# A Functional Task Analysis and Motion Simulation for the Development of a Powered Upper-Limb Orthosis

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***Abstract*—This paper describes research work directed towards the development and application of a design methodology to determine the optimal configuration of a powered upper-limb orthosis. The design objective was to minimize the orthosis complexity, defined as the number of degrees of freedom, while maintaining the ability to perform specific tasks. This objective was achieved in three stages. First, potential users of a powered orthosis were interviewed to determine their priority tasks. Secondly, the natural arm motions of able-bodied individuals performing the priority tasks were profiled using a video tracking system. Finally, a kinematic simulation algorithm was developed and employed in order to evaluate whether a proposed orthosis configuration could perform the priority tasks.**

**The research results indicate that task functionality is overly compromised for orthosis configurations with less than five degrees of freedom, plus prehension. Acceptable task performance, based on the specific priority tasks considered, was achieved in the simulations of two different orthosis configurations with five degrees of freedom. In the first design option, elevation (rotation about a horizontal axis through the shoulder) and radial/ulnar deviation are fixed, while in the second option wrist flexion and radial/ulnar deviation are fixed. A prototype orthosis is currently being developed using the first design option.**

## I. Introduction

A POWERED upper-limb orthosis is an exoskeleton worn on one arm by a person with severe arm muscle weakness or paralysis. A typical user of such a device has a neuromuscular disease such as poliomyelitis, muscular dystrophy or amyotrophic lateral sclerosis (ALS). Other possible candidates include people with high-level spinal cord injury, brachial plexus injury, multiple sclerosis, stroke or Charcot-Marie-Tooth disease, provided they fit the user criteria. By activating appropriate control inputs, the orthosis user directs the supported arm to perform tasks such as eating, reaching for objects, washing the facing etc.

In consultation with medical experts, the primary user characteristics assumed for this study were: 1) two flail arms, so that the orthosis is required to perform the entire task rather than acting as a secondary support, 2) loss of grasping ability, 3) full sensation of temperature, pressure and touch, both for safety reasons and because this makes it worthwhile to move the user's own arm, 4) ambulatory, such that the orthosis is expected to be worn by the user, although the user may employ a wheelchair, and 5) no spasticity, which could result in injury to the user or damage to the device. The primary goal is that, through the use of an orthosis, the user will regain a degree of independence through the performance of a variety of daily-living tasks.

A significant problem in design is to produce a device that is acceptable to users and can be manufactured with reasonable expertise and expense. In general, previous orthoses were either too complex, both mechanically and from a control point-of-view, or lacked function [1]–[7]. Based on past experiences, it is clear that design compromises are necessary to meet the requirements of both user acceptance and task functionality. Thus, the objective of this research is to develop a methodology for the design of the optimal configuration of a powered upper-limb orthosis by minimizing the complexity while maintaining acceptable function in user-defined tasks. It is believed that minimizing the number of degrees of freedom required to be controlled will reduce both the mechanical and control complexities of the device. It is also believed that a simpler device, having sufficient functionality, would be less expensive, less bulky, less prone to breakdown and more acceptable to a potential user.

The basic methodology to achieve this objective included three stages:

1) Task Analysis: identify a set of high-priority tasks for potential users;
2) Motion Analysis: obtain data on the arm motions involved in performing these tasks; and
3) Orthosis Simulations: determine which configurations are able to achieve the specified tasks, based on the motion analysis results.

This methodology was developed to fulfill several requirements essential to the successful design of any consumer product: 1) identification of consumer/user needs, 2) definition and quantification of basic required functions and their associated parameters and 3) evaluation of potential alternative conceptual solutions based on specific design requirements. The requirements with respect to an upper-limb orthosis are

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fulfilled by the three stages of work defined and allow for orthosis functionality to be evaluated prior to prototype construction. It is proposed that this methodology should form an integral part of the orthosis design process. It is clear that the resulting device configuration will also be assessed in terms of applicable control strategies, however this is beyond the scope of this paper and will be dealt with in subsequent work.

## II. Literature Review

While a review of the literature indicated that surveys of potential and current users of robotic manipulators are common for the field of rehabilitation robotics [8]–[14], it was found that interviews have not previously been conducted with potential users of a powered upper-limb orthosis. Since, with an orthosis, the user performs the tasks using his or her own arm, rather than with an independent robot, the tasks specified by potential users of an orthosis may differ from those suggested by potential users of a robot. It was therefore decided to perform our own interviews.

Of the whole-arm motion analyses that have been conducted previously [3], [15]–[24], only [19] has data on functional daily-living tasks, and it considered only eating tasks. As this review provided no data for orthosis simulation, a motion analysis was required in order to provide the motion data for the broad range of high-priority functional tasks.

A review of kinematic analyses shows that, in the past, researchers have based their designs on the priority of joint rotations or from tests with mechanical models [3], [25], [26]. An examination of the required degrees of freedom to perform high-priority tasks, however, has, to-date, never been quantified. In the current study, the quantitative evaluation allowed design options to be examined for a variety of tasks and individuals prior to prototype construction.

The remainder of this paper details the design methodology, proposes an orthosis configuration and presents some conclusions from the work.

## III. Stage 1: Task Analysis

In order to define task priorities in the current work, telephone interviews were conducted with eleven potential users, seven women and four men. Seven subjects had limb-girdle muscular dystrophy, two had ALS, one had polio and one had a C5/6 spinal cord injury. Three had no grasping ability, five had partial ability and three retained full grasping ability. The age of the subjects ranged from 27 to 65. Since the length of time since diagnosis ranged from four to 39 years, all subjects were accustomed to their disability. Four were single, one was divorced and six were married. All of the subjects lived at home. Four subjects had full-time jobs, one was a homemaker and another was retired. The other five subjects had no employment.

The interviews covered task priorities, task abilities (personal hygiene, domestic, recreational and vocational), orthosis acceptance criteria, the use of daily-living aids, medical details, living circumstances and personal data. The purpose of the interviews, in addition to determining task priorities directly from potential users, was to gather early feedback concerning the development of a powered upper-limb orthosis. The main concerns expressed by the respondents were regarding cost and aesthetics. Reliability and portability were also highlighted. Table I summarizes the responses to the question "What are the top five tasks that you would most like to do but cannot?" Detailed results can be found in [27].

TABLE I
TASK PRIORITIES FROM POTENTIAL-USER INTERVIEWS

| 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 |

Reaching and picking up objects (e.g. from a cupboard) was found to have the highest priority, concurring with the previous surveys. It was noted that the potential orthosis users gave personal hygiene a higher priority than the potential robotic manipulator users, and in most cases hobbies and crafts, one of the second highest frequency tasks, was not even mentioned in the previous surveys. It is possible that these differences occurred as it may be more personal and less intimidating to perform these tasks with an orthosis (and therefore with one's own arm) rather than with an independent robotic manipulator. In agreement with past surveys, eating and drinking were also found to have a high priority in this survey.

A selection of these tasks was studied using the motion analysis. Dressing and toileting were excluded from these orthosis design requirements for several reasons. The primary reason was that the tasks involve the use of other parts of the body in addition to the arm. Also, transferring to the toilet requires greater strength than would be found in a practical orthosis and dressing occurs only twice a day when an attendant would normally be present. While vocational tasks were not explicitly included in the task list because of the emphasis on daily-living activities, many vocational tasks would be possible in the resulting orthosis as they would involve similar arm motion to the suggested tasks. In addition to defining representative tasks for the motion analysis, the interview results will be used later to clinically evaluate the new prototype.

## IV. Stage 2: Motion Analysis

### A. Method

In order to acquire data for the orthosis simulations, the motions of six able-bodied subjects performing 22 daily-living tasks were recorded using the stereo image analysis system illustrated in Fig. 1. In order to follow the joint locations and to define the joint rotations, five markers (25 mm diameter

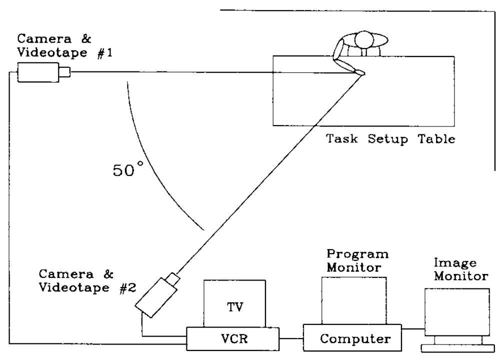


Fig. 1. Motion analysis setup.

Fig. 2. Subject performing pouring task.

white styrofoam spheres) were attached to the right arm of the subject: one at the shoulder (greater tuberosity), one at the elbow (lateral epicondyle), one at the wrist (midpoint between ulnar and radial styloids), another on an extension from the wrist and one on the hand (distal end of the third metacarpal), as shown in Figs. 2 and 3. In total, six able-bodied subjects, three male, three female, ranging in age from 22 to 44 and in height from 157 to 184 cm, participated in the study. All of the subjects were right-hand dominant.

The 22 standardized tasks included:

1) Eating & Drinking (4 tasks): with the hands/ with a fork/ with a spoon/ from a glass.
2) Reaching (6 tasks): three positions distributed along the curve of the average working envelope: at the far right of the normal working area (i), in front of the midline (ii) and in front of the left shoulder (iii) at two orientations: vertical (A) and horizontal (B).
3) Daily-Living (9 tasks): turning a page/ reaching for and turning a doorknob, a door lever and a tap lever/ pouring from a pitcher/ flipping a light switch/ pointing to a button/ lifting a phone receiver/ and reaching to the lap.
4) Personal Hygiene (3 tasks): washing the face/ combing the hair/ brushing the teeth.

The subjects were instructed to perform the tasks as naturally as possible, with two exceptions. The subject's trunk was constrained from moving forward while performing the tasks, since the defined potential orthosis user is not expected to be able to bend forward. The other distinction is that a foam handle, commonly used as a daily-living aid, was attached to all utensils. The subject therefore used the overhand cylindrical grasp for the eating tasks as opposed to the more traditional web-of-thumb grasp. This results in a different range of motion for some degrees of freedom than found by other researchers [27].

Based on motion analysis procedures similar to those previously employed at the University of Manitoba [28], software was developed to control a VCR, load and manipulate a video image, track markers between images and solve for the three-dimensional coordinates of each marker from the two video recordings. Coupled with the use of a calibration frame, the common Direct Linear Transform (DLT) method was used to convert the two sets of two-dimensional marker coordinates into three-dimensional coordinates [29]. Using these determined coordinates, the software displays stick figure diagrams of the movement and calculates the joint angles of the human arm throughout the task performance. The accuracy of the coordinates, including static and dynamic inaccuracies, was found to be $\pm 5$ mm, while the joint angle accuracy was found to be $\pm 4$ degrees. This was deemed to be sufficient for the purposes of this study.

The arm was modeled by seven active degrees of freedom: azimuth, elevation, roll, elbow flexion, forearm rotation, wrist flexion and wrist yaw. A passive degree of freedom, the carrying angle (CA), was also modeled. The angle definitions for each of these degrees of freedom and associated marker positions are shown in Fig. 3 and defined as follows. Azimuth (AZ) is rotation about a vertical axis through the shoulder with zero degrees defined as the upper arm directed towards the side, parallel to the edge of the table. Elevation (EL) is the angle of rotation up from a vertical position about a horizontal axis through the shoulder joint with zero degrees defined as the upper arm pointed straight down. Elbow flexion (EF) is defined to be zero with the arm fully extended. Roll (RL) occurs about the axis of the upper arm. At zero degrees roll, with the arm out to the side and the elbow flexed to 90 degrees, the hand points forward. The carrying angle is only defined with the arm fully extended, as the angle between the forearm and the extension of the upper arm (see Fig. 4). The subject's measured carrying angle was input into the model.

Forearm rotation (FR) occurs about the axis of the forearm (see Fig. 3). At zero degrees, the wrist marker and extension marker form a vector perpendicular to the plane of forearm movement. Conventionally, zero degrees pronation/supination is defined at only one position as the thumb facing up when the elbow is flexed by 90 degrees. In this study, the neutral position is rotated inward by the carrying angle (more pronated) because of the tilt in the plane of elbow flexion. This seems to correspond more closely with human anatomy and gives a constant definition throughout the movement. Pronation is defined here as positive forearm rotation while supination is defined here as negative. For wrist flexion (WF),

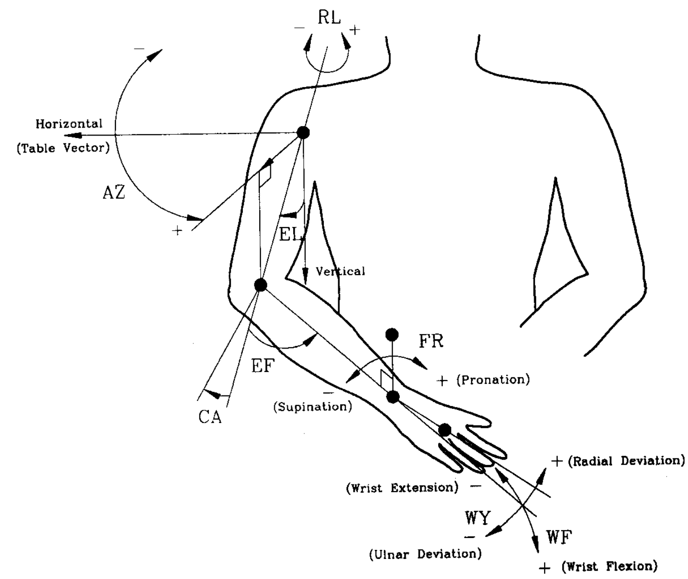


Fig. 3. Angle definitions with marker positions.

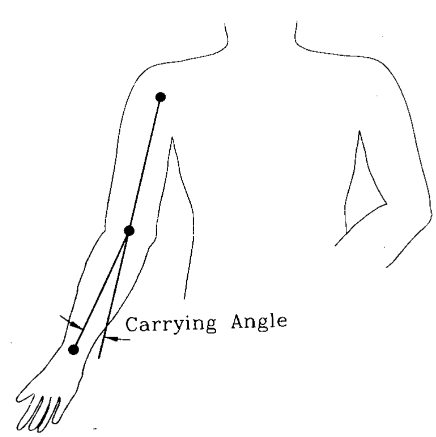


Fig. 4. Carrying angle.

a positive angle refers to wrist flexion, a negative angle to wrist extension. Positive and negative wrist yaw (WY) refer to radial and ulnar deviation respectively. In both cases, zero degrees occurs when the hand is in line with the forearm.

The analysis used in this research differs in four ways from studies performed by previous researchers:

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 as rotating the plane of elbow flexion; and
4) the marker positions were translated mathematically to the joint centres in order to improve the accuracy of the results.

Each of these differences is discussed in turn below.

The three degrees of freedom at the shoulder have traditionally been described as "flexion", "abduction" and "inward/outward rotation" (see Fig. 5(a)). In clinical terms, flexion describes rotating the arm forward, while abduction describes rotating the arm out towards the side. When abduction follows flexion, however, the axis of rotation changes. In contrast, this research uses "azimuth", "elevation" and "roll", where azimuth is rotation about a vertical axis through the shoulder, elevation is rotation about a horizontal axis through the shoulder and roll is rotation about the axis of the upper arm (see Fig. 5(b)). These definitions have only been used recently, for analyzing arm motion [18] and for orthosis design [7]. The first advantage of this definition is that the orthosis design and control is more likely to correspond to this coordinate system since it easily allows the arm to move horizontally across a table-top. The second is that, since both azimuth and elevation occur about fixed axes, the coordinates are easier to visualize.

Although the second difference, calculating the joint angles directly based on a model of the arm, is not as general as the Eulerian method, it is more consistent because the markers define a set of connected vectors and the solution is unique. Inconsistencies in the Euler angles result from inaccuracies in the axis definitions, which are based on the marker locations. Since the endpoint position calculated from inconsistent joint angles will also be inconsistent, and because the endpoint position is important for the orthosis simulations, it was decided to calculate each joint angle directly from the marker positions. Further details of these calculations can be found in reference [27].

A necessary assumption of the direct method, leading to the third difference in analysis, was to define how the carrying angle affects the plane of elbow flexion. For the purposes of this research, the carrying angle was considered constant, preceding elbow flexion in the sequence of rotations and therefore

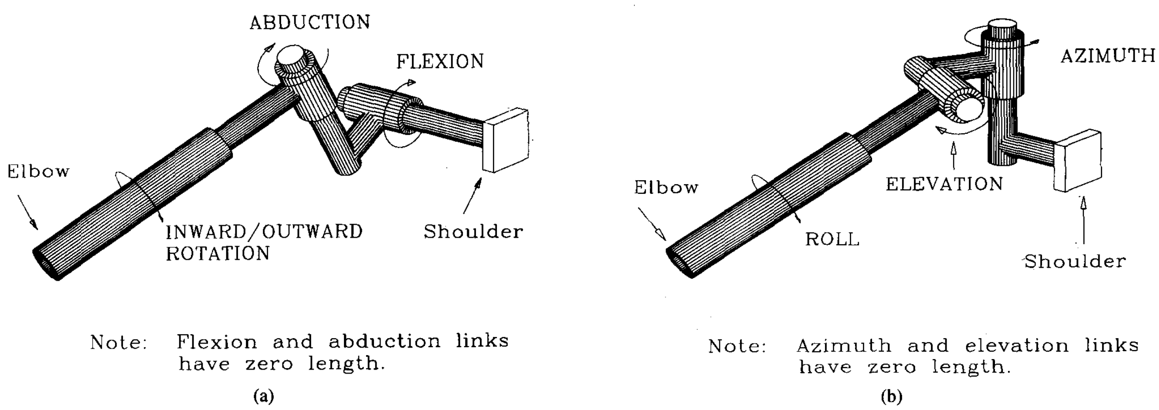


Fig. 5. (a) Flexion-abduction-rotation axis definitions. (b) Azimuth-elevation-roll axis definitions.

describing a constant tilt in the plane of elbow flexion. The only other assumptions made are that the trunk is vertical, since elevation is calculated relative to the vertical, and that the subject's body is parallel to the table, since azimuth is calculated relative to the table vector. These are reasonable assumptions since the subject's trunk is constrained.

In order to translate the marker positions to the joint centres, the translation distances were measured on each subject. This accounted for the error which would have resulted from the markers being located on the outside of the arm.

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. One subject performed each task eight times, with four trials being analyzed to examine the variability for a single individual.

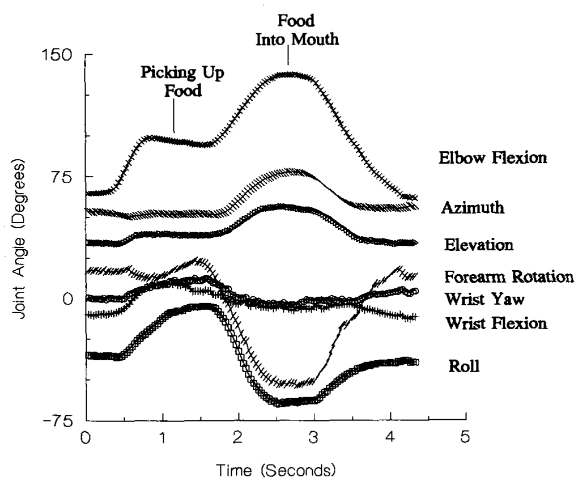


Fig. 6. Eating with the hands.

### B. Results

The data from the motion analysis were analyzed for joint angles, paths and orientations. Fig. 6, for example, shows the joint angle changes as a subject eats with the hands. Each point represents the raw data from one frame with a sampling rate of 30 frames per second. The starting position was on the table-top approximately 43 cm in front of the right shoulder. The graph shows that, in the normal execution of this task, roll increases significantly when picking up the food and decreases by an even greater amount when bringing the food to the mouth. It also shows that elbow flexion and supination (negative forearm rotation) are important for bringing the food to the mouth. The purpose of the orthosis simulations was to determine whether, if one or more of the degrees of freedom were fixed, the remaining degrees of freedom could compensate to achieve the required final endpoint position and orientation of the hand.

In order to give insight into the possibility of fixing a joint or the need to power that joint, the data were also examined joint by joint. Fig. 7 shows the average range of wrist flexion for each task. The leftmost end of each horizontal line represents the average minimum for that task, the rightmost end the average maximum; the vertical lines indicate the highest and lowest individual joint angle values for that task; the abscissa axis shows the approximate anatomical joint limits. The figure indicates that there may be the potential for reducing orthosis complexity without a major sacrifice in task performance if wrist flexion is fixed since the tasks are roughly centered around −10 degrees wrist flexion (i.e., wrist extension) and the ranges are reasonably small. The orthosis simulations were used to test the hypothesis that added motion in the remaining joints could compensate for fixing this degree of freedom. Fixing wrist yaw (radial/ulnar deviation) shows even greater potential. If either or both of the wrist rotations are fixed, the ability to orient the hand precisely for some tasks will be lost. Fortunately, orientation is not critical for most of the tasks and some of the resulting problems may be overcome through the use of special handles. Since both wrist rotations are at the end of the kinematic chain, no further joints are affected by changes at the wrist.

Since elbow flexion alone defines the distance from the shoulder to the wrist, it was deemed necessary that elbow flexion be powered. All of the tasks, except the reaching tasks, varied considerably in forearm rotation, as shown in Fig. 8. A potential simplification, used in previous orthoses,

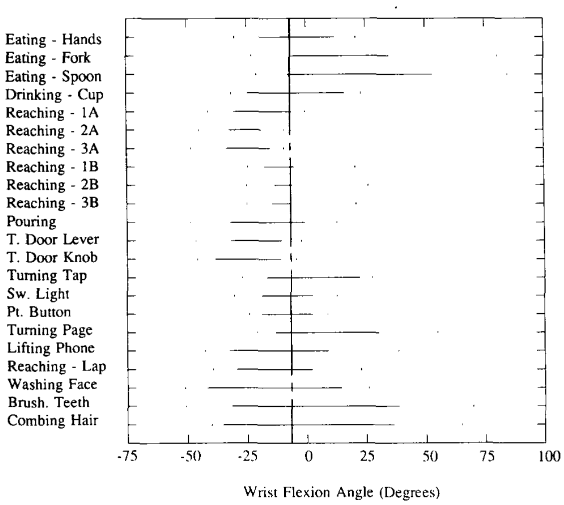


Fig. 7. Wrist Flexion: Average Min/Max & extremes for all subjects.

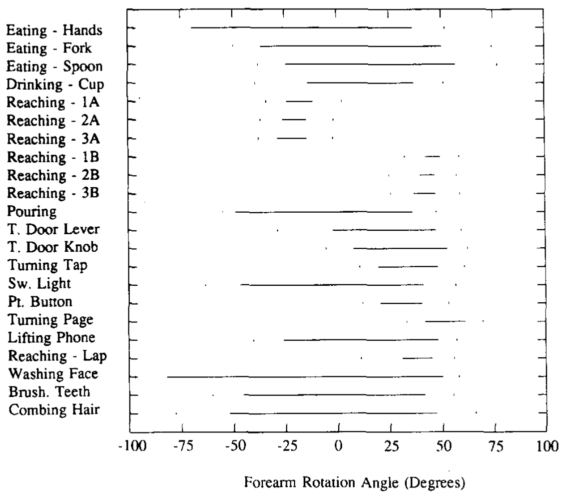


Fig. 8. Forearm rotation (pro/supination): Average Min/Max & extremes for all subjects.

is to couple forearm rotation to elbow flexion [3], [5]. This, however, suits only eating with the hands or with a fork. With forearm rotation and elbow flexion coupled, the user cannot reach for any object with the hand upright. Also, the personal hygiene tasks involve a different amount of forearm rotation than the eating tasks. Therefore, the indication from the motion analysis results was that forearm rotation should be independently powered.

All three joint rotations of the shoulder varied considerably from task to task. It was therefore not immediately obvious which one(s) could or should be fixed. While specific tasks would be sacrificed regardless of which shoulder degree of freedom is fixed, the loss of functionality may be offset by the increased simplicity. The decision concerning which degrees of freedom to fix was subsequently based on the results of the simulations and the priority of the tasks as identified in the interviews.

TABLE II
SUMMARY OF MOTION ANALYSIS RESULTS, ALL SUBJECTS

| | Least Avg. Min. (L.A.M.) (degrees) | Task Where L.A.M. Occurs | Greatest Avg. Max. (G.A.M.) (degrees) | Task Where G.A.M. Occurs | Average Range (degrees) |
|---|---|---|---|---|---|
| Azimuth | 7 | Page ($\sigma = 6$) Reach 1A (10) Reach 1B (7) Lap (23) | 108 | Reach 3A ($\sigma = 5$) Reach 3B ($\sigma = 7$) | 40 |
| Elevation | 15 | Lap ($\sigma = 3$) | 96 | Light ($\sigma = 6$) | 26 |
| Roll | -85 | Comb ($\sigma = 12$) | 20 | Lap ($\sigma = 25$) | 34 |
| Elbow Flexion | 42 | Knob ($\sigma = 4$) | 151 | Phone ($\sigma = 15$) | 39 |
| Forearm Rot'n | -86 | Wash ($\sigma = 18$) | 61 | Page ($\sigma = 6$) | 52 |
| Wrist Flexion | -42 | Wash ($\sigma = 10$) | 53 | Spoon ($\sigma = 16$) | 33 |
| Wrist Yaw | -39 | Tap ($\sigma = 6$) | 24 | Comb ($\sigma = 10$) | 21 |

Table II summarizes the average minimums, average maximums and standard deviations ($\sigma$) calculated for each joint angle during each task for the six subjects. The average standard deviation for all tasks and all subjects was found to be 8.0 degrees. For a single subject it was found to be 3.0 degrees. Appendix A provides the detailed results, as shown in Table IV.

The analysis of functional arm movements achieved two goals: 1) it provided new insight and data on how the arm moves while performing functional tasks and 2) it provided the desired positions, orientations and initial estimates of joint angles to be used in the subsequent orthosis simulations.

## V. ORTHOSIS SIMULATIONS

### A. Method

A kinematic simulation program was developed to determine how close a simulated orthosis could come to the desired positions and orientations corresponding to the functional points for each task as derived from the previous motion analysis results. With up to three degrees of freedom fixed or coupled, the program evaluated whether the remaining degrees of freedom were able to compensate for the fixed degrees of freedom and still achieve the functional points required for task performance, while remaining within the limb joint limits.

Using the same model as for the motion analysis, the simulated arm was modelled as a sequence of one-dimensional rotations connected by rigid link segments, a method commonly used in robotics [30] and motion analyses [15]–[24]. As shown in Fig. 9, 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. This excludes finger motion and complex shoulder motion. The axis definitions were based on the Denavit-Hartenberg formulation [30].

The software minimized a cost function to determine the actions required to move the simulated arm from an initial position to as close as possible to the desired position and orientation. Developed by the authors, the cost function was based on a positional error, an orientation error and a constraint that all joints remain within the joint limits. The cost function,

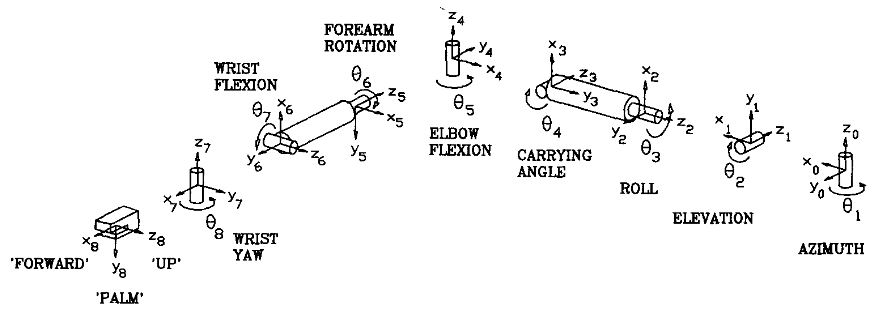


Fig. 9. Kinematic Formulation Axis Definitions.

$\Phi(\theta_i)$, is given by the following equation:

$$\Phi(\theta_i) = \begin{bmatrix} (|r_{\text{act}} - r_{\text{des}}|)^2 \\ +\text{wt}_{\text{forw}} \cdot (\text{forw}_{\text{act}} - \text{forw}_{\text{des}})^2 \\ +\text{wt}_{\text{palm}} \cdot (\text{palm}_{\text{act}} - \text{palm}_{\text{des}})^2 \\ +\text{wt}'_{\text{up}} \cdot (\text{up}_{\text{act}} - \text{up}_{\text{des}})^2 \\ +\text{penalty function} \end{bmatrix} \quad (1)$$

where,

$|r_{\text{act}} - r_{\text{des}}|^2$ is the squared distance between the actual and desired endpoint positions,

$(\text{forw}_{\text{act}} - \text{forw}_{\text{des}})^2$ is the squared angle between the actual and desired 'forward' orientation vectors,

$(\text{palm}_{\text{act}} - \text{palm}_{\text{des}})^2$ is the squared angle between the actual and desired 'palm' orientation vectors,

$(\text{up}_{\text{act}} - \text{up}_{\text{des}})^2$ is the squared angle between the actual and desired "up" orientation vectors and

$\text{wt}_{\text{for}}, \text{wt}_{\text{palm}}, \text{wt}_{\text{up}}$ are the respective weighting factors.

The assigned weightings were normally 0.10 for the most important orientation (e.g. "up" or along the fork for eating with a fork) and 0.05 for the remaining two orientations. With these values, 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 10 degrees. They, too, must therefore be matched closely.

The penalty function, based on the robotics work in [31], keeps the simulated arm within the natural joint limits of the arm. It is defined as

$$\text{penalty function} = \sum \text{penalty}_i \cdot (\theta_i - \theta_{\text{lim}})^2 \quad (2)$$

where

$$\text{penalty}_i = \begin{cases} 0 & \text{if } (\theta_i)_{\min} + \theta_{\text{tol}} \le \theta_i \le (\theta_i)_{\max} - \theta_{\text{tol}} \\ k & \text{otherwise} \end{cases} \quad (3)$$

and

$$\theta_{\text{lim}} = \begin{cases} (\theta_i)_{\min} + \theta_{\text{tol}} & \text{if } \theta_i \le (\theta_i)_{\min} + \theta_{\text{tol}} \\ (\theta_i)_{\max} - \theta_{\text{tol}} & \text{if } \theta_i \ge (\theta_i)_{\max} - \theta_{\text{tol}} \end{cases}. \quad (4)$$

The constant $k$ was specified large enough (0.5) to produce a cost function value that indicated an unsuccessful configuration even if the desired position and orientation were achieved since the configuration could not be accepted if the limb joint limits were exceeded. Instead, the minimization routine continued to search for solutions within the joint limits.

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 [32]. While the pseudoinverse method may be more efficient, the method used in this research provides a simple and effective method of handling singularities, weighting factors and joint limit penalties.

The minimization procedure, Brent's method with the use of first derivatives, was adopted from [33]. It was initiated by constructing a scalar function $f(c)$ having the value of the cost function along the line passing through the current point and in the direction of the gradient of $\Phi$

$$f(c) = \Phi\left(\theta_1 + c\frac{\partial\Phi}{\partial\theta_1}, \theta_2 + c\frac{\partial\Phi}{\partial\theta_2}, \cdots, \theta_8 + c\frac{\partial\Phi}{\partial\theta_8}\right). \quad (5)$$

The corresponding value of $c$ that minimized $f(c)$ was used to construct a new point of interest

$$\theta_i' = \theta_i + c\frac{\partial\Phi}{\partial\theta_i}. \quad (6)$$

The procedure was terminated when either the cost function value was less than a tolerance (6.0 cm$^2$) or the maximum number of iterations (10) was exceeded. The tolerance value was sufficiently low to ensure that the configuration met the success criteria yet sufficiently high to terminate successful configurations quickly.

Upon completion of the minimization procedure, the results were classified as successful, close-to-successful or unsuccessful. Table III lists the criteria, based on the distance between the actual and desired endpoint positions and the angles between the desired and actual orientations. The success criteria were set to be approximately equal to the position and orientation standard deviations for all of the tasks and all of the subjects.

## *B. Results*

Preliminary evaluations were conducted with a total of 34 positions, consisting of the critical functional positions for all tasks (e.g. picking up the food and at the mouth or

TABLE III
SUCCESS CRITERIA

| | 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 |

at the extreme of each reach point). Fixing azimuth, elbow flexion or forearm rotation led to many unsuccessful tasks (7, 30, and 5 respectively), including high-priority tasks. As a result, only elevation, roll, wrist flexion and wrist yaw were considered as potential 'fixed' joints. When either elevation or roll were fixed together with a wrist degree of freedom, fixing wrist yaw produced better results than fixing wrist flexion. The coupling of several joints was 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 (17 and 11 for the two combinations tested), including the high-priority eating and personal hygiene tasks, and it was concluded that an orthosis with three or more fixed degrees of freedom would not be versatile enough to be worthwhile to the user.

Four potential alternatives emerged from the preliminary evaluation: 1) fix elevation and wrist yaw, 2) fix roll and wrist yaw, 3) fix wrist flexion and wrist yaw and 4) couple roll and elbow flexion and fix wrist yaw. These were analyzed further using up to eight functional points from each task, for each of the six motion analysis subjects. Based on this further analysis the recommended alternatives are to power all but elevation and wrist yaw (to be fixed at approximately 53 degrees and $-2$ degrees respectively) or to power all but wrist flexion and wrist yaw (to be fixed at approximately $-8$ degrees and 2 degrees respectively).

Both of the final alternatives were unsuccessful at reaching for a doorknob, turning a page and some positions of brushing the teeth because of the fixed wrist yaw. 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 some positions of combing the hair, all of which required a higher elevation. The additional unsuccessful tasks for the second alternative, with both wrist rotations fixed, were eating with a fork, eating with a spoon and turning a tap lever.

The primary advantage of the first alternative, fixed elevation and wrist yaw, 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, speed of activation and physical bulk. Choosing to fix elevation as opposed to wrist flexion, however, not only reduces the work envelope and the flexibility of the shoulder but adds the need for separate control of wrist flexion. The advantage of controlling wrist flexion is to provide local control over orientation, thus allowing small adjustments to be made without moving the entire arm.

The primary advantage of the second alternative, fixing both wrist rotations, is to be able to reach any location that the arm could normally reach. Also, the redundancy of the three shoulder degrees of freedom allows for more natural arm positions. The disadvantages are that there is no small-scale control of orientation except forearm rotation and that the unsuccessful tasks are of a higher priority.

It is recommended that any fixed angles should be manually adjustable to suit the individual. Also, an individual user's remaining function should be utilized rather than restricted. In both options, the user's hand grasp is assumed to be powered or still functioning. A simple cylindrical or palmar grasp is expected to be used.

While both of the recommended options restrict the number of tasks that can be performed, the loss of functionality is offset by the advantages of design simplicity. A simpler design should lead to reduced costs, fewer breakdowns and a more aesthetically acceptable orthosis. An even simpler configuration would be possible if the task requirements were reduced, 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 unsuccessful tasks may be able to be performed differently or with daily-living aids. The simulations do not require that the user follow the same path as taken by the able-bodied subjects, only that specific functional positions are met.

## VI. SUMMARY AND CONCLUSION

This paper has described a new three-stage methodology for the optimal design of a powered upper-limb orthosis. In contrast to previous methods employed for the development of upper-limb assistance devices, the investigators have attempted to assess the necessary requirements of a powered upper-limb orthosis in terms of specific task requirements for the potential user, definition of the required motion and subsequent analysis of the capabilities of devices with varying degrees of freedom in order to increase the probability of user acceptance.

Interviews conducted with eleven potential users have defined the priority tasks to be performed by such a device and have indicated reaching as the highest priority task. This is a task which is not performed well by some existing devices [5]. This research has also identified requirements such as the ability to perform personal hygiene tasks and hobbies as having a higher priority for a potential orthosis user as compared to potential users of a robotic manipulator. This is an important difference as users appear to have different expectations and possibly different acceptance criteria for devices which can assist them in the performance of tasks using their own limbs in contrast to using an external device.

The motion analysis conducted in this study, performed using specially developed tracking software, has provided the necessary three-dimensional data for quantifying the motions of able-bodied subjects performing 22 identified high-priority daily-living tasks. While this data was essential as it provided the desired positions and orientations and initial estimates for the performance of subsequent orthosis simulation studies, it also provided a substantially improved understanding of the range of motion required to perform common daily-living tasks.

TABLE IV
APPENDIX A

| | AZIMUTH | | | | ELEVATION | | | | ROLL | | | | E-FLEX | | | | F-ROTN | | | | W-FLEX | | | | W-YAW | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TASK | 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 |

To allow for design optimization based on a defined criterion related to functional performance and to evaluate alternative orthosis configurations based on user priority task requirements prior to prototype construction, an orthosis simulation program was developed capable of assessing how close a given configuration could come to a desired task position and orientation. Through the kinematic simulation of numerous orthosis configurations having varying joint degrees of freedom, two orthosis configurations have been recommended for subsequent orthosis development. These recommendations are 1) to power all motions including prehension except for elevation and wrist yaw or 2) to power all motions including prehension except for wrist flexion and wrist yaw. Simulation work indicates that fixing more than two degrees of freedom will result in an unacceptably restrictive device although the user may be able to compensate with the head or trunk, with special aids or with residual motion in the arm. Evaluations of device configurations with coupled degrees of freedom did not indicate any increase in functionality over fixing of the coupled joint motion, thus coupling was not recommended.

A prototype has now been designed and built and is undergoing laboratory testing. For this prototype, the design option fixing elevation and wrist yaw was chosen, primarily due to the reduced bulk and power requirements (see Fig. 10). Elevation remains manually adjustable. The approach of maximizing simplicity while maintaining sufficient functionality is being applied throughout the design, including that of the control system. It is felt that this approach should lead to a higher probability of user acceptance. Endpoint control is employed to make the system easier, faster and more intuitive to control. Affordability, aesthetics, ease of use, safety, modularity and convenience (of repair and of donning and doffing) were all important criteria used to evaluate the various prototype designs considered. Interviews will be conducted throughout the development of the prototype in order to incorporate user feedback into the design. Clinical assessments of five of these devices fitted to selected users are also planned.

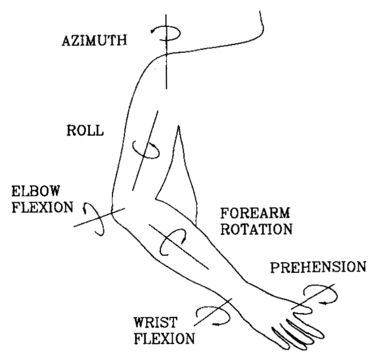

Fig. 10. Prototype Degrees of Freedom.

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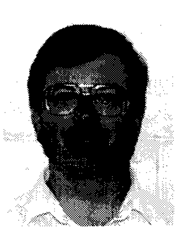


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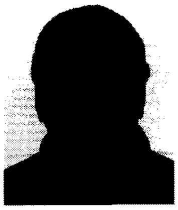

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