4.21
Cu2	Y	1.3	4	1	4	3.30
R1A	Y	1.3	5	6	4	5.32
R2A	Y	1.1	1	6	6	4.51
R3A	Y	1.7	6	8	3	8.88
R1B	Y	0.8	2	5	5	2.70
R2B	Y	1.0	2	4	4	2.02
R3B	Y	1.7	1	4	4	4.26
Po	Y	2.0	7	8	4	11.33
D1	Y	1.7	4	8	7	10.00
D2	Y	0.6	4	7	7	5.57
K1	N	3.4	5	14	13	36.67
K2	Y	1.0	5	6	6	7.04
T1	Y	0.8	4	6	8	5.76
T2	N	6.0	13	13	4	58.34
Li	Y	1.5	7	5	5	7.26
Bu	Y	2.6	1	2	2	8.99
Pa	N	4.8	12	20	17	75.40
Ph	Y	0.9	3	9	9	9.37
La	Y	2.3	3	3	2	5.98
W1	Y	1.0	5	3	6	6.42
W2	Y	0.8	6	4	6	6.21
Br1	Y	1.7	5	8	8	10.51
Br2	C	2.0	1	16	4	17.04
Co1	Y	1.7	3	4	3	4.77
Co2	Y	2.3	6	7	5	12.12
St1	Y	0.8	2	5	5	2.69
St2	Y	0.5	5	7	6	5.64

Table K-7: Actual vs. Desired Values for Fixed Wrist Flexion and Wrist Yaw

Task	Azim.	Elev.	Roll	Carry	Elbow	F. Rotn	W. Flex	W. Yaw
H1	48	48	13	13	95	20	-9	2
H2	50	46	-30	13	135	-68	-9	2
F1	38	70	17	13	100	38	-9	2
F2	31	61	-14	13	137	-32	-9	2
S1	41	76	8	13	105	36	-9	2
S2	28	109	-30	13	131	-34	-9	2
Cu1	47	42	-48	13	136	2	-9	2
Cu2	53	59	-61	13	134	8	-9	2
R1A	6	29	-31	13	76	-18	-9	2
R2A	86	30	-54	13	66	-6	-9	2
R3A	133	37	-78	13	52	7	-9	2
R1B	10	33	-26	13	72	46	-9	2
R2B	79	38	-26	13	64	43	-9	2
R3B	107	42	-25	13	58	40	-9	2
Po	68	88	-15	13	61	-28	-9	2
D1	68	54	-47	13	63	38	-9	2
D2	87	49	-79	13	55	19	-9	2
K1	66	57	-50	13	59	60	-9	2
K2	86	58	-89	13	44	48	-9	2
T1	57	64	-19	13	56	36	-9	2
T2	89	67	-74	13	22	69	-9	2
Li	66	109	-10	13	29	-85	-9	2
Bu	71	100	-28	13	33	9	-9	2
Pa	75	41	-24	13	72	54	-9	2
Ph	74	35	-91	13	155	-14	-9	2
La	80	33	-26	13	48	40	-9	2
W1	69	55	-42	13	136	-86	-9	2
W2	80	30	-89	13	151	-32	-9	2
Br1	37	84	-42	13	142	-53	-9	2
Br2	40	81	-31	13	135	-54	-9	2
Co1	65	95	-43	13	114	-46	-9	2
Co2	85	38	-76	13	133	4	-9	2
St1	43	37	-25	13	67	30	-9	2
St2	40	37	-24	13	72	35	-9	2

Table K-8: Resulting Joint Angles for Fixed Wrist Flexion and Wrist Yaw