

**DEVELOPMENT AND VALIDATION OF A POSTURE
PREDICTION ALGORITHM**

by

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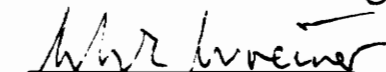
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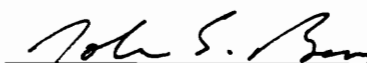
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(ABSTRACT)

Biomechanical models are used in many situations to help understand the risks associated with performing different work tasks. A necessary input to most biomechanical models is the body posture of the worker. Measuring posture has proven to be a difficult and time-consuming process. The research reported in this thesis investigated if a posture can be predicted instead of measured.

The posture prediction model employs a whole-body sagittal plane representation of the worker with five links using inverse kinematic procedures to calculate the postures. The model chooses a posture by optimizing an objective function using a nonlinear programming search. Three separate models have been formulated to predict the postures of 16 subjects humans performing four static sagittal lifting tasks. Each model uses a different objective function or criterion defined relative to the torques on the human joints. These criteria are labeled as Total Torque, Percent Strength, and Balance. The influence of gender, hand position, and criteria on the prediction accuracy were investigated.

The results showed that there was less postural variability for higher hand positions compared to lower hand positions. For lower hand positions there were two distinct types of postures chosen by subjects which implies that there are two different types of criteria being used by subjects at these hand positions. Student t tests, which investigated the accuracy of the predictions, showed that all of the prediction errors were significantly greater than zero at $\alpha=0.05$. A mixed factor, repeated measures ANOVA investigating the

prediction error showed that the Total Torque criterion was more accurate than the two other criteria.

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1.0 INTRODUCTION

1.1 Rationale

Biomechanical models have been used in many situations to help understand musculoskeletal functions, estimate muscle forces, or estimate the risk of performing a task. A necessary input to most biomechanical models is the body posture of the worker. Depending on the type of model, postural information can be obtained using expensive and time consuming methods such as a motion analysis system, or estimating the posture through direct observation. This thesis investigated if a posture can be predicted instead of measured. Predicting postures would save time and money since only a few measurements would be needed and a personal computer could calculate the posture. Investigating posture prediction will also help researchers understand why humans choose certain postures.

Several attempts have been made to develop algorithms that predict whole body posture, but in general, they have not been accurately validated. Researchers have not investigated how varied a person's posture is under the same conditions (e.g. hand position, motivation, weight lifted etc.). If humans choose a large range of postures, it may be impossible to accurately predict posture. Even when the variance is small, very little is known about what variables influence posture. These factors must be defined before an accurate algorithm can be developed.

1.2 Thesis Description

This thesis investigated postures assumed by subjects performing a sagittal static lifting task. Postures of subjects performing this lifting task were recorded and compared with the postures predicted by three posture prediction algorithms. These algorithms calculated postures using inverse kinematics where the horizontal and vertical distances between the hand and ankle, the link lengths of the human, the weight of the human, and

the load lifted are assumed to be known. The inverse kinematic solution was indeterminate because the forearm orientation and the hip location were unknown.

In order to solve for these unknown variables, three different criteria were used to describe how humans choose postures. These criteria were defined as nonlinear objective functions where a nonlinear programming search was used to find the optimal posture (or solution). The first criterion investigated the theory that humans choose a posture which requires the minimum effort. Effort was defined as proportional to the total torque summed over all the joints. This criterion assumed that when a large amount of torque is exerted, a human perceives that a large amount of effort is required. The second criterion was similar to the first except that effort was defined as the amount of torque exerted at a joint relative to the strength of the joint. This represents the posture which distributes the torque across all joints in proportion to each joint's ability to overcome that torque. The third criterion examined the theory that humans choose a posture where they feel most stable. Stability, in this case, was defined as the human's ability to resist falling forwards or backwards.

In addition, this thesis investigated the influences of hand position, criteria, and gender on prediction error. The subject variability, which affects the prediction error, was determined by looking at the range of postures chosen by a subject performing 8 repetitions of a task under the same condition. The influence of hand position, body joints, and gender on subject variability were also investigated.

1.3 Experimental Objectives

The objectives of this thesis were:

Objective 1: Determine the variation of postures chosen by each subject.

Objective 2: Determine if humans minimize the total joint torque when choosing a posture.

Objective 3: Determine if humans choose a posture which minimizes the maximum ratio of joint torque exertion to joint strength.

Objective 4: Determine if humans maximize stability when choosing a posture.

2.0 LITERATURE REVIEW

2.1 Overview

The literature review is divided into three sections. First, literature investigating posture prediction using regression models and inverse kinematic models are discussed. The second section presents literature that investigates the factors which influence a posture. The third section discusses the sources of potential posture prediction error such as instrument error, measurement error, and subject variation.

2.2 Posture Prediction Models

Posture prediction models are developed to learn more about the human body and to find out why humans choose certain postures. If a posture can be predicted accurately then it does not have to be directly measured which can save time and money.

The models discussed in this thesis consist of links which represent bone links where the end points of the link represent the joints of the body. The orientation of the links is defined by angles. The goal of many whole body posture prediction models is to predict the angles of each link knowing the hand position relative to a base (such as the ankle or L5/S1). The literature shows that there have been two different approaches for creating posture prediction models. One approach is to create regression equations developed from postural data. This has mostly been used in the biomechanics field. The other method, called inverse kinematics, is used mainly in the robotics field. This method first uses the solution of a forward kinematic problem and then solves for the orientation of each link. In forward kinematics, the opposite of inverse kinematics, the angles of each link are known and the purpose is to calculate the end point (usually the hand). This determinate problem is relatively easy to solve compared to inverse kinematics where the end point is known and the goal is to

calculate the angles. In many cases there are an infinite number of solutions for one hand position making the problem indeterminate (Fu, Gonzalez, and Lee, 1987). An optimal solution is found by fitting the data under a criterion such as a solution which minimizes torque at the wrist.

2.2.1 Regression Analysis Posture Prediction Models

Regression models are used to study how predicted behavior relates to the observed phenomena (in this case posture choice). In a regression equation, dependent variables are expressed as a linear (or nonlinear) combination of a set of independent variables. The assumption is that for each set of fixed values of the independent variable, the dependent variable is normally distributed and the variance is constant (Winer, 1991). Posture prediction regression models make this assumption and incorporate independent variables which influence posture. The following posture prediction models use regression equations.

Kilpatrick (1970) developed equations to predict the posture of the upper body (elbow, shoulder, and back) in a seated position by collecting postures for five male subjects reaching 35 hand positions. The development of this model was to be used as an evaluation tool in workstation design. This model used regression equations to predict the elbow location assuming that shoulder position is a linear function of the elbow angle. In addition to regression equations, Kilpatrick used linear programming to predict the orientation of the back by minimizing the angular deviation from resting posture. The constraints of range-of-motion for each joint were also used to help predict posture. Kilpatrick had difficulty predicting postures partly due to the accuracy of the elbow and shoulder predictions. The predicted position of the elbow and shoulder joints were 1.5-5 inches away from the observed joints.

Snyder, Chaffin, and Schutz (1972) developed posture prediction algorithms for seated and standing postures using data from 20 males in 48 sitting and 22 standing positions. Subjects placed an elbow in a designated location rather than their hand (as in Kilpatrick's study). Linear and nonlinear least squared error regressions were calculated using the marker locations of the spine, shoulder, and elbows. The models used the independent variables of 3-D elbow positions and anthropometry such as stature, weight, chest circumference, biacromial breadth, and humeral lengths to predict the locations of the acromion, vertebrae disks, and the anterior superior iliac spine. Using the position data and the anthropometric measurements, the model had a coefficient of determination greater than 0.70.

Anderson, Chaffin, and Herrin (1986) had two males and two females perform a sagittal isometric lifting task at various knee angles (180°, 135°, 90° and deep knee squat) and torso angles (erect, half flexed and fully flexed). A nonlinear second order regression equation was developed to predict the rotation angle of the sacrum and L5/S1 knowing the torso and knee angle. The regression model was found to be accurate with an R^2 value of 0.89.

Bloswick and Weiler (1990) had seven males perform three repetitions of twelve squat lifts and recorded the postures under the following conditions: weight of the load (15 and 30 lbs), horizontal distance of load from the ankles (14, 19, and 24 inches), and vertical distance from the floor (8.5 and 18 inches). Regression equations with independent variables of hand position, subject height and weight were used to predict the orientation angle of the upper arm, lower arm, trunk, upper leg, and lower leg. The equations had R^2 values ranging from 0.656 to 0.796. These R^2 values imply that these independent variables do influence posture but there are additional variables that have not been included in the regression equations which would improve the prediction accuracy.

Beck (1992) developed a 3-D posture prediction model of the whole body using regression equations from Kilpatrick (1970), Snyder et al. (1972), and Anderson et al. (1986). Nine postures from a subject performing drilling and lifting tasks were predicted, though no statistical analysis was performed. The prediction algorithms were used as an aid for the Three Dimensional Static Strength Prediction Program™ (3DSSPP) to see if posture prediction could improve the speed and accuracy of posture estimation. Beck's model also tried to predict link lengths which created addition error in the model. Though the accuracy of the prediction model was not fully validated, this research does show that posture predictions can increase the speed for posture quantification.

2.2.2 Robotic Inverse Kinematics with Human Models

As discussed in the beginning of this section, the orientation of the links in a posture can also be solved for using inverse kinematics. Since this solution is usually indeterminate, a criterion is used such as minimizing jerk (for dynamic situations) or minimizing moments at the joints in order to come up with an optimal solution.

Most of the research that investigated human models using inverse kinematics has been in the robotics field to research dynamic tasks. Humans have been used as models allowing engineers to determine the mathematics and validate the calculations before working with expensive robots. Benati, Marasso, and Tagliasco (1982) developed calculations for a seven degrees-of-freedom upper arm performing a dynamic reach task. Benati et al. calculated an optimal path by using a quadratic optimization criterion which tried to find the path that minimized the distance between two points (starting and ending of a path) while considering the constraints of the other joints. Asano (1989) analyzed the arm kinematics for turning a wrench (1 degree of redundancy) and grasping a glass (two degrees of redundancy). The

optimal posture was found by assuming that the hand posture chosen minimizes the torque around the wrist. Asano predicted the posture of one male subject performing nine tasks. The results showed that he positioned his arm and hand to minimize the torque on the wrist. Although no statistical analysis was performed, Asano stated that the predictions were accurate.

Byun (1991) used inverse kinematics to develop a 2-D posture prediction algorithm that predicts isometric postures knowing the hand locations relative to the ankle. Four criteria were used to obtain different optimal postures: minimize energy expenditure, minimize compressive force at L5/S1, minimize perceived stress, and maximize hand load. Characteristics of humans such as height, weight, link lengths and joint strengths were randomly generated to describe fifteen humans. These simulated humans fit into three categories (5th, 50th, and 95th percentile) and were used to analyze the criteria. Byun investigated these four criteria by changing the load lifted (10 and 40 lbs) and the hand position from the ankle (horizontal distance- 10 and 20 inches, vertical height- 20 and 40 inches). Though Byun found the four criteria to represent different postures, these criteria were not validated with human subjects. Part of this thesis used some of Byun's calculations and attempted to validate the criteria.

Jung, Kee, and Chung (1992) used inverse kinematics to predict the 3-D path of the upper limb (wrist, elbow, and shoulder) performing a reaching task. This model was designed to be used for ergonomic interface models such as CAD systems with built in human models. The inverse kinematic solution is indeterminate for this model so an optimal solution is found by calculating the path which minimizes jerk. Jung et al. predicted the posture of one subject performing six reaching tasks. The results showed that the predicted and observed angles at the elbow and shoulder were not significantly different for $\alpha=0.05$.

2.3 Posture Prediction Factors

If it is assumed that humans choose a posture for a particular reason, then a suitable model should be able to predict postures using these reasons. Unfortunately, at this date, research has not adequately identified the factors which influence posture choice. The influences on posture have been investigated in four areas: task conditions, experience, biomechanical conditions, and sensory information.

Haslegrave, Tracy, and Corlett (1988), Haslegrave and Corlett (1988), and Haslegrave (1991, 1990) investigated several factors which influence posture. Most of the identified factors come from an experiment with six miners performing maximal single handed isometric exertions (pushing and pulling). Figure 2.1 describes how each factor interacts with the others and with posture. This figure describes factors that are known before the task is performed such as anthropometry and experience (previous injury, fatigue, and training are difficult to quantify though) and factors that are known during or after the task such as the nature of the exertion (e.g. direction, force level, and body interference).

2.3.1 Task Conditions

Posture depends on the task being performed. Each task may have different factors (or task conditions) that affect posture choice. An accurate posture prediction algorithm should consider the task conditions which will influence posture. The literature has shown that task conditions such as hand position, motivation, reach requirements, and direction of force exertion will influence posture.

Haslegrave, Tracy, and Corlett (1988) conducted an experiment with five miners performing maximum isometric pushing, pulling, lifting and pressing downward exertions on a cylindrical handle. The handle was set at two heights so that subjects assumed a standing and kneeling posture. The subjects were free to choose any posture they felt was

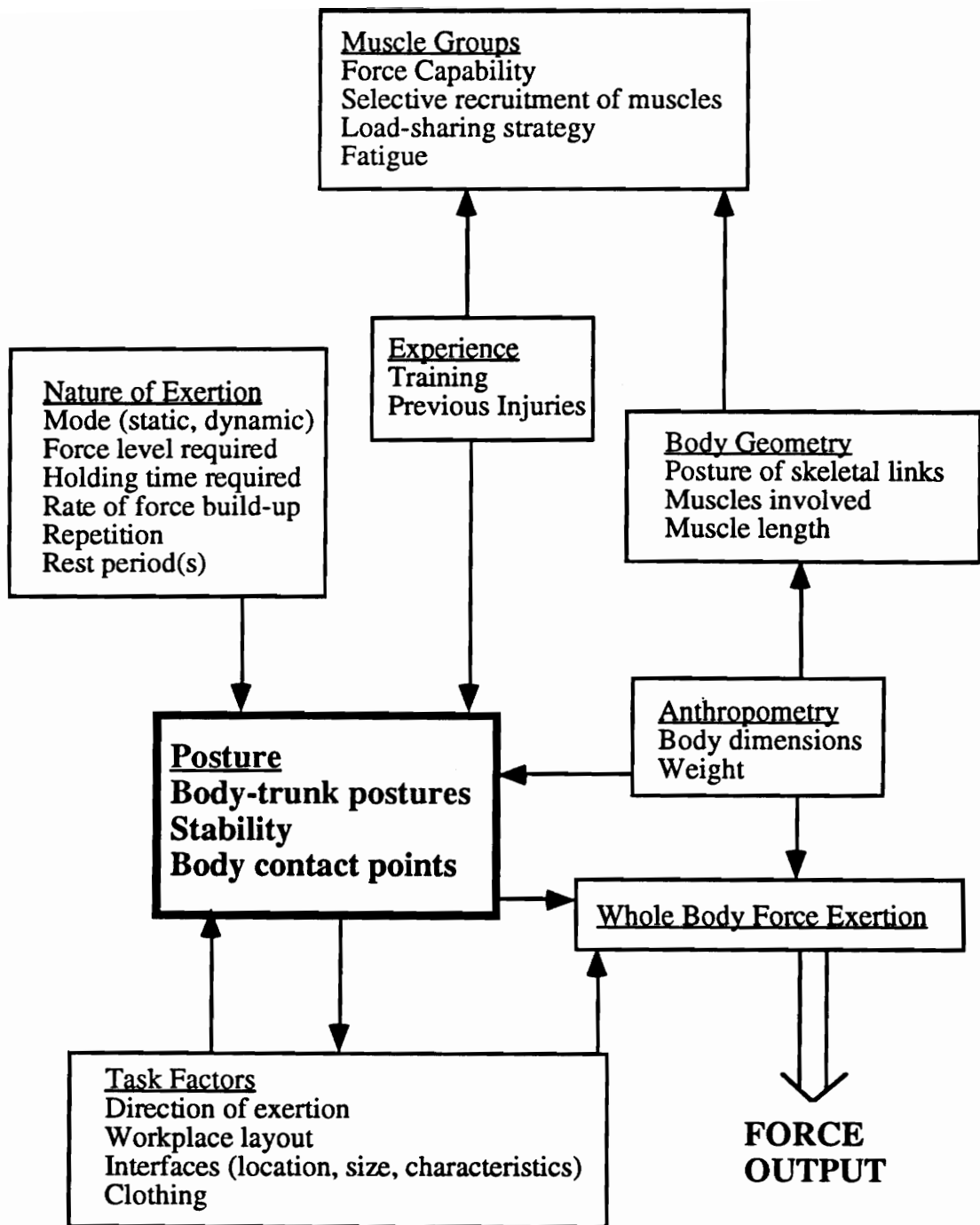


Figure 2.1 Factors which influence posture choice. (Adapted from Haslegrave, 1991).

necessary to perform the task. The postures were recorded as the task was performed. Haslegrave (1991) found that when the force direction or task height changed, subjects did not just change foot positions or lean forward, but tended to change the posture of the whole body. The experiment in this thesis controlled the factors of force direction, foot position, and hand position which were shown to influence posture.

Bloswick and Weiler (1990) investigated the postures of seven males performing squat lifts by looking at the effects of three factors used for the NIOSH lifting guide: weight of the load, horizontal distance of load from the ankles, and vertical distance from the floor. Bloswick and Weiler found that vertical distance, horizontal distance, subject weight and subject height had a significant effect on the posture at $p > 0.05$. Bloswick and Weiler's findings confirm that postures change due to reach distances and due to subject anthropometry. Due to their significant effect on posture, these variables were used as input for the posture prediction algorithm.

Snyder et al. (1972) hypothesized that postures may vary strictly due to factors such as motivation. If the environment is stressful as opposed to relaxing, the postures chosen could be different. These ideas were not tested but experimenters should be aware of possible changes of posture due to motivation. For this thesis, the influence on a subject's motivation was kept relatively constant in order to reduce its effects on posture. Reading material was provided between trials but there was no music which might have influenced the subject's motivation.

2.3.2 Experience

Previous experience such as training can affect posture but depends greatly on the type of task, as shown by the following two experiments. Haslegrave and Corlett (1988) found that experience influences posture when pushing and pulling maximal loads. They had previously observed that naive subjects didn't consider their force exertion when

maintaining their balance and often adopted postures that would be hazardous in actual working conditions. From these observations, they proposed that the perceived risk of slipping or falling, the skill of exerting force, the knowledge of the safe use of body weight, and the perception of a potential injury may affect posture choice and variance. Anderson et al. (1986) tested two male workers engaged in daily manual material handling and two females who were unaccustomed to heavy lifting while performing static lifts at 0%, 50% and 100% of their maximum. The same model was used for both experienced and unexperienced subjects because the relationship of the sacral angle with the knee angle for both groups are similar. However, the actual postural data for the two groups were significantly different at 0.05 level. Previous lifting experience was not controlled in this thesis, but all subjects were screened for previous injuries through a questionnaire. None of the subjects reported any history of back injuries or other musculoskeletal injuries.

2.3.3 Biomechanical Factors

Biomechanical factors relate to the characteristics of musculoskeletal system such as fatigue and strength capabilities. Research has observed that possible biomechanical factors such as posture stability (Byun, 1991, Haslegrave, 1991, Lacquanti and Maioli, 1992), postural discomfort (Byun, 1991, Haslegrave, 1991), and joint stability (Haslegrave, 1991) may have large influences on posture choice.

Byun (1991) investigated the hypothesis that humans choose postures that minimize energy expenditure, maximize hand load, minimize back compression, or minimize perceived stress level. Byun predicted the postures for 15 simulated subjects using each of these criteria. At some conditions, the different criteria predicted similar postures, while at other conditions these criteria predicted much different postures. Byun suggests that humans may use different criteria depending on the conditions (such as the

load and hand position) though this was not validated with actual subjects. Part of this thesis investigated if different criteria were used at different hand positions.

Asano (1989) looked at the arm kinematics for turning a wrench and grasping a glass. The optimal posture is found using inverse kinematics by assuming that the hand posture chosen minimizes the torque around the wrist which was validated using one subject. In order to minimize the torque around the wrist, the human positions the wrist to create a moment arm of zero. One goal in this thesis was to test if humans minimize the torque in all the body joints which is similar to what Asano found with grasping tasks.

2.3.4 Sensory Information

Psychologists have been investigating posture choices using a different approach. An important influence of posture choice is the central nervous system (CNS). For example, certain movements, once learned, become almost subconscious unless there is fatigue or an injury. The CNS must have information about the skeletal system (the frame work for postures) such as joint degrees of freedom, the characteristics of the muscles, and other constraints which control posture. The peripheral sensors keep the CNS updated on the state of the musculoskeletal system so the CNS can appropriately control the muscles (Winter, 1989). Researchers must keep in mind that the factors that influence posture must provide information that is understood by the central nervous system. Sensory information from a number of different modalities is used to determine the location of the object relative to the hand. Information is needed concerning the orientation of the eyes relative to the head, orientation of the head relative to the trunk and the orientation of the trunk relative to the arm, thus the vestibular receptors and proprioceptors in all the joints as well as the neck must be used (Soechting, 1989).

Lacquanti and Maioli (1992) investigated the postural control of cats standing on a tilted platform. They view body posture as the result of a highly integrated multisensory

system of neural control that is hierarchically organized using visual, vestibular, and somatosensory information. Lacquanti and Maioli discuss the theory that animals try to stay in equilibrium keeping the projection of their center of mass within safe bounds on the support surface. An experiment investigated the posture of a cat standing on a platform which tilted over a duration of 24 hours. The results showed that the cat tried to maintain the same posture instead of shifting its body to adjust the center of mass. Lacquanti and Maioli concluded that maintaining equilibrium is not as high in the hierarchy as remaining still for this task. This thesis investigated how humans maintain their equilibrium while performing a lifting task.

2.4 Posture Prediction Error

With any posture prediction model there will be error. It is important to identify what errors were found in previous models in order to avoid or reduce them in the model for this thesis. Many studies attribute error, outside of the model, to three sources: instrument error, errors in estimating the joint center of rotation, and subject variation. The magnitudes of these errors should be understood in order to distinguish between the error caused by the actual model and other factors.

2.4.1 Instrument Error

Instrument error is attributed to the instrument collecting the postural data. There are two types of instrument error: systematic (e.g. optical distortion) and random (e.g. converting an analog signal to a digital signal) which can be calculated by most motion analysis systems (Cappozzo, 1991). For this research, a WATSMART motion analysis system was used and defines error as the distance between the calculated 3D location of each marker to its absolute 3D location. The error is determined during a calibration procedure which calculates the root mean squared (RMS) error. The magnitude of the error depends on the distance between the camera and the object being observed, the angle

between the cameras, the infrared diode errors, and the amount of reflectivity in the environment.

2.4.2 Estimation of Joint Center of Rotation

The objective of marker placement is to minimize the relative displacement while accurately estimating the center of rotation. Errors may be attributed to the movement of markers relative to the underlying bone due to soft tissue deformation. There have been many studies concerned with external marker placement used to predict internal center of rotation (COR) of joints (Cappozzo, 1991).

Cappozzo (1991) performed an experiment to determine the movement of a hip marker on an adult male performing a walking task. He found that the marker error due to movement ranged from 4 mm to 14 mm depending on the task performed. With isometric exercise, the movement was about 4 mm which affected the calculations of joint angles by +/- 1 degrees.

The knee has an instantaneous center of rotation which changes when the knee bends. The range of instantaneous COR's occupy a large volume and to calculate the position in this volume can be difficult (Cappozzo, 1991). Ramakrishnan (1991) investigated the error of surface markers on the knee and found that the movement of skin and soft tissue over and around the condyles can be large. While the knee was abducted or adducted, a $\pm 5^\circ$ variation in the orientation of the knee flexion-extension axis was found.

Unfortunately, many studies which use surface markers don't pay much attention to the quantitative assessment of marker placement errors (Cappozzo, 1991). Cappozzo discussed the criteria that should be used for choosing a marker location. He notes that the relative movement between marker and underlying bone due to soft tissue deformation should be minimal and the distance between markers should be sufficiently large so that error from measured marker coordinates to the actual segment orientation is minimal.

2.4.3 Subject Variability

Subjects have different anthropometry as well as different experiences with respect to fatigue, injury, and training. There is variation within one subject as well as variation between subjects when choosing a posture. Snyder et al. (1972) hypothesized a concept called the feasibility volume. If the same subject performs the same test twice, there is a high likelihood that the postures will not be exactly the same. If the test is performed several thousand times, a given surface marker would generate an egg-shaped volume which represents a feasibility volume. There is a different feasibility volume for each surface marker. Each point in a volume is not equally likely but is equally acceptable. The density of points is expected to be higher at the center of the volume compared to the periphery. It is important to determine the size of the feasibility volume for a task because if a subject chooses a large range of postures for one task, the posture will be difficult to predict.

The amount of variability depends on the type of task being performed. Kilpatrick (1970) observed that two thirds of the variance over all joint center coordinates was less than 0.25 inches for a reaching task. Kilpatrick discusses a Boeing Aircraft study similar to his experiment investigating cockpit designs. The 25 subjects in the Boeing experiment had markers vary by 4.0 inches. This wide range of variability between Kilpatrick's and Boeing's experiment show that the accuracy of posture prediction will vary depending on the task. Haslegrave and Corlett (1988) observed in their mining experiment that subject variability did not represent a continuous range of positions but in most cases there were two or more distinct postures chosen by the subjects. Subjects chose two postures for pushing down tasks but for lifting tasks all subjects chose very similar postures. They also observed in previous experiments, that naive subjects chose a large variety of postures. In this case, not only was variance dependent on the task but also the experience of the worker.

There hasn't been much research quantifying the variability of posture using a large number of repetitions (greater than three) under the same conditions. One of the objectives of this thesis was to determine the variability of posture choice for a static lifting task.

3.0 POSTURE PREDICTION MODEL

3.1 Overview

This chapter describes the algorithm developed for this thesis to predict human posture. First, there is an overview of the posture prediction model. Secondly, the inverse kinematic solution calculations and the torque and force calculations for a posture are described. Finally, the method for finding the predicted posture is discussed. Appendix A contains the Mathematica programming code for this posture prediction non-linear algorithm.

3.2 Overview of Posture Prediction Model

Figure 3.1 is a flowchart of how the model predicts a posture. The model employs a whole-body sagittal plane representation of the worker with five links corresponding to the calf, thigh, torso, upper arm, and forearm as shown in Figure 3.2. The model uses the inputs of the horizontal and vertical distances between the hand and ankle, the link lengths, the whole body weight, and the magnitude and direction of the load lifted. With these inputs, the model calculates the joint locations of postures using inverse kinematic procedures. These methods are often used in robotics (Fu, Gonzalez, Lee, 1987), and use analytic and geometric equations. The equations to calculate the postures have three degrees of freedom which means that three variables, in this case, the forearm orientation ϕ and the x and y coordinates of the hip joint must be defined in order to calculate a posture. A criterion was used to determine the value of these three variables which describes how a human might choose a posture. The criterion was defined mathematically in terms of a non-linear objective function. This thesis tested three different possible criteria.

The model chooses a posture by optimizing an objective function using a nonlinear programming search. The non-linear search finds a posture within a feasible solution set which is defined by three constraints: 1) the human must not dislocate a joint, 2) the joints

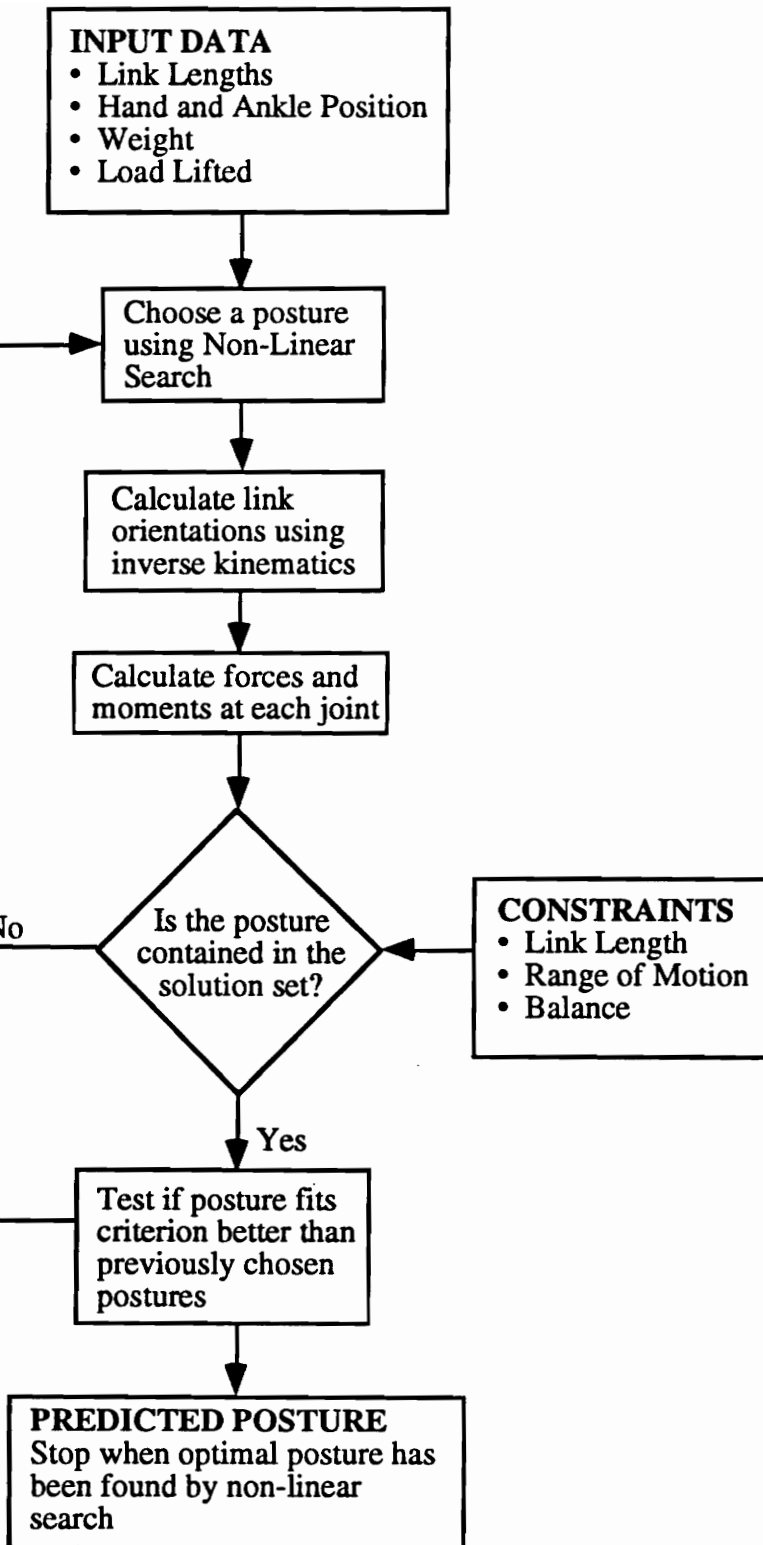


Figure 3.1 Flowchart of posture prediction model.

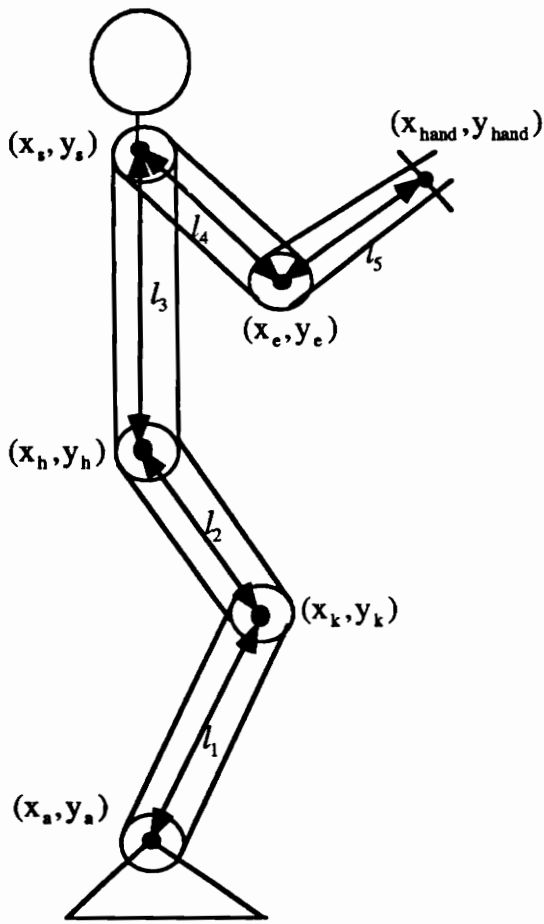


Figure 3.2 Link lengths and joint locations.

should not go beyond a human's range of motion, and 3) the human should not fall forwards or backwards. With this solution set defined, the non-linear programming search is able to find an optimal posture according to the criterion.

3.3 Calculating the Posture and its Forces

3.3.1 Review of Kinematics

In the science of robotics, forward kinematics and inverse kinematics are used to describe robot arm motions. The goal of forward kinematics is to determine the end point of a manipulator or arm knowing the angles which define the orientation of each link. Inverse kinematics deals with the opposite problem in that the end point is known and the angles must be determined. Inverse kinematics solutions usually result in indeterminate equations and thus require a criterion to find a determinate solution.

An objective of this thesis is to determine if a human posture can be predicted from a known hand position relative to the ankle. This is equivalent to an inverse kinematic problem, and thus many of the methods for the proposed algorithm have been adapted from robotic research.

3.3.1.1 Definition of Links

The first important concept is the definition of the location and orientation of links. A link is represented by a vector which describes its length and direction. At the base of each vector (or link) is a reference frame from which the vector is defined.

3.3.1.2 Transformations

A vector can be defined in any coordinate system by multiplying the vector units by the appropriate transformation matrix. In the two dimensional linkage system used in this thesis, two types of transformations were used: 1) rotation around the z-axis $T_{z,\theta}$ and 2) translation T_{x,a_1} along the x-axis.

For example, in Figure 3.3 a transformation matrix is used to define the point B in reference frame A. In this example, the transformation matrix contains a rotation and translation. To transform from reference frame A to reference frame B, there is a translation of l along the x axis in reference frame A (T_{x,a_1}) as shown by the dashed lines and then a rotation of θ around the z axis in reference frame A ($T_{z,\theta}$).

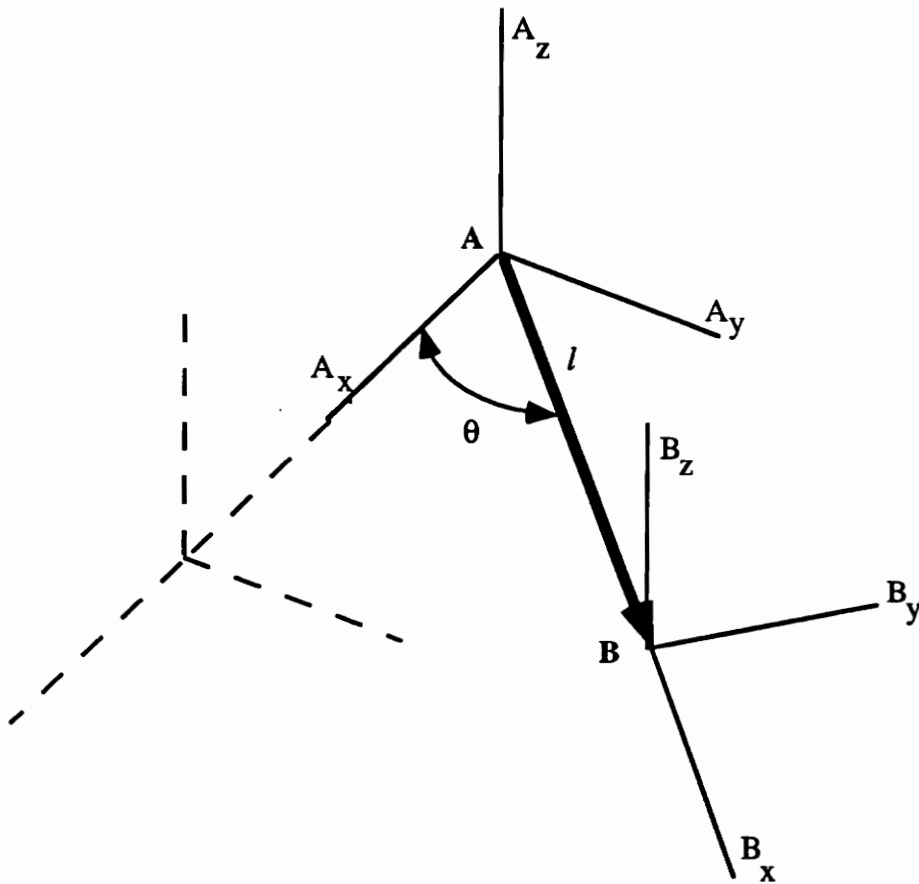


Figure 3.3 Example of a transformation. The dashed lines represent the translation.

A translation and rotation is defined by the matrix below:

$$\mathbf{T} = \left[\begin{array}{c|c} \begin{matrix} 3 \times 3 \\ \text{rotation} \\ \text{matrix} \\ \hline 0 \ 0 \ 0 \end{matrix} & \begin{matrix} 3 \times 1 \\ \text{position} \\ \text{matrix} \\ \hline 1 \end{matrix} \end{array} \right] \quad (3.1)$$

where the rotation matrix of angle θ , is defined by

$$\mathbf{R} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (3.2)$$

and the position matrix is defined by

$$\mathbf{P}_{xyz} = \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix}. \quad (3.3)$$

The above example in Figure 3.3 can be represented by a transformation matrix:

$${}^A\mathbf{T}_B = \mathbf{T}_{z,\theta} \cdot \mathbf{T}_{x,l} \quad (3.4)$$

where

$$\mathbf{T}_{z,\theta} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \text{ and} \quad (3.5)$$

$$\mathbf{T}_{x,l} = \begin{bmatrix} 1 & 0 & 0 & l \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.6)$$

so

$${}^A\mathbf{T}_B = \mathbf{T}_{z,\theta} \cdot \mathbf{T}_{x,l} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & l\cos\theta \\ \sin\theta & \cos\theta & 0 & l\sin\theta \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (3.7)$$

This is how the links in the human body are defined. Each joint represents a separate reference frame (see Figure 3.4). Once all reference frames have been defined,

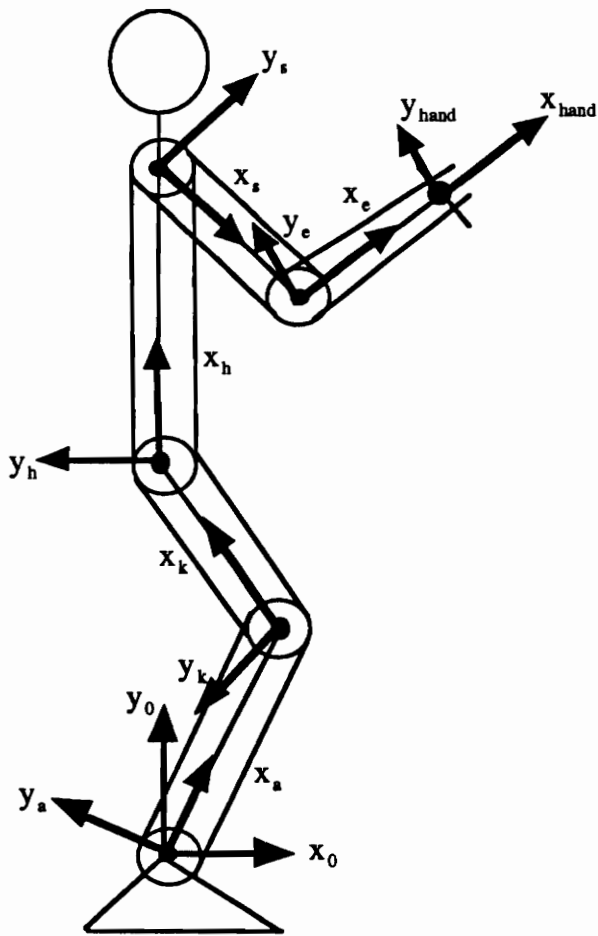


Figure 3.4 Reference frames for each joint. Note that all z axes are perpendicular to the paper surface, pointing toward the reader.

each joint can be described relative to all other joints using rotation and translation transformations. To determine a point in the 0th reference frame in terms of the Nth reference frame, the following transformation matrix would be used.

$${}^0T_N = {}^0T_1 {}^1T_2 {}^2T_3 \dots {}^{N-1}T_N \quad (3.8)$$

3.3.2 Forward Kinematics

3.3.2.1 Description of the Whole Body Model

The human was modeled with five links using six reference frames as shown in Figure 3.4. Each link's orientation is described by an angle as shown in Figure 3.6. Table 3.1 describes the human model using the Denavit-Hartenberg definition which is used to systematically establish a coordinate system for each link of an articulated chain (Fu, 1988). Figure 3.5 explains the Denavit-Hartenberg definition structure.

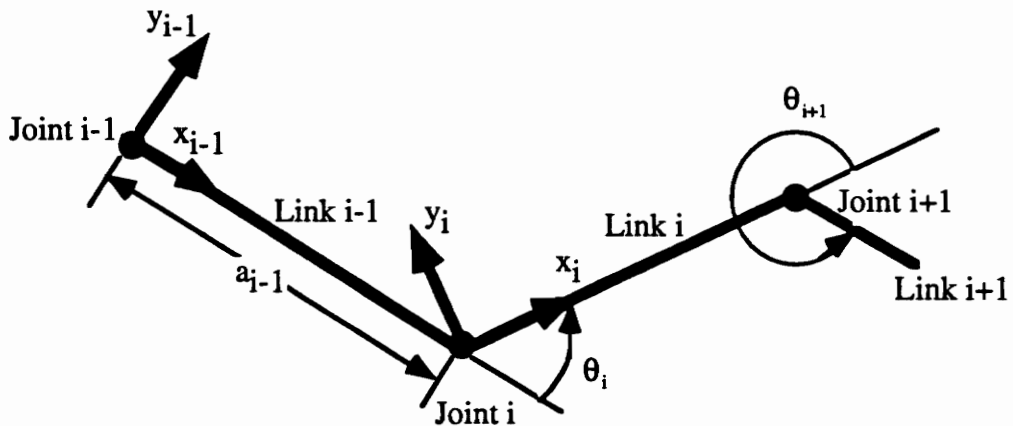


Figure 3.5 Description of Denavit-Hartenberg definition.

TABLE 3.1 Denavit-Hartenberg definition of whole body model

i	a_{i-1}	θ_i
1	0	θ_1
2	l_1	θ_2
3	l_2	θ_3
4	l_3	θ_4
5	l_4	θ_5
6	l_5	0

The variable ${}^0T_{hand}$ is the transformation matrix that defines the hand reference frame relative to the 0 (or base) reference frame.

$${}^0T_{hand} = {}^0T_a {}^aT_k {}^kT_h {}^hT_s {}^sT_e {}^eT_{hand} \quad (3.9)$$

A translation is represented by:

$$T_{x,l_i} = \begin{bmatrix} 1 & 0 & 0 & l_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.10)$$

and a rotation is represented by:

$$T_{z,\theta_i} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (3.11)$$

So that in general, the transformation matrix is defined as:

$${}^iT_{i+1} = T_{z,\theta_i} \cdot T_{x,l_i} \quad (3.12)$$

$${}^iT_{i+1} = \begin{bmatrix} C_i & -S_i & 0 & 0 \\ S_i & C_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & l_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_i & -S_i & 0 & l_i C_i \\ S_i & C_i & 0 & l_i S_i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.13)$$

where C_i and S_i represent $\cos\theta_i$ and $\sin\theta_i$ respectively.

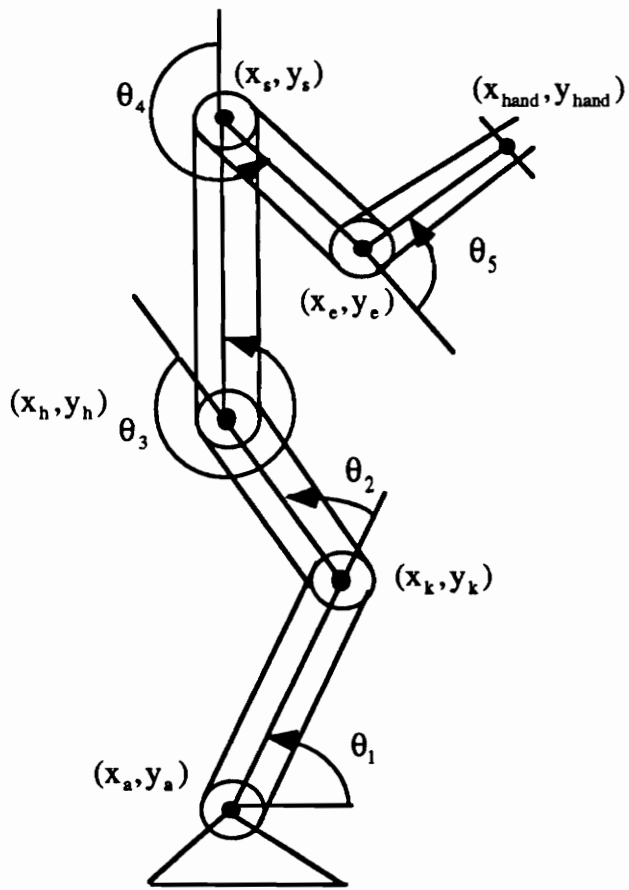


Figure 3.6 Definition of angles and joints.

The goal of forward kinematics is to solve for the hand position (p_x, p_y) knowing the angles (the orientation of each link). Using the equations from (3.9) and (3.13), the transformation matrix ${}^0T_{hand}$ can be calculated.

$${}^0T_{hand} = \begin{bmatrix} C_\phi & -S_\phi & 0 & p_x \\ S_\phi & C_\phi & 0 & p_y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.14)$$

where

$$\begin{aligned} \phi &= \theta_1 + \theta_2 + \theta_3 + \theta_4 + \theta_5, \text{ and} \\ p_x &= l_1 C_1 + l_2 C_{12} + l_3 C_{123} + l_4 C_{1234} + l_5 C_{12345} \\ p_y &= l_1 S_1 + l_2 S_{12} + l_3 S_{123} + l_4 S_{1234} + l_5 S_{12345} \end{aligned} \quad (3.15)$$

and where

$$\begin{aligned} C_{123..i} &= \text{Cos}[\theta_1 + \theta_2 + \theta_3 + \dots + \theta_i] \\ S_{123..i} &= \text{Sin}[\theta_1 + \theta_2 + \theta_3 + \dots + \theta_i]. \end{aligned} \quad (3.16)$$

If the angles are known, equation (3.15) can be used to calculate the hand position.

3.3.3 Inverse Kinematics

3.3.3.1 Description of Inverse Kinematic Solution

Given a method to calculate the hand position from the link angles, the next step is to go backwards and solve for the link angles knowing the hand position. The approach taken is to break the five link system into two separate 2 link problems and assume the forearm orientation is fixed.

The solution shown in this section is indeterminate since there are three unknown variables, the x and y hip position and ϕ (which defines the forearm (l_5) orientation relative to the horizontal) as shown in Figure 3.7. A criterion was used to solve for these three variables discussed in section 3.4.2.

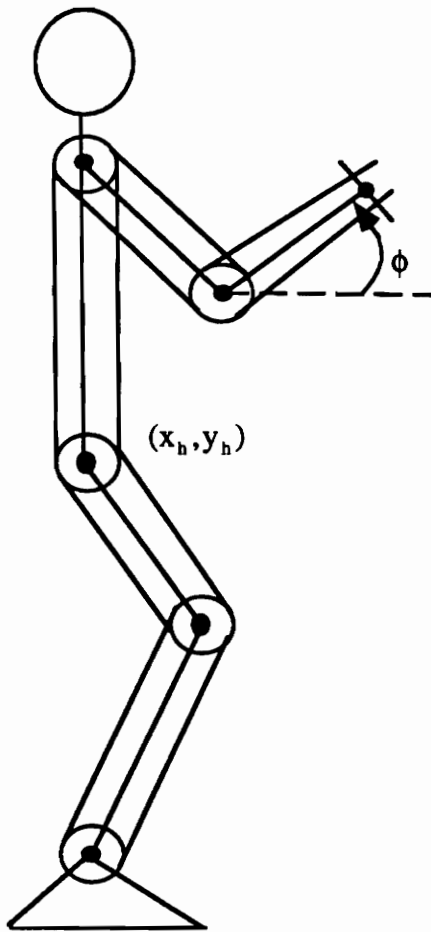


Figure 3.7 Description of unknown variables. Note: known variables are link lengths, hand position, ankle position, weight of body and load lifted.

For a two link problem, assuming the outer points are fixed, there are only two solutions. In other words, there are only two locations where the endpoints of the links will intersect. For example, there are two solutions for the knee assuming the hip and ankle position are known. Since one of the two solutions requires the knee to be beyond it's range of motion, it is a safe assumption that this is not the correct solution. The same is true in general for the shoulder: if it is assumed that the elbow and the hip are known, there is usually only one solution that is feasible given the kinematic and range of motion constraints for the shoulder. In rare cases, there are situations where both solutions for the shoulder are feasible. This situation will be discussed in greater detail in section 3.3.3.3.

In defining the inverse kinematic solution, the "atan2" function as described in Table 3.2 is used. This function is used to avoid getting incorrect results due to signs (Fu, Gonzalez and Lee, 1987). For example the atan function does not distinguish between (-y/x) and (y/-x) but atan2 does make this distinction. So $\text{atan}(-y/x)=\text{atan}(y/-x)$ but $\text{atan2}[-y,x]\neq\text{atan2}[y,-x]$.

TABLE 3.2 Definition of atan2.

		atan2[y,x]:		$\tan^{-1}\left(\frac{y}{x}\right) = \theta$	
where		x	y		
	if	+	+	then	$0 \leq \theta < 90$
	if	-	+	then	$90 \leq \theta \leq 180$
	if	-	-	then	$-180 \leq \theta \leq -90$
	if	+	-	then	$-90 \leq \theta \leq 0$

There are two parts to this inverse kinematic problem: the knee position is found analytically using algebraic relationships based on Byun (1991) and the shoulder and elbow positions are solved geometrically using geometric relationships. Note that for the calculations in this section, the hip location (x_h, y_h) and the forearm orientation ϕ are

assumed to be known. A method to estimate these three variables is discussed in section 3.4.

3.3.3.2 Analytical Solution to Solve the Ankle Angle θ_1 and Knee Angle θ_2

First an arbitrary hip point (x_h, y_h) is chosen and is defined relative to the known ankle point:

$$x_h^* = x_h - x_a, \text{ and} \quad (3.17)$$

$$y_h^* = y_h - y_a. \quad (3.18)$$

From equation (3.15) it is known that

$$x_h^* = l_1 C_1 + l_2 C_{12}, \text{ and}$$

$$y_h^* = l_1 S_1 + l_2 S_{12}. \quad (3.19)$$

the knee angle θ_2 can be solved by squaring and summing equation (3.19):

$$(x_h^*)^2 = l_1^2 C_1^2 + 2l_1 l_2 C_1 C_{12} + l_2^2 C_{12}^2$$

$$(y_h^*)^2 = l_1^2 S_1^2 + 2l_1 l_2 S_1 S_{12} + l_2^2 S_{12}^2 \quad (3.20)$$

so that,

$$(x_h^*)^2 + (y_h^*)^2 = l_1^2 + l_2^2 + 2l_1 l_2 C_2$$

$$\cos \theta_2 = \frac{(x_h^*)^2 + (y_h^*)^2 - l_1^2 - l_2^2}{2l_1 l_2} \quad (3.21)$$

where,

$$-1 \leq \frac{(x_h^*)^2 + (y_h^*)^2 - l_1^2 - l_2^2}{2l_1 l_2} \leq 1 \quad (3.22)$$

and,

$$\sin \theta_2 = \pm \sqrt{1 - \cos^2 \theta_2} \quad (3.23)$$

$$\theta_2 = \arctan 2[\sin \theta_2, \cos \theta_2]. \quad (3.24)$$

To solve for ankle angle θ_1 :

$$\begin{aligned}x_h^* &= k_1 C_1 - k_2 S_1, \text{ and} \\y_h^* &= k_1 S_1 + k_2 C_1\end{aligned}\quad (3.25)$$

where

$$\begin{aligned}k_1 &= l_1 + l_2 C_2 \\k_2 &= l_2 S_2\end{aligned}\quad (3.26)$$

let

$$\begin{aligned}r &= \sqrt{k_1^2 + k_2^2}, \text{ and} \\ \gamma &= a \tan 2[k_1, k_2]\end{aligned}\quad (3.27)$$

then

$$\begin{aligned}k_1 &= r \cos(\gamma), \text{ and} \\k_2 &= r \sin(\gamma)\end{aligned}\quad (3.28)$$

$$\begin{aligned}\frac{x_h^*}{r} &= \cos(\gamma + \theta_1), \text{ and} \\ \frac{y_h^*}{r} &= \sin(\gamma + \theta_1)\end{aligned}\quad (3.29)$$

$$\gamma + \theta_1 = a \tan 2[\sin(\gamma + \theta_1), \cos(\gamma + \theta_1)] = a \tan 2\left[\frac{y_h^*}{r}, \frac{x_h^*}{r}\right]\quad (3.30)$$

$$\gamma + \theta_1 = a \tan 2[y_h^*, x_h^*]\quad (3.31)$$

and

$$\theta_1 = a \tan 2[y_h^*, x_h^*] - a \tan 2[k_2, k_1].\quad (3.32)$$

3.3.3.3 Geometric Solution for Hip Angle θ_3 and Shoulder Angle θ_4

As in the analytical solution, the hip location is assumed to be known when solving for θ_3 and θ_4 . See Figure 3.8 for a description of the variables used in this geometric solution.

Assuming ϕ (forearm orientation) is known, the elbow position can be calculated:

$$x_e = x_{\text{hand}} - l_5 \cos \phi, \text{ and}$$

$$y_e = y_{\text{hand}} - l_5 \sin \phi \quad (3.33)$$

$$\begin{aligned} x_e^* &= x_e - x_h, \text{ and} \\ y_e^* &= y_e - y_h \end{aligned} \quad (3.34)$$

$$\begin{aligned} x_e^* &= l_3 \cos \theta'_3 + l_4 \cos(\theta'_3 + \theta_4), \text{ and} \\ y_e^* &= l_3 \sin \theta'_3 + l_4 \sin(\theta'_3 + \theta_4) \end{aligned} \quad (3.35)$$

$$\theta'_3 = \theta_1 + \theta_2 + \theta_3 - 2\pi \quad (3.36)$$

$$(x_e^*)^2 + (y_e^*)^2 = l_3^2 + l_4^2 + 2l_3l_4C_4. \quad (3.37)$$

Equation (3.35) is squared and then summed:

$$-1 \leq \cos \theta'_4 = \frac{(x_e^*)^2 + (y_e^*)^2 - l_3^2 - l_4^2}{2l_3l_4} \leq 1, \text{ and}$$

$$\sin \theta'_4 = \pm \sqrt{1 - \cos^2 \theta'_4} \quad (3.38)$$

$$\theta'_4 = a \tan 2[\sin \theta'_4, \cos \theta'_4] \quad (3.39)$$

$$\begin{aligned} k_3 &= l_3 + l_4 C_4, \text{ and} \\ k_4 &= l_3 S_4. \end{aligned} \quad (3.40)$$

$$\theta'_3 = a \tan 2[y_e^*, x_e^*] + a \tan 2[k_4, k_3] \quad (3.41)$$

$$\theta_3 = \theta'_3 + 2\pi - (\theta_1 + \theta_2) \quad (3.42)$$

$$\alpha = a \tan 2[(y_e^* - l_3 \sin \theta'_3), (x_e^* - l_3 \cos \theta'_3)] \quad (3.43)$$

$$\theta_4 = \alpha + 2\pi - \theta'_3 \quad (3.44)$$

Then the elbow angle θ_5 can be calculated:

$$\theta_5 = \phi - (\theta_1 + \theta_2 + \theta_3 + \theta_4) \quad (3.45)$$

Given this procedure, it is possible to have two feasible shoulder locations with the same hip location and forearm orientation as shown in Figure 3.9. The other solution is

calculated in the same way as above except that equation (3.41) is replaced by the following equation.

$$\theta'_3 = a \tan 2[y_e^*, x_e^*] - a \tan 2[k_4, k_3] \quad (3.46)$$

Thus if $0 \leq \theta_3 \leq \pi$ for both solutions then both postures are feasible. One of the two solutions is chosen by selecting the posture that best fits the criteria (discussed in section 3.4.2).

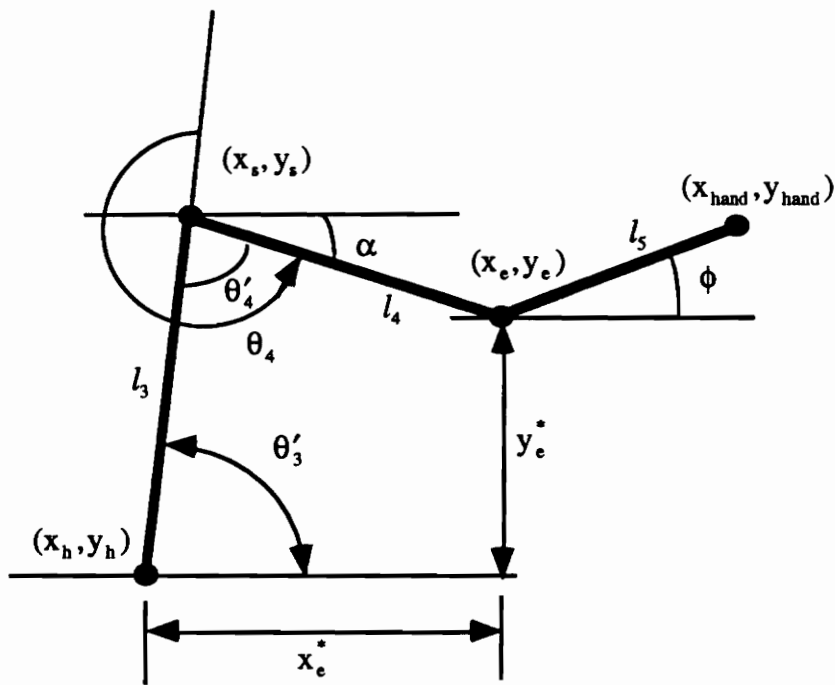
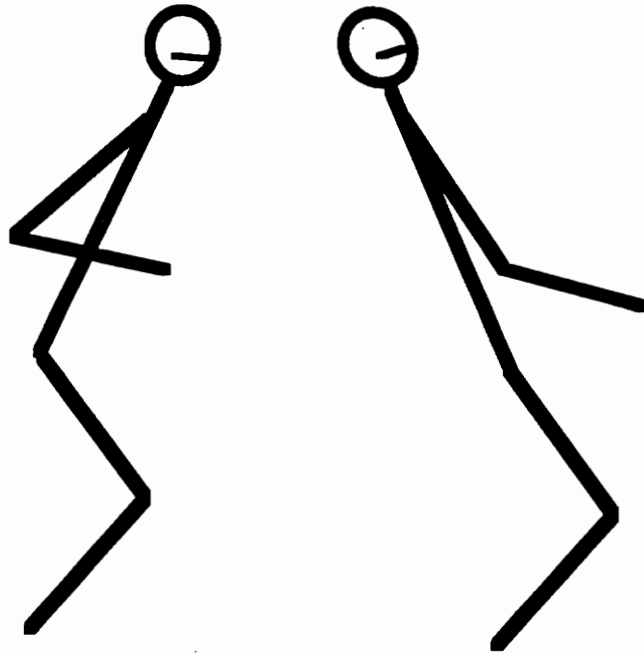
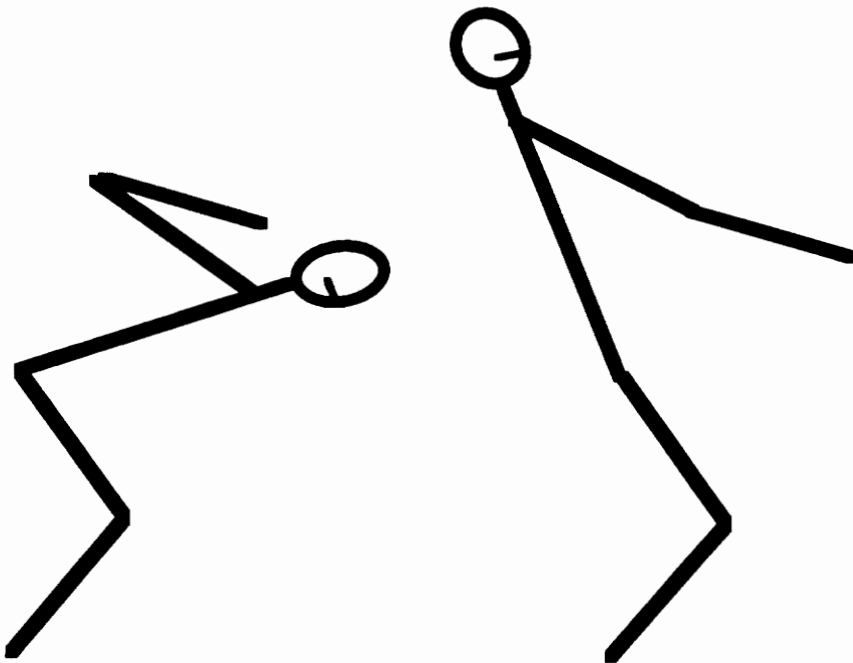


Figure 3.8 Description for geometric solution for the shoulder angle θ_4 .



a) Both postures are feasible



b) Only the right posture is feasible because the elbow angle is beyond the range of motion in the left posture.

Figure 3.9 Postures with same hip position and forearm orientation: a) Description for two feasible geometric solutions, b) One feasible posture of the two geometric solutions.

3.3.4 Forces and Torques

As shown in the previous section, the posture can be calculated if the hip position and forearm orientation are known. To estimate these values an optimization procedure was employed. This procedure, discussed in section 3.4, used three criteria or objective functions defined in terms of torques at the joints. This section describes how the values for the torques at the joints are calculated.

An approximation of each link mass as a percentage of the total body weight was used as shown in Table 3.3. Figure 3.10 describes where the center of mass for each link is located in terms of percentage of link length. These link lengths were measured for each subject using a WATSMART motion analysis system to be discussed in Chapter 4.

TABLE 3.3 Percentage distribution of total body weight according to different segmentation plans (from Webb Associates, 1978)

Grouped Segments, % of Total Body Weight	
Head, neck and torso = 58.4 %	
(2 arms) Upper arms = 5.6 %	
(2) Forearms = 4.6 %	(including hand)
(2) Thighs = 20.0 %	
(2) Shanks = 8.6 %	
(2) Feet = 2.8 %	

The solution for calculating forces and moments is adapted from Byun (1991) using the approximations of mass and center of mass for each link. Figure 3.11 describes the variables that were used to calculate the torques at each joint defined as τ_a , τ_k , τ_h , τ_s , and τ_e . One of the criterion uses the torque levels at the ball τ_{ball} and heel τ_{heel} of the foot (shown in Figure 3.12) which will be discussed in section 3.4.2. Appendix B

contains the calculations used to obtain the forces and moments at all the joints as well as the heel and ball of the foot.

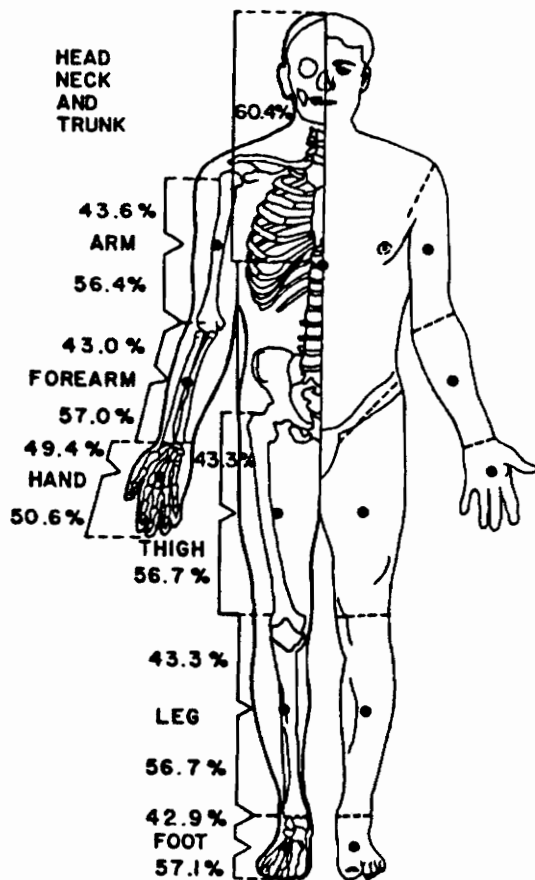


Figure 3.10 Location of link center of mass. Adapted from Chaffin and Andersson (1991).

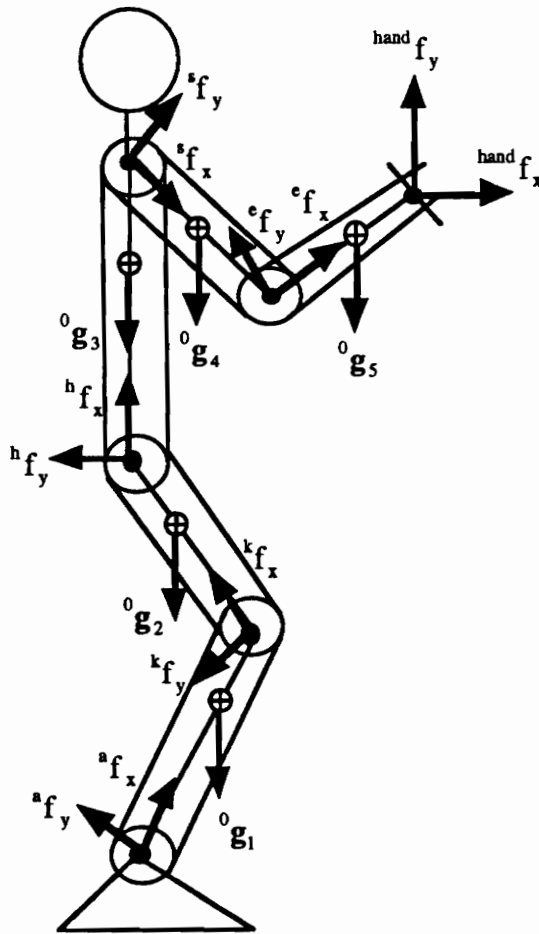


Figure 3.11 Definition of forces on body.

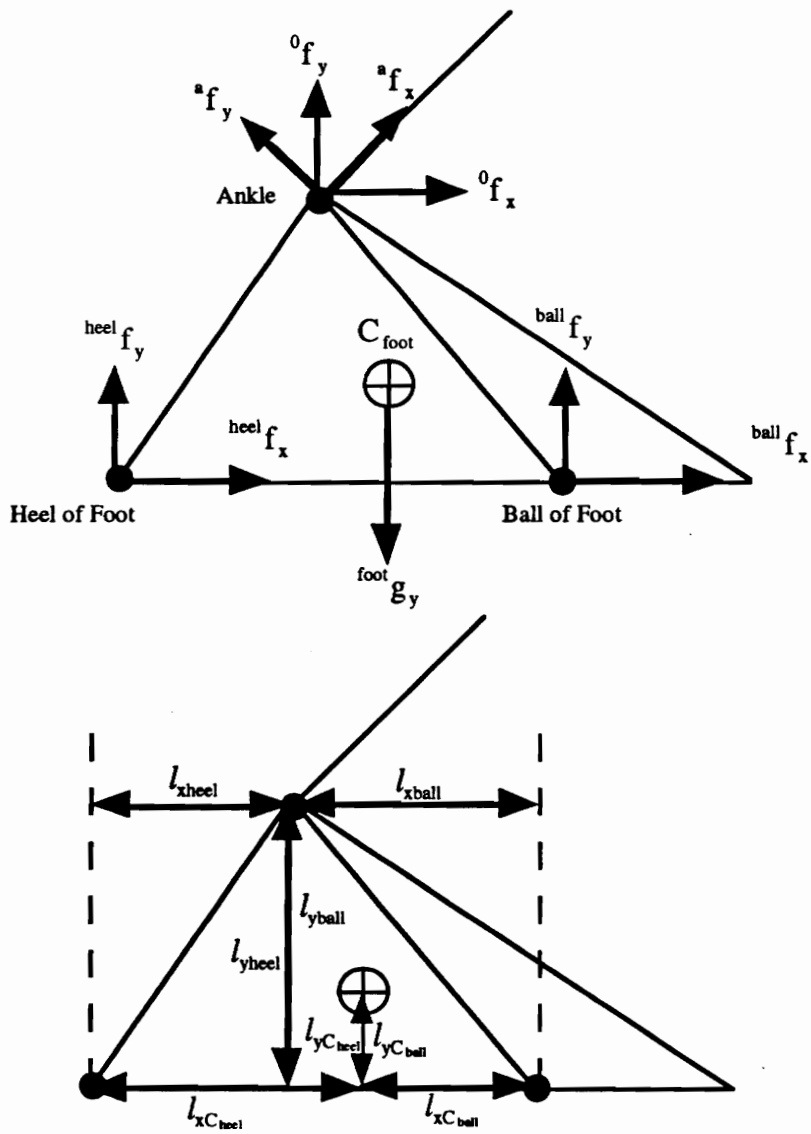


Figure 3.12 Forces at the foot.

3.4 Non-Linear Optimization

One goal of this thesis was to predict the posture, given the hand position relative to the ankle. The calculations in the above sections are indeterminate because there are three unknown variables: ϕ , the angle of the forearm relative to the horizontal, and two variables that define the hip position (x_h, y_h) . This section will describe how an optimal solution was chosen.

3.4.1 Constraints

A solution set is an area where all values of forearm orientation ϕ and hip position (x_h, y_h) are feasible. The boundaries of this solution set are defined by the following constraints:

- 1) The joints cannot be dislocated. As shown in Figure 3.13, the hip joint (x_h, y_h) must be inside the feasible solution defined by the link constraints. If the hip joint is outside this area, the inverse kinematic calculations can not solve the problem.
- 2) All the joints of a posture must be within the defined joint range of motions. Each link angle for a chosen posture is checked with the values in Table 3.4 to make sure the chosen posture is feasible for a human.

TABLE 3.4 Constraints on each joint range of motion. Adapted from Webb Associates, 1978.

θ_i	lower	upper
θ_1	29°	153°
θ_2	0°	174°
θ_3	-50° ¹	180° ²
θ_4	120°	370°
θ_5	0°	180°

- 1 - Spine flexion
2 - Hip extension

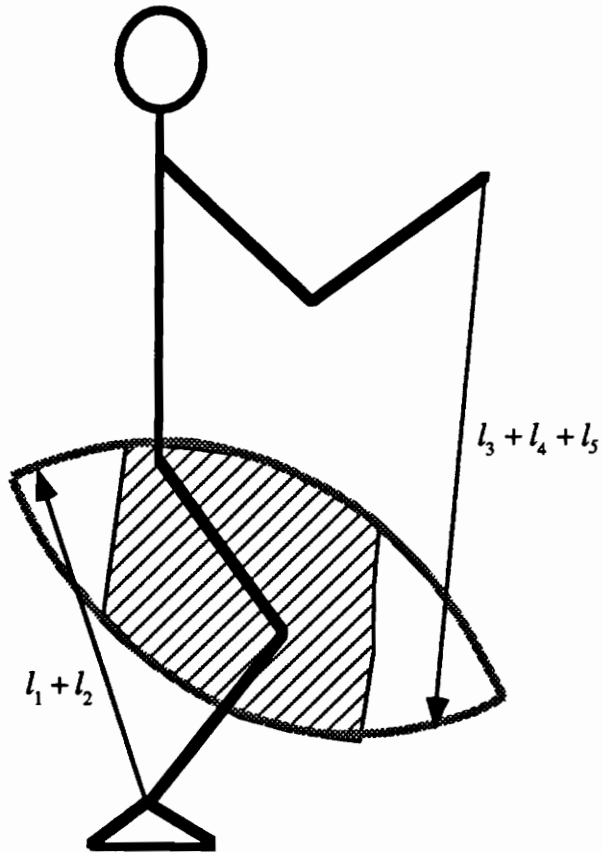


Figure 3.13 Feasible solution for the hip with link length constraints assuming the same hand position. The body will not tip over if the hip is in the cross-hatched area.

3) A person in the chosen posture should remain standing as defined by the balance constraints.

The third constraint uses Kerk's (1992) research which investigated the stability of a posture by looking at the predicted torque at the ball and heel of the feet. This thesis used calculations from Byun (1991) who modified Kerk's equations into matrices which is described in Appendix B. Kerk's model assumes that if the amount of torque at the heel or ball exceeds a certain limit then the body is not static thus falling either forwards or backwards. In this case, if the torque at the heel is less than or equal to zero $\tau_{heel} \leq 0$, it is assumed that the body will not tip over backwards. If the torque at the ball is greater than or equal to zero $\tau_{ball} \geq 0$, it is assumed that the body will not tip over forwards.

Figure 3.13 shows a solution set defined by both the first and third constraints. The optimal solution for the hip location must be inside the shaded area.

3.4.2 Criteria

A criterion must be used to determine the optimal solution (posture) inside this feasible region. For this research, the criterion was defined as a mathematical objective function. A search method (described in section 3.4.3) was used to choose the optimal solution to each of the objective functions. There are three criteria that were investigated for this thesis.

Total Torque: The first criterion investigates the theory that humans choose a posture which requires the least amount of effort. For this criterion, effort is defined as proportional to the total torque in all the joints. The objective function can be defined as:

$$\text{Minimize } \{|\tau_a| + |\tau_k| + |\tau_h| + |\tau_s| + |\tau_e|\} \quad (3.47)$$

Percent Strength: The second criterion is similar to the first in that it assumes that humans choose a posture that has the smallest amount of effort, but this criterion defines effort as the torque exerted at a joint relative to the subject's joint strength. This assumes

that the higher the ratio of torque exerted to the joint strength, the more exertion is perceived at that particular joint. This theory suggests that humans try to choose a posture where the overall perceived exertion is minimal. The posture with the smallest "largest percent of torque" is chosen as the optimal posture. Where the percentage of a torque is the moment exerted divided by the predicted mean strength of a joint. Table 3.5 describes the equations used to predict the mean strength. The objective function is:

$$\text{Minimize } \left\{ \text{Max} \left[\frac{\tau_a}{S_a}, \frac{\tau_k}{S_k}, \frac{\tau_h}{S_h}, \frac{\tau_s}{S_s}, \frac{\tau_e}{S_e} \right] \right\}. \quad (3.48)$$

Balance: The third criterion examines the theory that humans choose a posture where they feel most stable. If a human chooses an unstable posture, this person will not be able to remain standing. Thus a posture is chosen where a human doesn't feel like he or she is falling forwards or backwards. The objective function is defined as:

$$\text{Minimize } \{ \tau_{\text{ball}} - \tau_{\text{heel}} \} \quad (3.49)$$

Figures 3.14 shows an example of postures that fit the three criteria for a male with 50 percentile stature lifting 39 N. The non-linear search for getting these postures is described in section 3.4.3. Notice for these particular hand positions, the postures for each criterion are different.

TABLE 3.5 Joint moment-strength mean prediction equations (adapted from Chaffin and Andersson, 1991).

Strength	Predicted Mean Strength (N m)	Gender	
		Male	Female
Elbow flexion	$S_E = [336.29 + 1.544\alpha_E - 0.0085\alpha_E^2 - 0.5\alpha_S][G]$	0.1913	0.1005
Elbow extension	$-S_E = [264.153 - 0.575\alpha_E - 0.425\alpha_S][G]$	0.2126	0.1153
Shoulder flexion	$S_S = [227.338 - 0.525\alpha_E - 0.296\alpha_S][G]$	0.2845	0.1495
Shoulder extension	$-S_S = [204.562 - 0.099\alpha_S][G]$	0.4957	0.2485
Hip flexion	$S_H = [-820.21 + 34.29\alpha_H - 0.11426\alpha_H^2][G]$	0.1304	0.0871
Hip extension	$S_H = [3338.1 - 15.711\alpha_H - 0.04626\alpha_H^2][G]$	0.0977	0.0516
Knee flexion	$-S_K = [-94.437 + 6.3672\alpha_K][G]$	0.1429	0.0851
Knee extension	$S_K = [1091.9 - 0.0996\alpha_K - 0.17308\alpha_K^2 - 0.00097\alpha_K^3][G]$	0.0898	0.0603
Ankle extension	$-S_A = [3356.8 + 18.4\alpha_A][G]$	0.0816	0.0489

Where:

$$\alpha_E = \pi - \theta_5$$

$$\alpha_S = \theta_4 - \pi$$

$$\alpha_H = \theta_3 - \pi$$

$$\alpha_K = \pi - \theta_2$$

$$\alpha_A = \theta_1$$

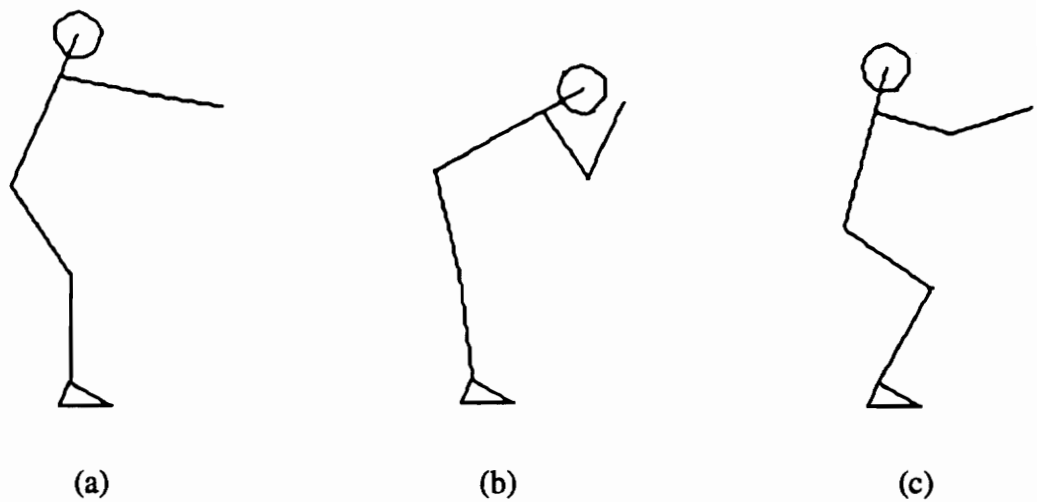


Figure 3.14 Examples of the solution for a 50 percentile male lifting 39 N. The figures represent the solutions for a) Total Torque, b) Percent of Strength, and c) Balance. The hand position is (0.65 m, 1.2 m) from the ankle.

3.4.3 Non-Linear Search Method

The three criteria are functions in a 3-dimensional space that have a unique minimum. Figure 3.15 shows the function of a 50th percentile stature male holding 1 kg weight at a hand position of (0.5 m, 1.3 m) from the ankle . This graph plots the Total Torque criterion as a function of hip location over all forearm orientations. This figure shows that the Total Torque criterion is non-linear and non-convex, but there is one unique solution.

A non-linear search algorithm was used to search for the solution inside the feasible solution area as defined in the previous section. The non-linear search used was developed by Nelder and Mead (Bazaraa, Sherali, and Shetty, 1993). Because 192 solutions (4 hand positions x 16 subjects x 3 criteria) were calculated, the search had to be computationally efficient. The search took about 5 to 25 minutes to find a solution, compared to other searches (such as line searches which could take up to two hours to find a solution). The Nelder and Mead search is much faster because it searches in three dimensional space where a line search looks at only one dimension at a time. Unfortunately the Nelder and Mead search procedure sacrifices accuracy in exchange for speed. Figure 3.17 gives an example of what is actually happening in the search. The following is a description of the algorithm which is also described in a flowchart in Figure 3.16.

Let $f(x_h, y_h, \phi)$ equal the function that is trying to be minimized, where the point $x = \{x_h, y_h, \phi\}$ is in the feasible solution set described above.

Initialization Step: Choose four points x_1, x_2, x_3, x_4 (a starting simplex) which are in the feasible solution set.

Choose the following constants, where:

reflection coefficient: $\alpha > 0$

expansion coefficient $\gamma > 1$

positive contraction coefficient $\beta > 1$

Note: The constants were set as $\beta=1.4$, $\gamma=1.4$, $\alpha=0.5$.

Main Step

1. Let $\mathbf{x}_r, \mathbf{x}_s \in \{\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \mathbf{x}_4\}$ be such that

$$f(\mathbf{x}_r) = \text{minimum } f(\mathbf{x}_j) \text{ where } 1 \leq j \leq 4$$

$$f(\mathbf{x}_s) = \text{minimum } f(\mathbf{x}_j)$$

$$\text{Let } \bar{\mathbf{x}} = \frac{1}{3} \sum_{\substack{j=1 \\ j \neq s}}^{n+1} \mathbf{x}_j, \text{ and go to step 2.}$$

2. Let $\hat{\mathbf{x}} = \bar{\mathbf{x}} + \alpha(\bar{\mathbf{x}} - \mathbf{x}_r)$. If $f(\mathbf{x}_r) > f(\hat{\mathbf{x}})$, let $\mathbf{x}_e = \bar{\mathbf{x}} + \gamma(\hat{\mathbf{x}} - \bar{\mathbf{x}})$, and go to step 3.

Otherwise, go to step 4.

3. The point \mathbf{x}_s is replaced by \mathbf{x}_e if $f(\hat{\mathbf{x}}) > f(\mathbf{x}_e)$ and by $\hat{\mathbf{x}}$ if $f(\hat{\mathbf{x}}) \leq f(\mathbf{x}_e)$ to yield a new set of 4 points. Go to step 1.

4. If $\max_{1 \leq j \leq 4} \{f(\mathbf{x}_j) : j \neq s\} \geq f(\hat{\mathbf{x}})$, then \mathbf{x}_s is replaced by $\hat{\mathbf{x}}$ to form a new set of 4 points, and go to step 1. Otherwise go to step 5.

5. Let \mathbf{x}' be defined by $f(\mathbf{x}') = \min \{f(\hat{\mathbf{x}}), f(\mathbf{x}_s)\}$, and let $\mathbf{x}'' = \bar{\mathbf{x}} + \beta(\mathbf{x}' - \bar{\mathbf{x}})$. If $f(\mathbf{x}'') > f(\mathbf{x}')$, replace \mathbf{x}_j with $\mathbf{x}_j + \frac{1}{2}(\mathbf{x}_r - \mathbf{x}_j)$ for $j=1 \dots 4$ and go to step 1. If $f(\mathbf{x}'') \leq f(\mathbf{x}')$, then \mathbf{x}'' replaces \mathbf{x}_s to form a new set of 4 points. Go to step 1.

Note: The algorithm went to step 1 three times and then stopped.

The most important part of this search is to start with good starting points (a good simplex). The quality of the simplex depends on the characteristics of the search method and the function being searched. Since these functions are non-convex, there is a danger of calculating a local minimum rather than the global minimum of the function. Choosing a quality starting simplex can be extremely difficult because each of the 192 functions have different characteristics. To find the global minimum of each function, several starting simplices were used. The choice of these starting simplices are described in Appendix C.

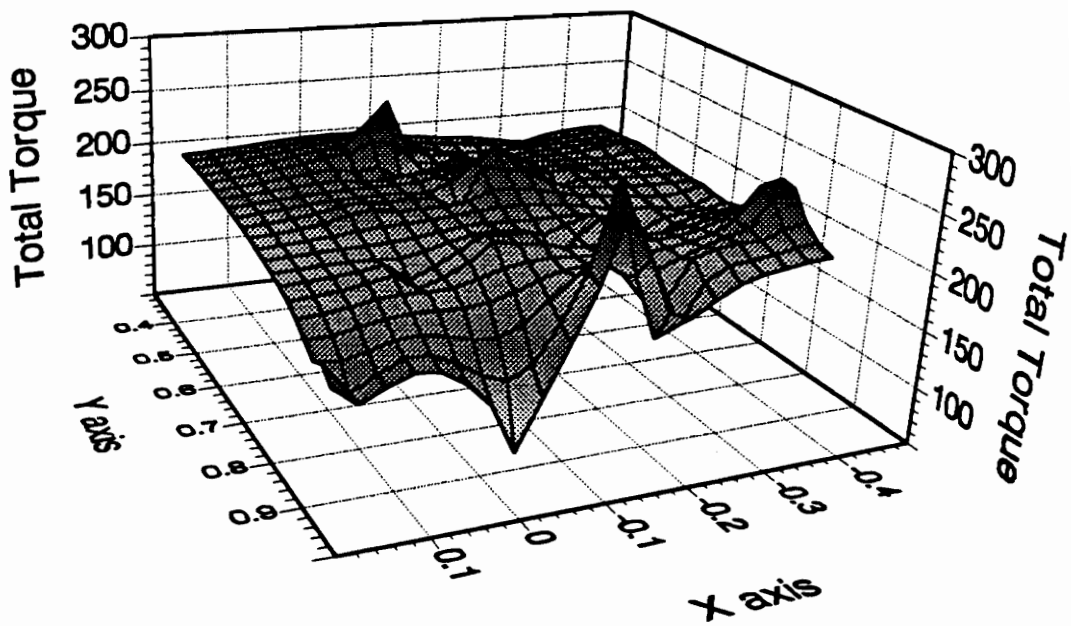


Figure 3.15 Graph of Total Torque as a function of hip position.

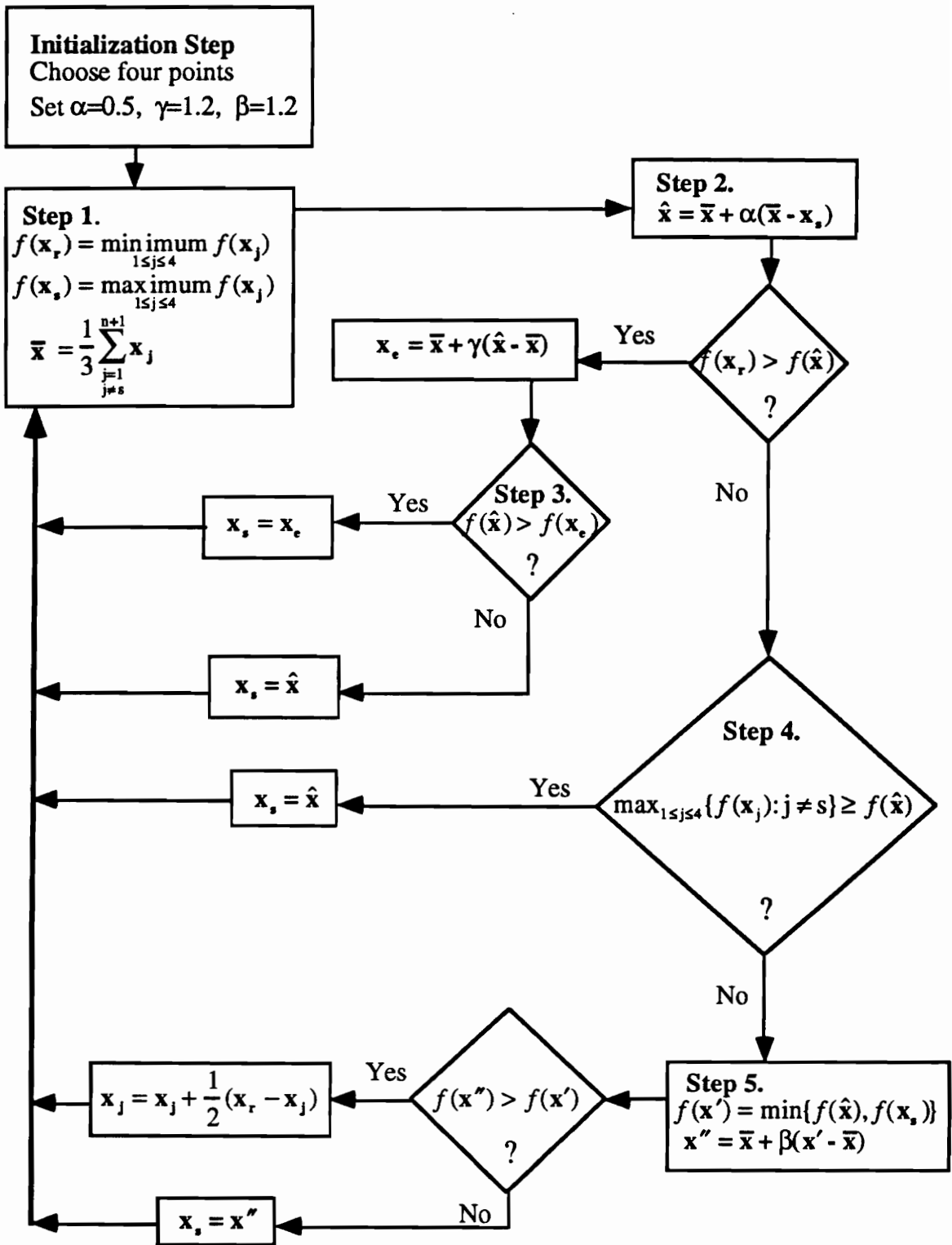


Figure 3.16 Flowchart of Nelder and Mead Nonlinear minimum search

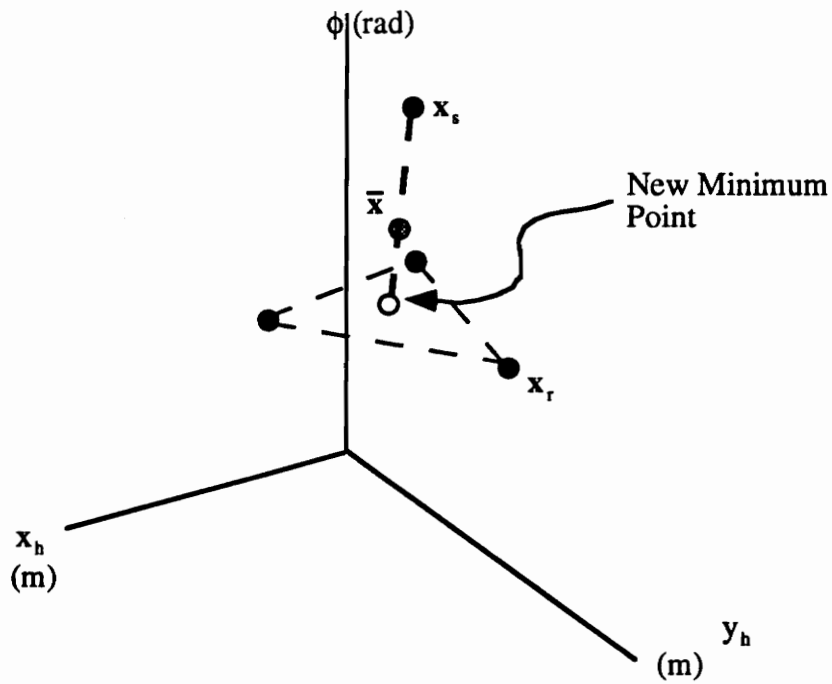


Figure 3.17 Example of Nelder and Mead search. The open circle is the new point.

4.0 EXPERIMENTAL METHOD

This chapter describes the experiment to validate the algorithms described in Chapter 3. Subjects performed a static lifting task and their posture was recorded. The posture data collected from this experiment was compared with the predicted postures to determine the accuracy of each of the three criteria proposed in Chapter 3.

4.1 Subjects

Sixteen college students (eight male and eight female) served as participants in the research. They were recruited from the student body at Virginia Tech by means of advertisement. All participants were in good health with no history of back pain and no injuries in the past year. Each subject filled out an informed consent form prior to the study shown in Appendix F. Table 4.1 shows the relevant statistics for the subject group. Subjects were reimbursed \$5 per hour for the three hour experiment for a total of \$15.

TABLE 4.1 Subject statistics

Measure	Males	Females
Age (years)		
Mean	23.13	21.50
Std.	2.80	4.00
Minimum	20	18
Maximum	28	30
Stature (cm)		
Mean	181.21	165.35
Std.	6.65	4.96
Minimum	171.1	154.8
Maximum	188.9	171.3
Weight (kg)		
Mean	77.45	56.63
Std.	6.78	6.83
Minimum	67.4	48.2
Maximum	83.9	67.0

4.2 Apparatus

The equipment used for this experiment included a posture recording system and a lifting apparatus.

4.2.1 Posture Measurement System

A Northern Digital WATSMART three-dimensional motion analysis system was used to record subjects' posture during the experimental trials. The system components included infrared emitting diodes, three infrared cameras, a calibration frame, and the system unit which interfaced to a GRID 386 personal computer. The WATSMART system tracked the infrared diodes when they were attached to body targets. The cameras were positioned on the right side of the subject, as shown in Figure 4.1, to record all diodes in a three dimensional area at a collection frequency of 20 Hz. The cameras were mounted to stainless steel poles that were anchored in small circular concrete bases. The cameras are extremely sensitive to reflections and therefore the experimental area was bordered by black non-reflecting foam material hung as drapes on three sides. A video recorder was used as backup in case a posture could not be fully recorded by the WATSMART system.

4.2.2 Lifting Apparatus

The lifting apparatus consisted of a weight and a height marker. The weight was a 4 kg weight piece attached to a wooden dowel (total weight of 4.6 kg) as shown in Figure 4.2. The weight was designed to be held by two hands on either side of the weight with the dowel aligned with the height marker. A piece of tape was placed on each side of the weight so that the subject could align their middle finger with that piece of tape. A WATSMART diode was attached to the right end of the dowel to record the hand position.

The height marker, shown in Figure 4.3, consisted of an anthropometric measuring scale and a base to hold the scale perpendicular to the ground. The subject aligned the dowel of the weight with the marker on the anthropometric measuring scale. The height and horizontal distance of the marker from the ankle were adjusted for the appropriate condition in the experiment. The subject aligned the back of the heels to a strip of tape on the floor.

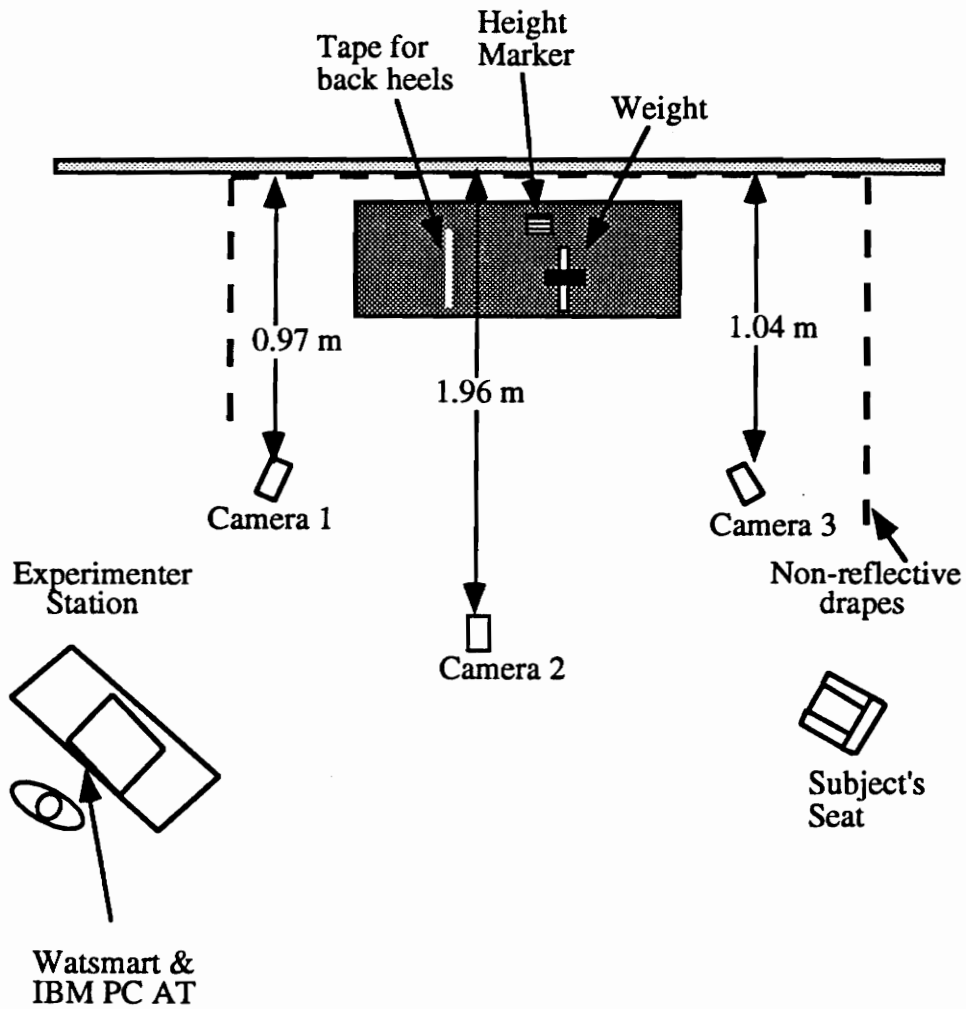


Figure 4.1 Arrangement of experimental setup.

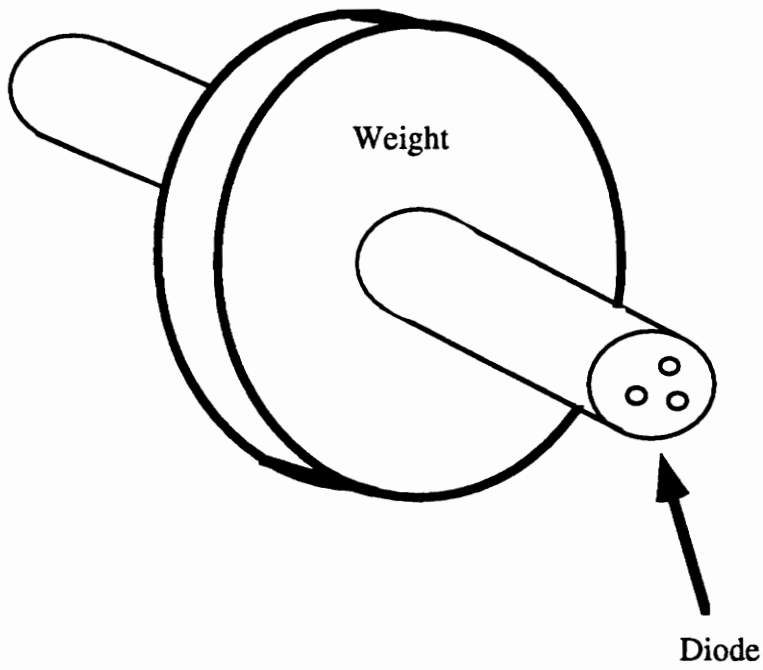


Figure 4.2 Arrangement of weight.

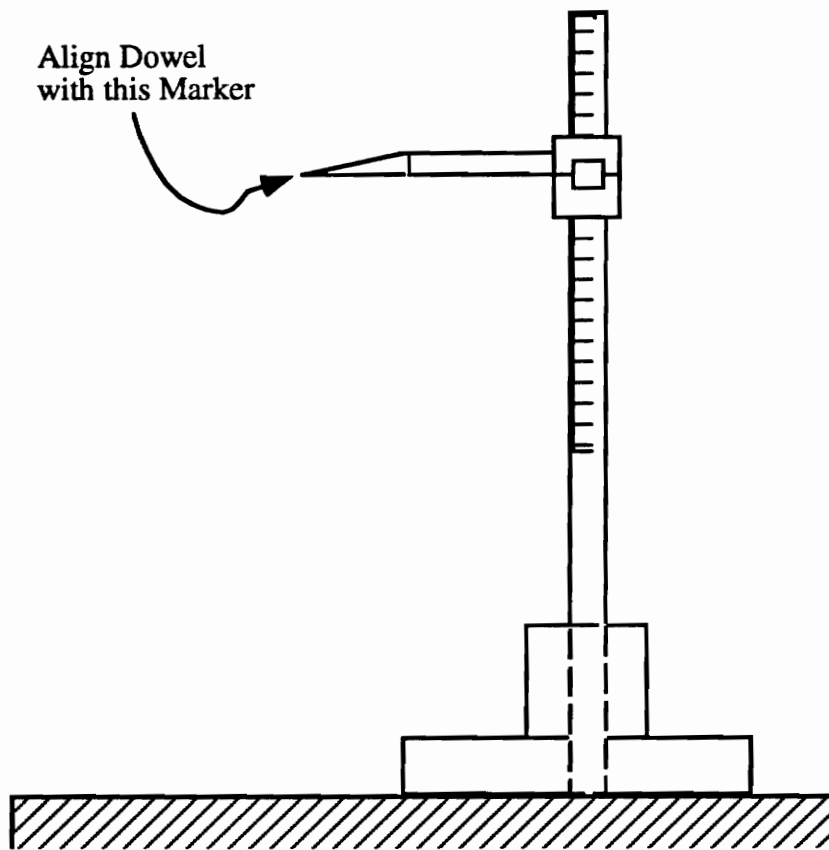


Figure 4.3 Picture of height marker.

4.3 Marker Placement

Figure 4.4 describes where the five WATSMART markers were placed on the right side of the body. The joint COR's were defined by the following bony landmarks as described in NASA/Webb (1978):

- Elbow:** Midpoint on a line between (1) lowest palpable point the medial epicondyle of the humerus and (2) a point 8 mm above the radiale (radiohumeral junction).
- Shoulder:** Midpoint position of the palpable junction between the proximal end of clavicle and the sternum at the upper border of the sternum
- Hip:** A point at the tip of the femoral trochanter, 1 cm anterior to the most laterally projecting part of the femoral trochanter.
- Knee:** Midpoint of a line between the center of the posterior convexities of the femoral condyles.
- Ankle:** Level of a line between the tip of the lateral malleolus of the fibula and a point 5 mm distal to the tibial malleolus.

Table 4.2 describes the anthropometric measurements that were taken as inputs for the posture prediction algorithm and to estimate the joint CORs.

TABLE 4.2 Anthropometric measurements used for the algorithm and COR estimation.

Measurement	Description
stature	with shoes
weight	with shoes
l_{xheel}	Horizontal distance from ankle to back of heel (shoes on)
l_{xball}	Horizontal distance from ankle to edge of toe (shoes on)
l_{yball}	Vertical distance from ankle to bottom of foot.
Shoulder to diode	Distance between shoulder and a diode on the elbow
Hip to diode	Distance between hip and a diode on the knee

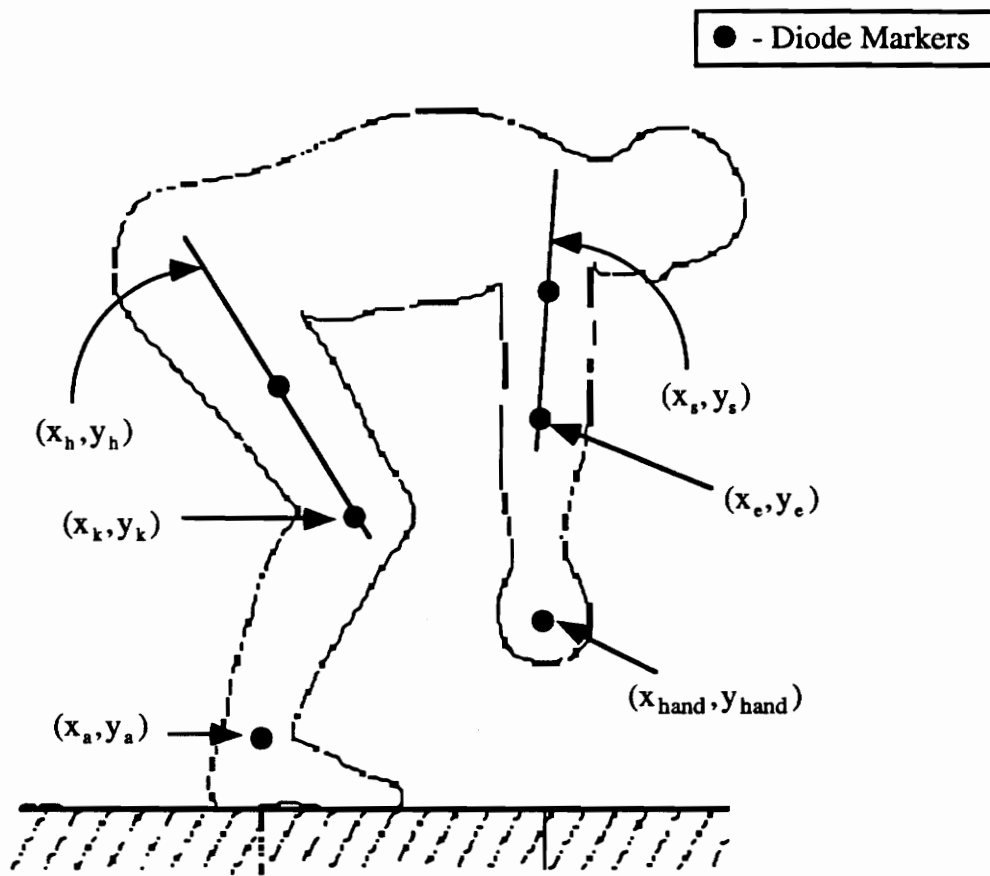


Figure 4.4 Description of the diode locations.

4.4 Joint Center Estimation

As discussed in section 2.4.2, joint centers of rotation (COR) are difficult to determine from surface markers due to movement of the skin over the joints. The following sections discuss the method used to calculate the joint CORs.

4.4.1 Hip and Shoulder estimation

The hip location was calculated by using the diode on the second link (the thigh) and the diode on the knee to create a vector pointing towards the hip. Since the distance between the hip and the knee was known, the hip location was determined with respect to the knee diode. Shoulder location was calculated in an identical manner using the vector created by diodes on the bicep and the elbow.

4.4.2 Ankle, Knee, and Elbow estimation

As shown in Figure 4.4, the diodes for the ankle, knee and elbow were placed directly over the joints. Diodes were attached to the clothing worn by the subjects and occasionally shifted during the trials. To control for this, the diodes were checked between trials to make sure that they were aligned correctly.

4.5 Experimental Task

The experimental task consisted of maintaining a posture for four seconds while holding a weight at the specified height. The experimenter did not explain how to perform the task but only emphasized that the purpose of the task was to hold the weight at the appropriate height for 4 seconds.

4.6 Experimental Design

There were 32 trials for each of the 16 subjects. Each subject performed the lifting task 8 times at each of the four hand positions. All 32 trials were presented to the subject in random order.

4.6.1 Independent Variables

Gender: between-subjects, male and female.

Hand Position: within-subjects, four levels: (0.3 m,1.2 m), (0.3 m,0.5 m), (maximum reach distance, 1.2 m), (maximum reach distance, 0.5 m). These are the hand positions where the dowel (see Figure 4.2) must be placed relative to the ankle. The maximum reach distance was determined by having the subjects put their back to a wall and reach forwards. The distance between the back of their shoulders to their finger tips was defined as the maximum reach distance.

4.6.2 Dependent Variables

Two-dimensional body posture: The body posture was recorded with the WATSMART system described in section 4.2.1 for each trial. Posture was expressed as a set of two-dimensional coordinates (m) defined by the calibrated space recorded before the experiment.

4.7 Experimental Protocol

The experimental session took three hours for each subject. Upon arrival, the participant filled out the informed consent form (see Appendix F). The experimenter explained the procedure of the experiment. The subject donned black clothing, worn to reduce reflections, and wore flat sole shoes. The experimenter then attached the infrared diodes of the WATSMART system to critical limb locations as described in section 4.3. Anthropometric measurements were recorded as described in Table 4.2.

The subject was instructed on where to put the feet and how to align the weight to the height marker. Tape was placed on the floor and the subject was asked to align the back edge of their heel in the middle piece of the tape. A piece of tape was placed on either side of the weight on the dowel. The subject placed the middle finger along this piece of tape as a guide to align their hands correctly. The location of the tape was determined by

having the subject hold the weight so that the elbows moved freely on the side of their torso.

Once the experiment was set up, the subject approached the task area. The experimenter aligned the diodes to the bony landmarks and plugged the subject to the WATSMART system. The subject slowly bent down and picked up the weight from the ground and aligned the weight to the height marker. Once the subject had aligned the weight, he or she verbally cued the experimenter and the posture was collected for four seconds. After the trial, the subject disconnected the WATSMART cord and sat down to rest. The rest period was at least 2 minutes between trials.

During the rest period, the experimenter checked the data collected for the previous trial and determined if the WATSMART system collected all the postural data. If the WATSMART system did not record a diode, the trial would either be redone or the diode position was estimated from the video tape backup. There were three reasons why the WATSMART system did not record a diode: 1) there was a short in a diode wire and had to be replaced, 2) at least two cameras could not see every diode due to the type of posture assumed, or 3) clothing covered up the diode. The equations used to calculate the diode locations from the videotape are provided in Appendix D.

The subject was given something to read or the experimenter kept a conversation going in order to prevent them from thinking about how they chose their postures. When all 32 trials were completed, the experimenter removed the diodes and debriefed the subject. The subject was paid and thanked for his or her time.

5.0 DATA ANALYSIS AND RESULTS

This chapter describes the techniques for analyzing the collected posture data. First, the methods used to analyze the collected data and the experimental results are discussed. The results of the observed postures as well as the accuracy of the posture prediction criteria are then investigated.

5.1 Data Analysis

Table 5.1 lists all the programs used to analyze the posture data. The position of the each diode was averaged between the 2nd and 3rd second of the lifting task using the AVG_POS.EXE program which saved the results in a file called POST_##.DAT (where ## is subject number). Each file was checked to see if any of the diodes had more than 10 mm in standard deviation between the 2nd and 3rd second. If a trial was identified, then the program 'plot High Variance' was used to determine why there was a high standard deviation, which was usually due to a short in the wire of a diode. If this was the case then an average was taken during a time period when the variability was low which indicated that there was a good connection in the wire at that time. If the WATSMART was not able to record the diode position or the diodes had a high standard deviation, then the 'Calc Missing Points' program was used. This program used the angles measured off the video tape and calculated the missing points (see Appendix D). The new calculations for the positions of the diodes were changed in the POST_##.DAT file.

Once the POST_##.DAT file was prepared, the program 'ReformatPosture.m' was used to calculate the actual joint center of rotation locations as described in section 4.4. The files created (PosObserved_##.DAT and AlgorInput_##.DAT) were used as input for 'PosturePrediction.m' to predict the postures and the results were saved in the file called PredictOut_##.DAT.

TABLE 5.1 Data Analysis Programs. Raw Posture Data: 3D0aa.S## where aa - trial number and ## - subject number.

Program	Language	Input	Output
Data Analysis			
AVG_POS.EXE	Turbo Pascal	3D0aa.S##	POST_##.DAT
ReformatPosture.m	Mathematica	POST_##.DAT	PosObserved_##.DAT AlgorInput_##.DAT
PosturePrediction.m	Mathematica	PosObserved_##.DAT AlgorInput_##.DAT	PredictOut_##.DAT
Adjustments			
plot High Variance	Mathematica	3D0aa.S##	
Calc Missing Points	Mathematica	Data from video tape	
Statistics			
StatisticalAnalysis.m	Mathematica	PosObserved_##.DAT AlgorInput_##.DAT PredictOut_##.DAT	
Graphics			
PredictResults.m	Mathematica	PosObserved_##.DAT AlgorInput_##.DAT PredictOut_##.DAT	

5.2 Observed Postures

As discussed in section 2.4, there was variability in postures due to instrument error, joint center of rotation estimation, and subject variability.

5.2.1 Instrument Error

In this experiment, the WATSMART estimated error in terms of root mean squared (RMS) as between 2-3 mm.

5.2.2 Estimation of Joint Center of Rotation

Error of diode shifts due to skin and clothing movements is very difficult to quantify. The diode positions was checked between each trial to minimize diode shifts. Cappozzo (1991) estimated that the error is at least 4 mm for a isometric task which is assumed to be true for the isometric task in this experiment.

5.2.3 Subject Variability

An important goal of this project was to determine the variability of the postures selected within the same condition. Figures 5.1 through 5.4 show all the observed postures with the eight repetitions for each condition graphed on top of each other. These figures show that there was variability between each repetition. To quantify this variability, the mean deviation of the joint locations was defined as:

$$\frac{1}{N} \sum_i |a_i - \bar{a}| \quad (5.1)$$

where $N=8$ and \mathbf{a} is the (x, y) coordinate of a joint. The joints moved 0.005 m to 0.116 m within the 8 repetitions for each hand position as shown in Table 5.2. Note that this variability is due not only to subject variability but also could result from errors in estimation of joint center of rotation and instrument error.

A repeated measure analysis of variance (ANOVA) was used to investigate how Gender, Joint, and Hand Position affected the mean deviation as shown in Table 5.3. The results showed that Joint ($p=.0190$), Hand Position ($p=.0013$) and the interaction of Joint x Hand Position ($p=.0001$) were significant at $p<0.05$. Figure 5.5 shows that the knee had smallest amount of variability (0.018 m) and the shoulder had the most (0.024 m). The main effect of hand position is shown in Figure 5.6. This figure shows that tasks with higher hand positions had less postural variability than those with lower hand positions. This can also be seen in Figure 5.7 which shows the Joint x Hand Position interaction. There is variability at the hand positions in part because the hands were not constrained and subjects started shaking or moving their hands. It is possible that these hand movements influenced the variability of the other joints.

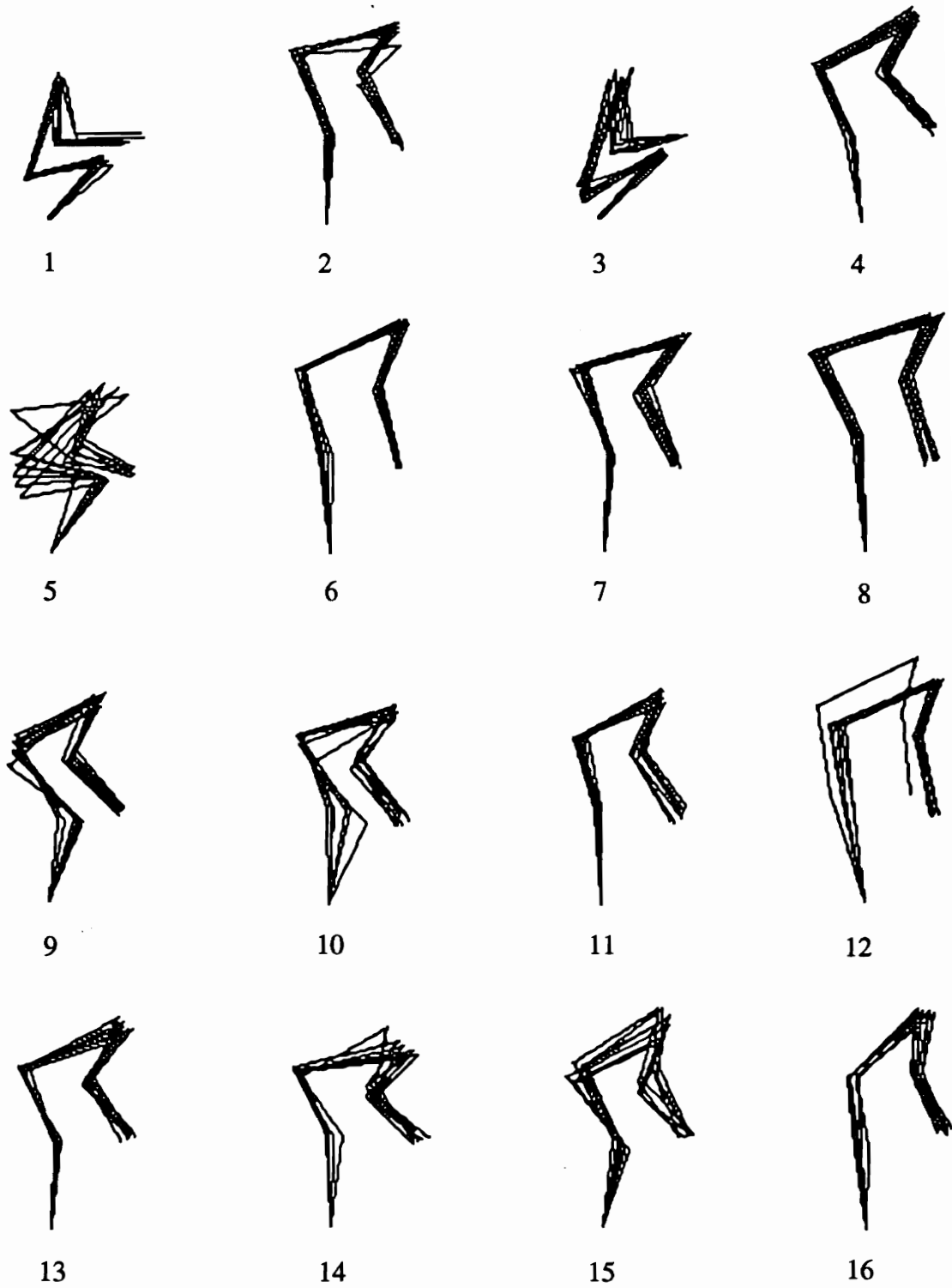
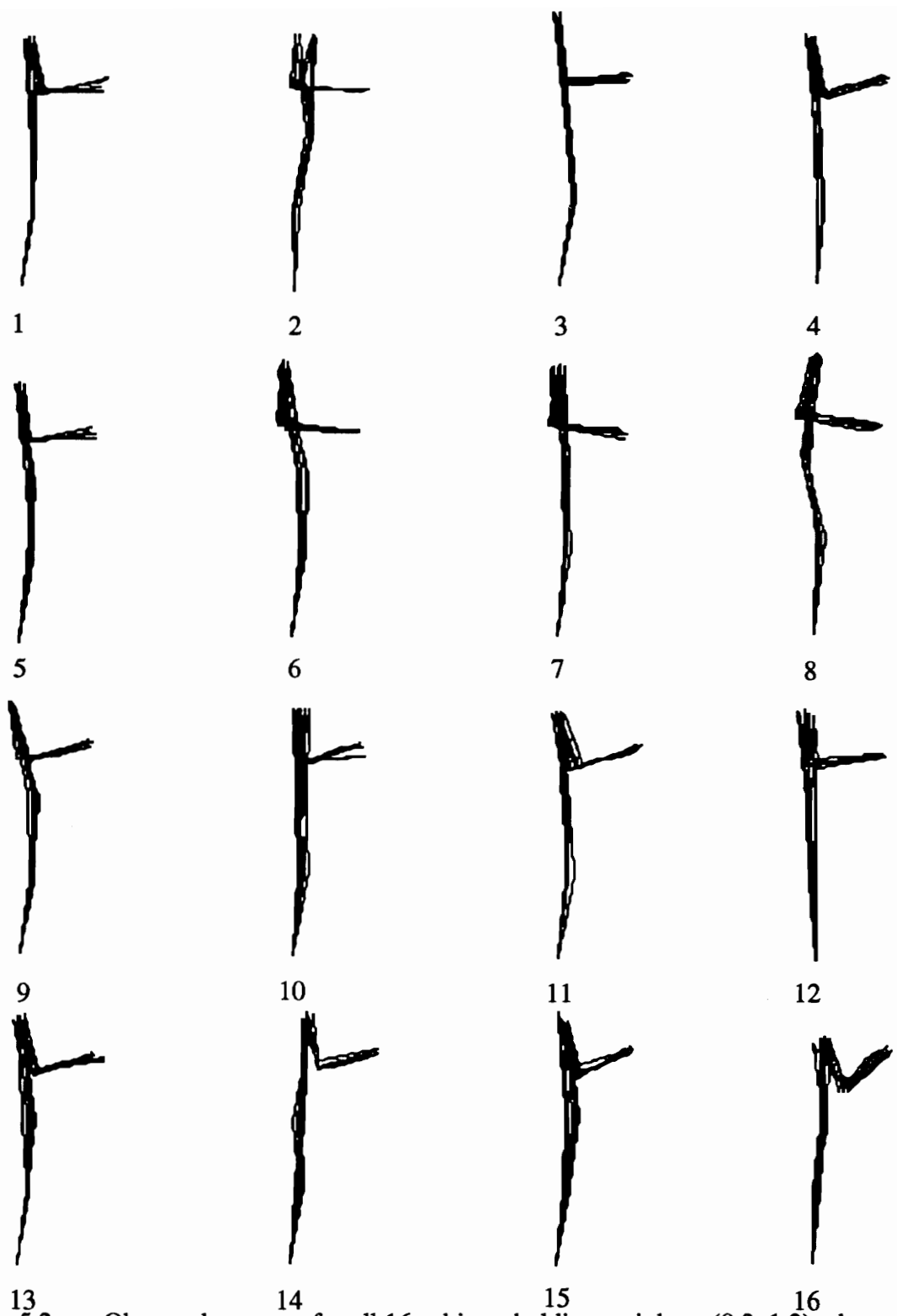


Figure 5.1 Observed postures for all 16 subjects holding weight at (0.3,0.5) where all eight repetitions are graphed on top of each other.



13
14
15
16
Figure 5.2 Observed postures for all 16 subjects holding weight at (0.3, 1.2) where all eight repetitions are graphed on top of each other.

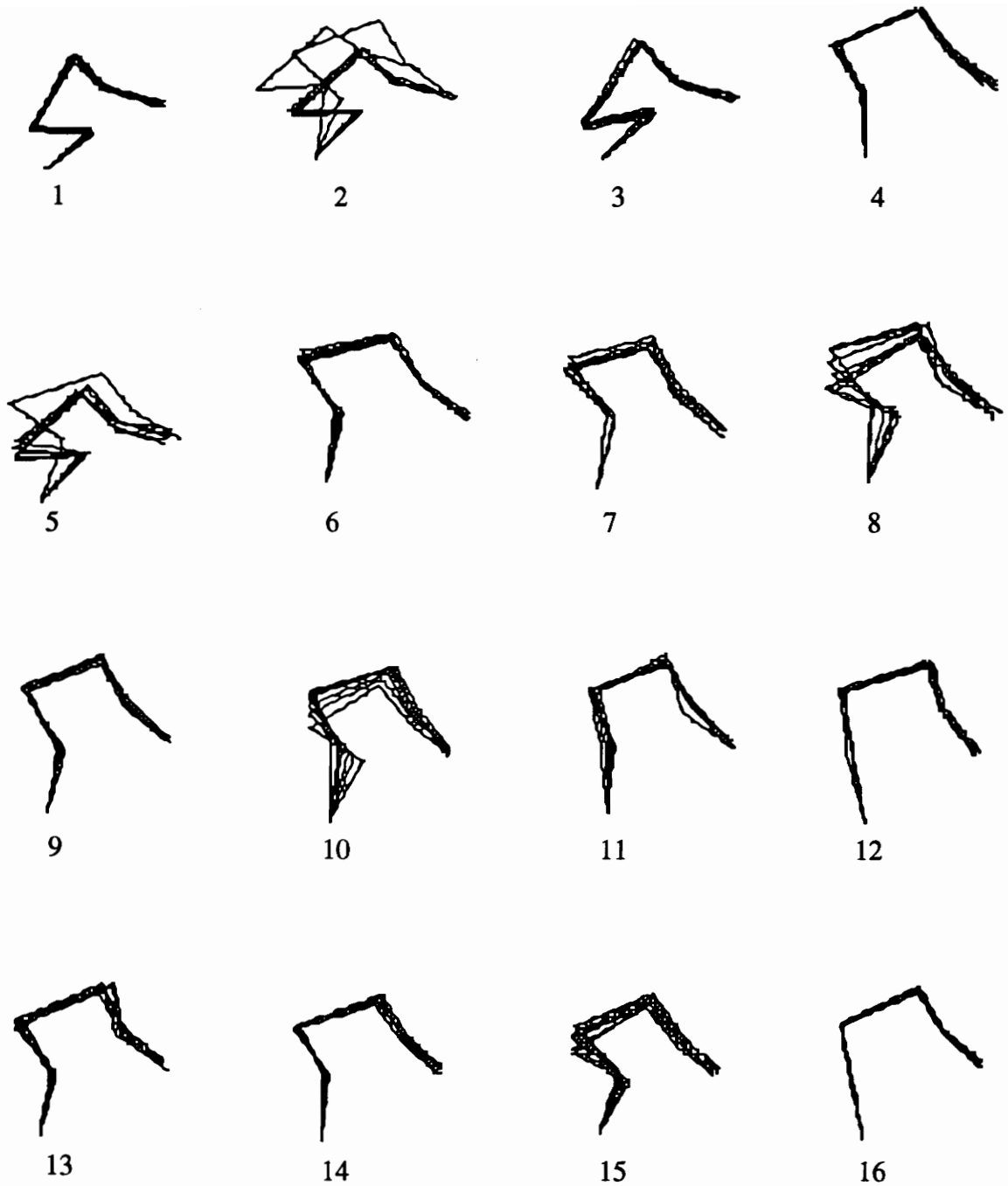


Figure 5.3 Observed postures for all 16 subjects holding weight at (Max, 0.5) where all eight repetitions are graphed on top of each other.

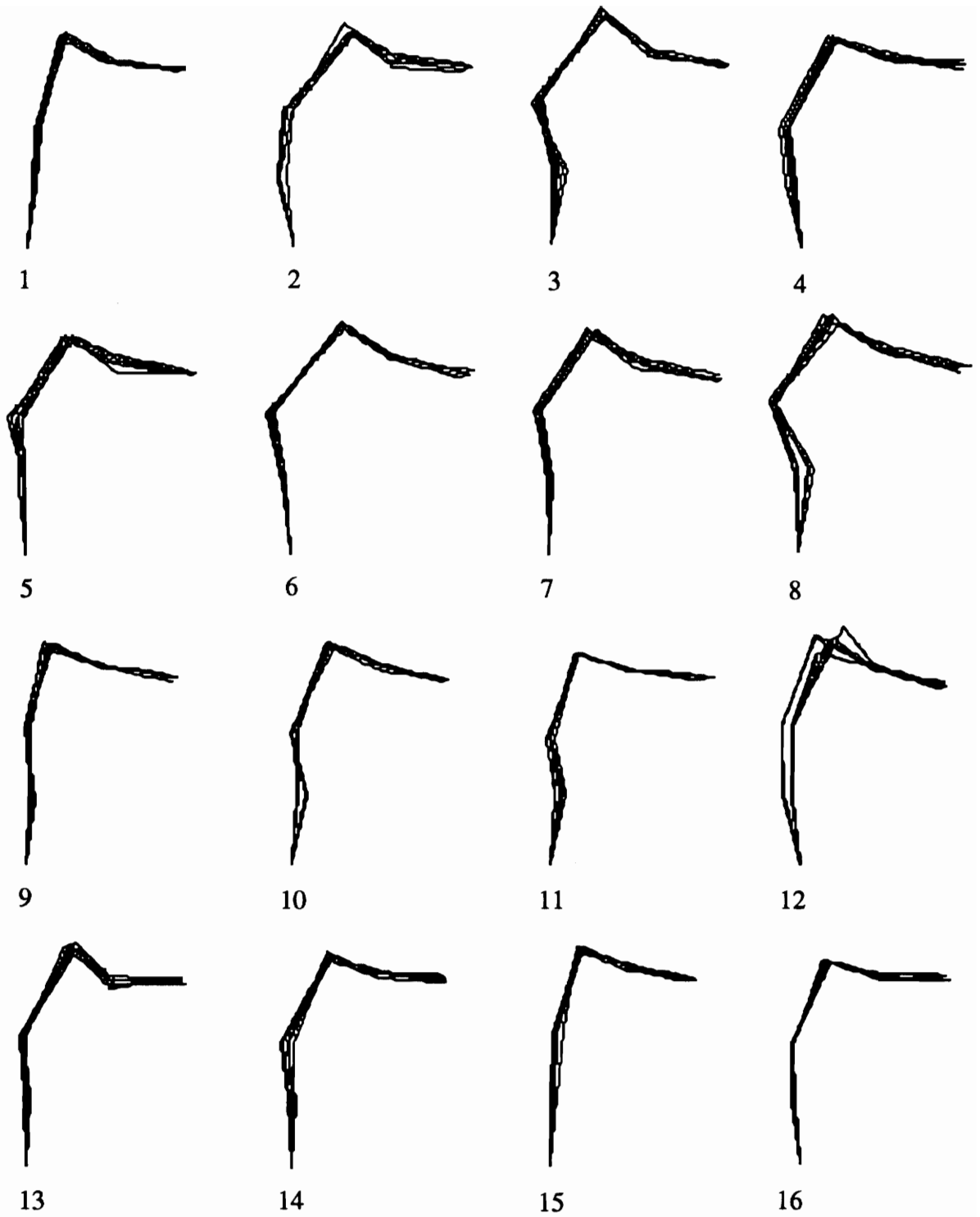


Figure 5.4 Observed postures for all 16 subjects holding weight at (Max, 1.2) where all eight repetitions are graphed on top of each other.

TABLE 5.2 Subject joint mean deviation (m) summary results

Joint	Hand	Elbow	Shoulder	Hip	Knee
Average	0.022	0.022	0.024	0.022	0.018
St. Dev.	0.007	0.011	0.014	0.022	0.013
Minimum	0.009	0.010	0.007	0.005	0.007
Maximum	0.056	0.077	0.089	0.116	0.075
Overall					
Average	0.022 m				
St. Dev.	0.014 m				
Minimum	0.005 m				
Maximum	0.116 m				

TABLE 5.3 ANOVA summary table for mean deviation analysis.

Factors	df	SS	MS	F	p
Between-Subjects					
Gender(G)	1	.00042	.00042	.480	.4998
S/G	14	.012	.001		
Within-Subjects					
Joint (J)	4	.001	.00035	3.216	.0190
J * G	4	.00023	.000058	.537	.7091
Joint * S/G	56	.006	.00011		
HP	3	.009	.003	6.289	.0013
HP * G	3	.003	.001	1.825	.1574
HP * S/G	42	.020	.00049		
J * HP	12	.003	.00023	3.726	.0001
J * HP * G	12	.00041	.000035	.564	.8683
J * HP * S/G	168	.010	.000062		

Dependent: Mean Deviation

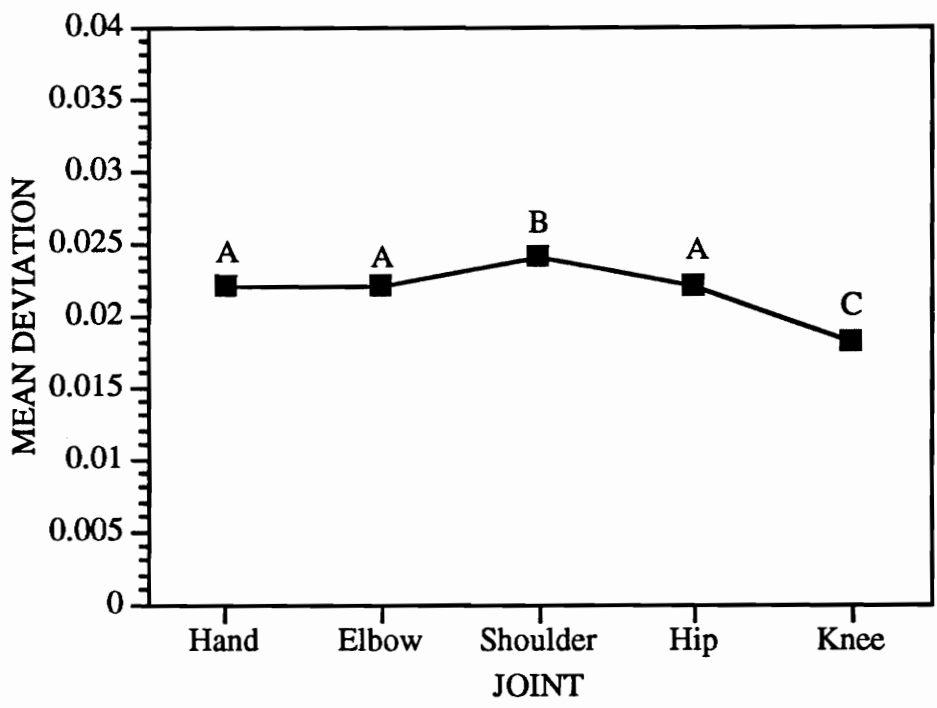


Figure 5.5 Mean Deviation of the Joint main effect. Points with same letters are not significantly different using a Newman-Keuls post hoc test with $\alpha=0.05$.

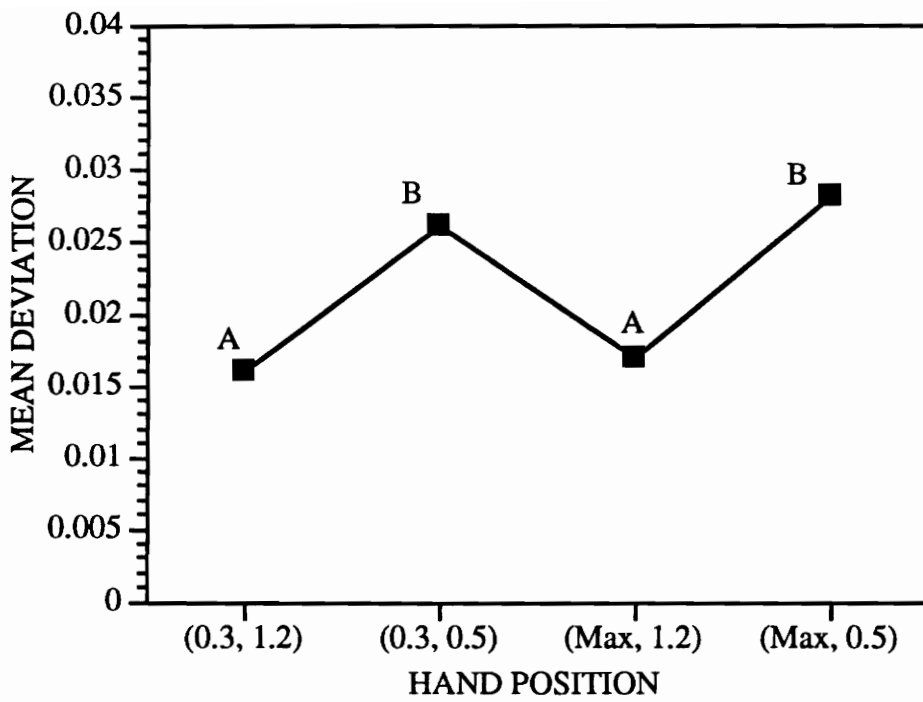


Figure 5.6 Mean Deviation of the Hand Position main effect. Points with same letters are not significantly different using a Newman-Keuls post hoc test with $\alpha=0.05$.

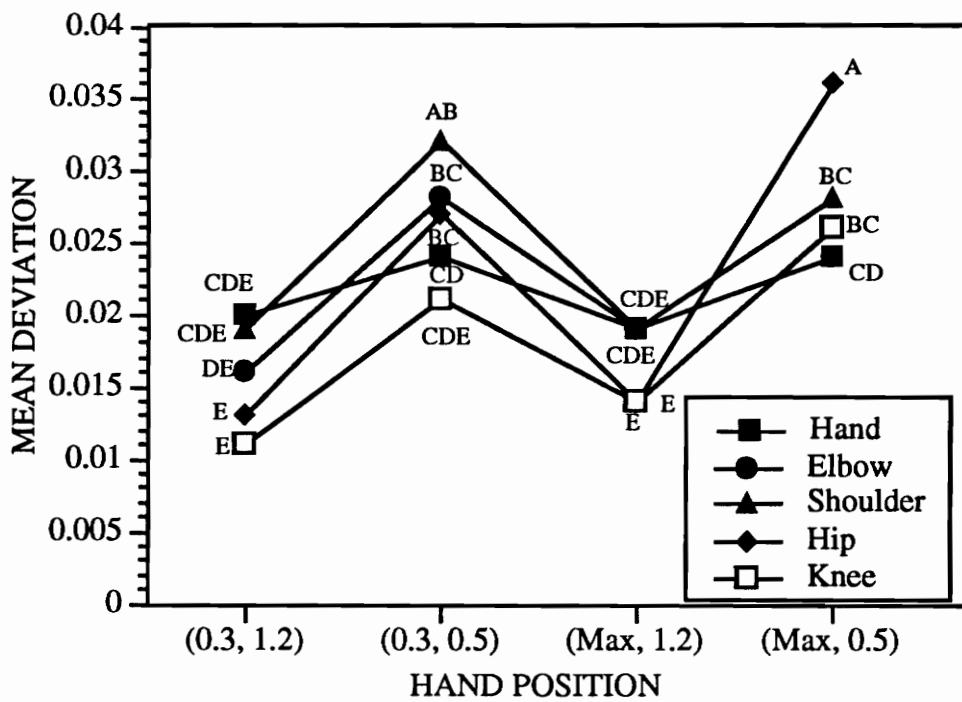


Figure 5.7 Mean Deviation of the Joint x Hand Position interaction. Points with same letters are not significantly different using a Newman-Keuls post hoc test with $\alpha=0.05$.

As can be seen from the Figures 5.1 through 5.4, all subjects choose similar postures as summarized in Figure 5.8. For Hand Position (0.3, 0.5), 3 subjects chose a crouching posture compared to the 13 other subjects who assumed a standing posture. Similarly for the (Max, 0.5) condition, 4 subjects chose a crouching posture compared to the other 12 subjects who assumed a standing posture.

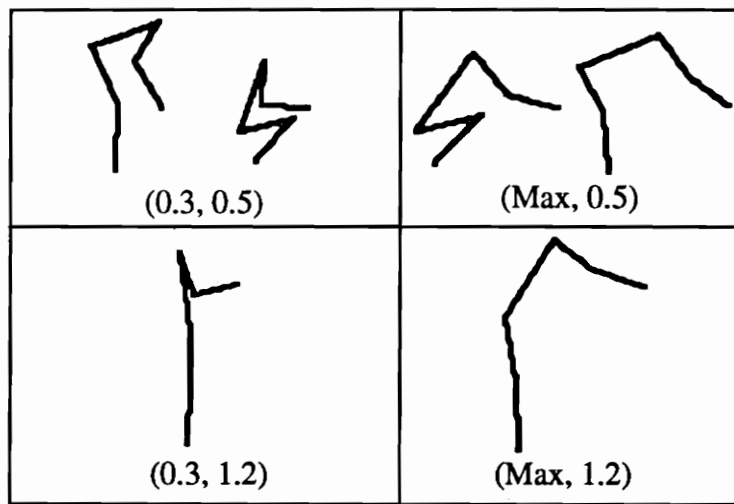


Figure 5.8 Generalization of the types of postures chosen by the subjects.

5.3 Predicted Posture Results

5.3.1 Prediction Accuracy Analysis

The error between the predicted posture and the collected posture for each trial was defined as the Euclidean distance between the predicted and observed posture:

$$\epsilon = \sqrt{(x_{h(\text{obs.})} - x_{h(\text{pred.})})^2 + (y_{h(\text{obs.})} - y_{h(\text{pred.})})^2 + (\phi_{\text{obs.}} - \phi_{\text{pred.}})^2} \quad (5.1)$$

where $(x_{h(\text{obs.})}, y_{h(\text{obs.})}, \phi_{\text{obs.}})$ indicate the x and y hip position and the forearm orientation that define the observed posture, and $(x_{h(\text{pred.})}, y_{h(\text{pred.})}, \phi_{\text{pred.}})$ are the same three variables that define the predicted posture.

To test whether any of the criteria were accurate, a Studentized t test was conducted where:

$$H_0: \epsilon = 0 \tag{5.2}$$

$$H_1: \epsilon \neq 0.$$

The test evaluated the sample set of eight repetitions for a total of 192 (16 subjects x 4 hand positions x 3 criteria) tests. All p values were below 0.04 demonstrating that all the predictions were significantly different from the observed postures at $\alpha= 0.05$. Table C.1 shows the p values for each test. Appendix E gives examples of what the predicted postures looked like compared to the observed postures for all subjects at each condition.

5.3.2 Error Evaluation

Even though all of the models predicted postures with error significantly greater than zero, it is important to understand how the model should be improved. A four-way repeated measures ANOVA was performed to determine the effects of Hand Position, Gender, Criterion, and Repetition on using prediction error (ϵ) as defined in Equation 5.1.1. The results of this analysis are shown in Table 5.4. In performing the ANOVA, there was concern that Criterion was not circular since the same inputs were used for each criterion. This resulted in a correlation between the three criteria which is a violation of one of the assumptions when using an analysis of variance (Winer, 1991). A Geisser-Greenhouse correction was used to correct for the deviation from circularity.

The ANOVA showed that the main effects of Gender ($p=.0034$), Hand Position ($p=.0001$), Criterion ($p=.0001$), and the Hand Position x Criterion interaction ($p=.0001$) were significant at $p<0.05$. The Geisser-Greenhouse correction did not significantly change any of the p values. The gender effect occurred because the models predicted males more accurately than females (males $\epsilon=0.89$; female $\epsilon=1.09$). In comparing the three criteria, Figure 5.9 shows that the Total Torque criterion predicted postures more accurately

than the Balance criterion or the Percent Strength criterion. For the different hand positions, Figure 5.10 shows that (0.3, 1.2) predicted the best and (0.3, 0.5) was predicted the worse. Figure 5.11 shows the Hand Position x Criterion interaction. At the hand position (0.3,1.2) all the criteria had the same accuracy although at (0.3,0.5) and (Max, 1.2) the Total Torque criterion was the most accurate. The criteria Total Torque and Percent Strength predicted more accurately than the balance criterion at the (Max, 0.5) criterion.

TABLE 5.4 ANOVA summary table for prediction error.

Factors	df	SS	MS	F	p	G-G
Between-Subjects						
Gender (G)	1	15.95	15.95	12.43	.0034	
S/G	14	17.96	1.28			
Within-Subjects						
Criteria (C)	2	22.99	11.49	18.63	.0001	.0001
C * G	2	1.78	.89	1.44	.2531	.2541
C * S/G	28	17.28	.62			
Hand Position (HP)	3	388.11	129.37	78.51	.0001	.0001
HP * G	3	1.06	.35	.22	.8853	.8247
HP * S/G	42	69.20	1.65			
Repetition (R)	7	.52	.07	1.59	.1465	.1971
R * G	7	.20	.03	.61	.7504	.6396
R * S/G	98	4.61	.05			
C * HP	6	35.57	5.93	14.37	.0001	.0001
C * HP * G	6	3.76	.63	1.52	.1817	.2169
C * HP * S/G	84	34.65	.41			
C * R	14	.33	.02	.63	.8416	.6832
C * R * G	14	.61	.04	1.18	.2940	.3281
C * R * S/G	196	7.30	.04			
HP * R	21	.93	.04	1.09	.3625	.3760
HP * R * G	21	.56	.03	.65	.8816	.6639
HP * R * S/G	294	12.04	.04			
C * HP * R	42	.79	.02	.52	.9947	.8185
C * HP * R * G	42	1.17	.03	.77	.8495	.6136
C * HP * R * G * S/G	588	21.15	.04			

Dependent: Prediction Error

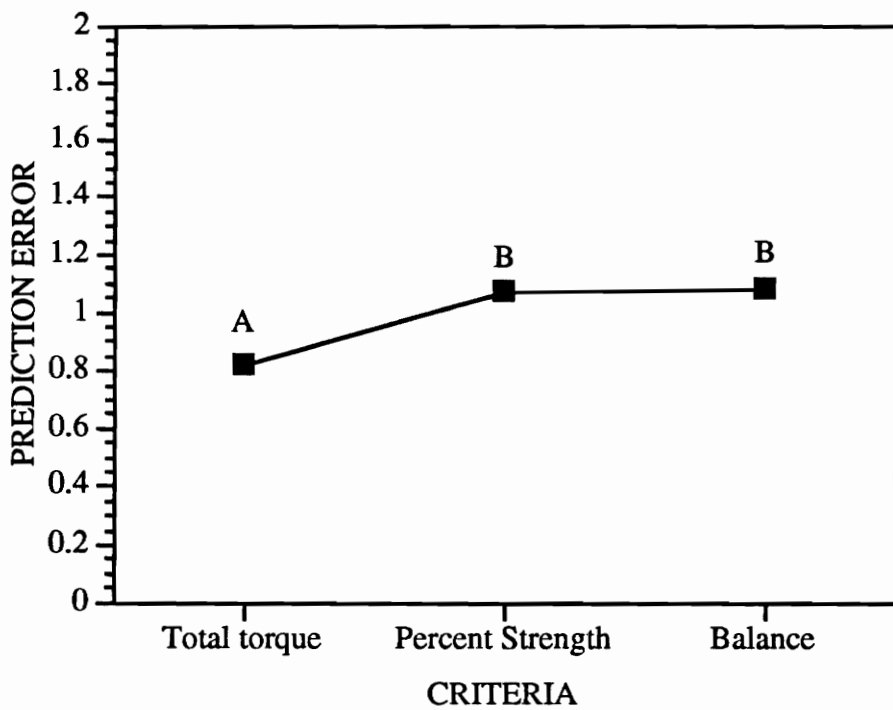


Figure 5.9 Criteria main effect on prediction error. Points with same letters are not significantly different using a Newman-Keuls post hoc test with $\alpha=0.05$.

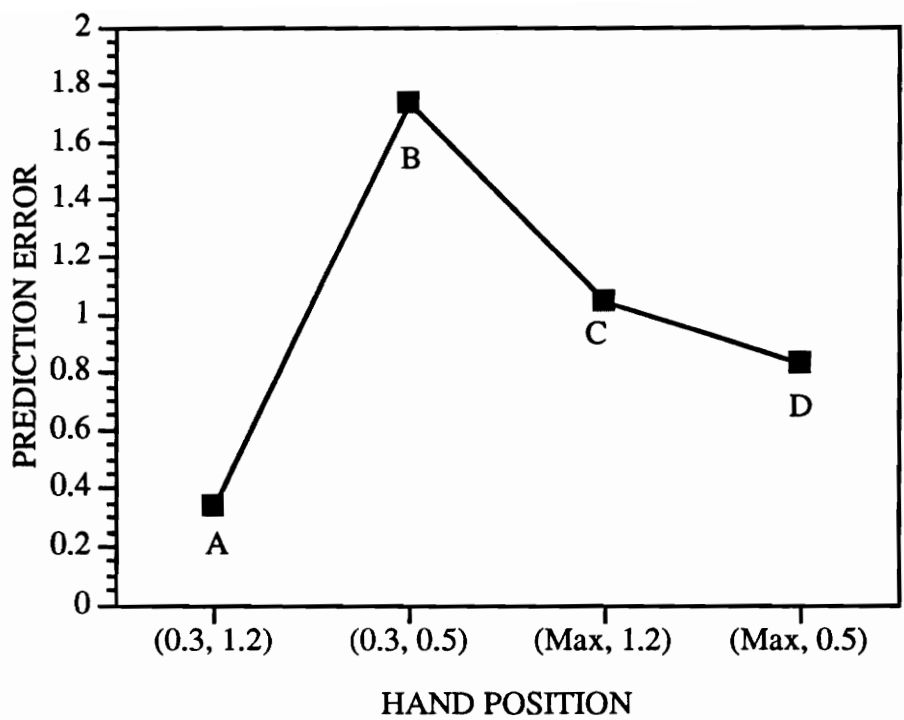


Figure 5.10 Hand Position main effect on prediction error. Points with same letters are not significantly different using a Newman-Keuls post hoc test with $\alpha=0.05$.

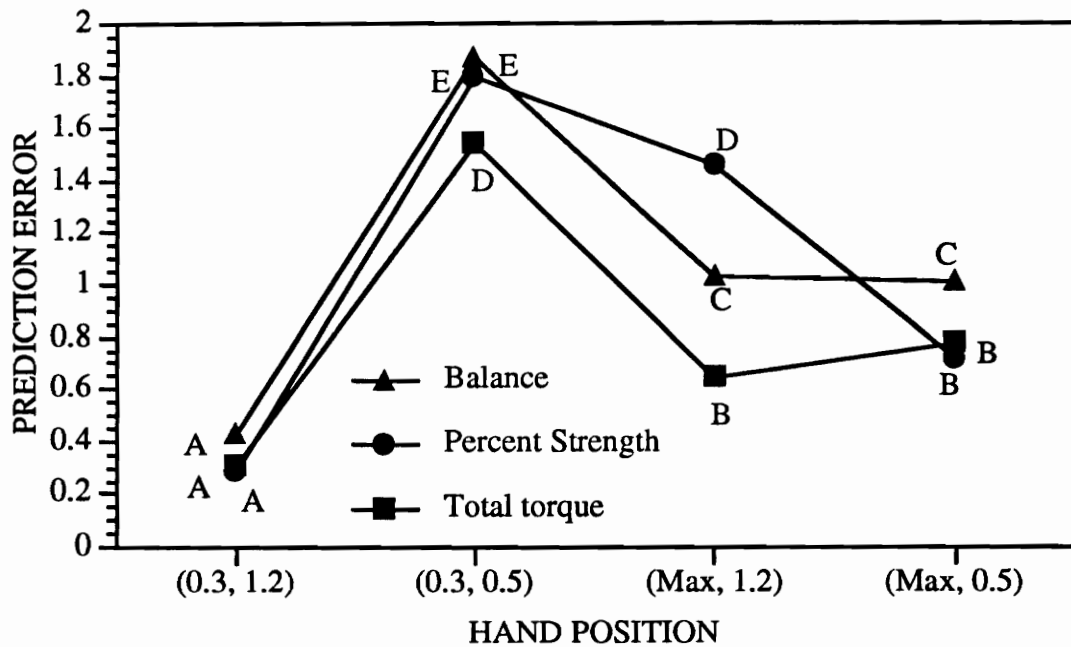


Figure 5.11 Hand Position x Criteria interaction on prediction error. Points with same letters are not significantly different using a Newman-Keuls post hoc test with $\alpha=0.05$.

6.0 DISCUSSION

In chapter 1, four objectives were listed for this thesis. This chapter discusses the results obtained with respect to each of these objectives and discusses what could be done in the future.

6.1 Discussion of Results

The first objective was to determine the variation of postures chosen by each subject. The observed postures show that postures for a static lifting task can be predicted with an accuracy between 0-12 cm depending on the subject. There were two types of postures that were chosen for the lower hand positions ((0.3, 0.5) and (Max, 0.5)) which is believed to be due to previous experience. Haslegrave and Corlett (1988) found similar results where subjects didn't choose a range of postures but chose two distinct types of postures.

Variability of posture is higher for low hand positions compared to postures at high hand positions. Thus one might assume that the accuracy of the posture prediction model will be affected in a similar way; the model will be less accurate when the hand positions are low to the ground (around knee height) compared to higher hand positions (around chest height). However, as shown in Figure 5.10, the models predicted the low hand positions better than higher hand positions for maximum reaches. This indicates that the prediction error is due more to the model's inaccuracy rather than the subject variability.

The last three objectives of this thesis were to determine if humans chose postures using any of the three criteria. Unfortunately, the results did not produce a simple yes or no answer to these questions. None of the postures were predicted accurately by any of the three criteria as shown by the t-tests. Influences on prediction accuracy not only include the accuracy of the criterion definition and the measurement accuracy but also the fidelity of

the human model. The next section discusses various ways to improve the accuracy of the algorithm in terms of fidelity of the model and the criterion.

The effects on prediction error showed that postures of males were predicted better than postures of females which may reflect that the two genders choose postures differently as Anderson et al. (1986) had found. Total Torque, in general, was the best predictor of the three criteria which indicates that the torque applied at each joint does influence posture choice.

6.2 Future Research

An important result of this research effort is that it has defined more clearly what needs to be done and what needs to be known in order to develop an accurate human posture prediction algorithm. This section describes what needs to be done in order to improve the criterion definition humans use to choose postures. The validity of the assumptions made by the three criteria are discussed. This discussion presents ideas for new types of posture criteria.

- ***Improve the accuracy of the forearm orientation prediction.***

One main cause of prediction error was due to the accuracy of the forearm orientation. A major influence on forearm orientation is the head orientation which was not included in the models evaluated in this thesis. Subjects maintained their head in an upright position where they could see the weight. However, if humans assumed many of the predicted postures, they would have had difficulty seeing the weight (See Appendix E). Future research should investigate how the required line of sight of a task influences the orientation of the forearm. Also, future research should evaluate if minimizing the torque about the neck is a function of the head orientation. In other words, the head may be trying to keep vertically upright in order to reduce the moment arm.

The forearm link included the hand and forearm to simplify the model by reducing the degrees of freedom of the algorithm. When some subjects grasped the weight, they tended to bend their wrists which may be related to their wrist strength. Therefore, the wrist was not necessarily straight even though the model assumed it was straight. Because of this assumption, the link length and orientation of the forearm are not an exact representation in the model. Future research should investigate how wrist posture affects whole body posture and include it in future models.

- ***Improve the accuracy of predicting hip position.***

The hip position predictions were relatively accurate compared to the forearm orientation predictions. Future research, however, should consider improving the accuracy by combining criteria. For example, combining Total Torque and Percent Strength may be more accurate because the observed postures at hand positions (Max, 0.5) and (0.3, 1.2) were between these two criteria's predictions (See Appendix E).

Future models should also include the possibility that the subjects will lock their knees enabling their knee angle to be less than zero degrees which was observed in this experiment.

- ***Include the influence of experience in the model.***

Additional research should investigate how experience influences posture and determine how an algorithm can quantify experience to improve prediction accuracy. The results show that there were two distinct types of postures that people chose at certain hand positions, which is probably related to anthropometry (length of body links) and experience such as training or previous injuries. If there is a way to quantify experience such as through a questionnaire before the experiment, the algorithm may be able to determine which of the two types of postures the subject will assume.

- ***Reevaluate the Balance criterion.***

During the experiment, subjects did not always keep their heels on the ground (especially for the hand positions of maximum reach) which violates an assumption for the balance equations. Since it is nearly impossible to determine if their heels are on the ground (except with a force platform), this cannot be a valid assumption. Kerk's (1992) model makes this assumption by having the subjects wear a ski boot which constrains the heel and ball position but this situation can not be found in an industrial setting. Kerk's model also makes the assumption that the foot can be represented as one link from the heel to the ball of the foot. A better representation might be a two link model (heel to ball, ball to toe), because in some trials, subjects were standing on their ball and toe while their heel was above the ground. This was especially true for subjects who assumed a crouching posture. Kerk's equations should be altered to include a two link foot and this balance criterion should be reevaluated.

- ***Develop a more accurate and efficient non-linear search method.***

One concern is if the non-linear search was actually finding the true minimum. To get more information about the search's accuracy, the observed postures were compared with the predicted postures. The observed postures were evaluated with respect to three objective functions and this value was compared to the value that the non-linear search found as the minimum. The observed postures were smaller than the predicted postures for less than two percent of the solutions which indicates that for some objective functions, the global minimum was not found. This may be due to poorly chosen starting points which prevented the Nelder and Mead search to find a global minimum instead of just a local minimum. Better methods for choosing starting points can be developed by investigating the shapes of these objective functions in the solution space set by the constraints.

The characteristics of the objective function should also be evaluated to develop a more efficient and accurate non-linear search method. One problem with the search used in this research was that it took between 5 and 25 minutes to find the minimum solution using Mathematica on a Macintosh Quadra 950. Increasing the efficiency will enable a posture prediction algorithm to be implemented in CAD systems which use human models as a tool when designing workstations.

- ***Evaluate the use of non-linear functions in criteria.***

Since it took a computer 5 to 25 minutes to predict a posture and only a few seconds for a human to choose a posture, humans may use a simpler method for choosing postures. The criteria used in this thesis assumed that humans use an optimal non-linear function which raises the question: do humans actually think non-linearly when choosing a posture. If non-linear functions are being used as criteria, future research should investigate if humans are choosing a local minimum instead of a global minimum. Assuming that a minimum is being searched, researchers should investigate how a human chooses this point.

The models of this thesis did not consider that these human subjects have been choosing postures for at least 18 years. This experience may have reduced the solution set to a small number of postures. Future research should investigate the size of the solution set defined by 18 years of experience. It is possible that the solution set is so small that humans randomly choose a posture inside this area. If this is the case, then the goal is not to define an accurate criterion but to determine all the constraints which define the small solution set.

- ***Implement more detailed data when it becomes available.***

The models for this thesis used a lot of generalizations of the human body in order to reduce the degrees of freedom. For example, the posture at each joint depends on the

characteristics of tendons, ligaments, muscle co-contraction, fatigue, etc. Since it is difficult to quantify these characteristics at this time, the model used many generalizations. As more data becomes available, the model can become more complicated. As the models become more accurate, the degrees of freedom should be increased to improve the link representation of the models. For example, future models should include more links to represent the curvature of the spine and the intricate movements of the shoulders.

A big problem to control is motivation as discussed by Snyder et al. (1972). In this experiment, the subjects were given magazines, encouraged to do homework or read a book, or the experimenter talked to the subject between trials. One subject wanted to continually talk about the experiment and why the individual chose certain postures: "because my mom hurt her back doing it this way", "I want to give you a variety of postures to study". The experimenter assumed that a person in an industrial setting does not constantly think about different postures, so this subject's data was not analyzed. Future research should investigate how to quantify the effects of various types of motivation on posture choice.

- ***Include passive tissue in the definition of effort.***

Evaluating these criteria has raised some questions about how humans choose posture. The Total Torque and the Percent Strength criteria assumes that more effort is perceived when more torque is applied at the joint. This assumption does not consider the forces applied by passive muscles and tissues. For example, Figure 5.8 shows that some subjects chose a crouching posture where passive tissues at the knee absorb most of the force. Even though more torque is applied at the knee in this posture (compared to standing postures), less effort is perceived because the passive tissues are used to control the posture. Future research should investigate how to quantify the effects of passive tissues at each joint. These effects should be incorporated into the model by applying a

weight to each joint torque. For example, the Total Torque criterion had all the torques for each joint weighted evenly instead of putting more or less emphasis on the joints depending on the perceived effort. These weights could be determined by using psychophysical data which quantify the perceived effort at each joint as a function of posture.

- *Apply model to other types of tasks*

If static sagittal lifting tasks can be predicted accurately, other tasks with more variables should be evaluated such as asymmetric tasks (3 dimensional). Future research should investigate if humans use a similar criterion for different types of work tasks.

Researchers should also analyze how hand grip type (prone, semi-prone, supine) influences posture. It would be important to know if humans use different criterion for different grip types.

Another area of research is the prediction of motion in dynamic tasks. Researchers should examine how to combine these two types of prediction models. For example, if the hand positions at the beginning and end of a dynamic task are known, the static prediction model can predict these two postures and the dynamic prediction model can determine the motion of each joint during the dynamic movement.

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APPENDIX A: Posture Prediction Mathematica 2.1 Program

ASSUMPTIONS

This is a list of the assumptions that are made for predicting the postures. This thesis studied this task under the following assumptions:

DESCRIPTION OF TASK

- 1) Symmetric sagittal lifting task.
- 2) Supine grip.
- 3) Links do not touch each other (the elbows do not rest on the torso).
- 4) Slow lifting.
- 5) Hold the weight for 4 seconds.
- 6) Same amount of motivation for each trial.
no music in the background, subjects read a magazine or talked to the experimenter, one person (the experimenter) is watching the task.
- 7) Lifted 4.6 kg.
- 8) Clothing: shorts, t-shirt, sweat shirt and sweat pants, sneakers.

MODEL ASSUMPTIONS

- 1) Knowns: link lengths, body weight, hand position, ankle position.
- 2) The center of mass for each link can be estimated.
- 3) Body segments can be represented as straight links.
- 4) The torso can be represented as one straight link.
- 5) The forearm included the weight and length of the hand and the forearm.
- 6) Tendons as well as other muscular attachments do not influence the amount of torque exerted at a joint.
- 7) Joint range of motions are known.

Nonlinear Search Assumption

- 8) There is one minimum.

Balance Criterion Assumption

- 9) Both heel and ball of foot are on the ground at the same time.
Note: This is not in the description of the task.

(*POSTURE PREDICTION ALGORITHM*)

(*Written by Marc J. Dysart January, 1994*)

(*Other Functions*)

(*writeMatrix*)

```
writeMatrix[filename_String,data_List] :=  
  Block[{  
    file = OpenWrite[filename]  
  },  
  Scan[  
    (  
      WriteString[file,First[#]];  
      Scan[  
        WriteString[file,"\t",#]&,  
        Rest[#]  
      ];  
      WriteString[file,"\n"]  
    )&,  
    data  
  ];  
  Close[file]  
]
```

(*Change Angle to a percentage*)

```
checkAngle[angle_Real]:=  
Module[{  
},  
test=N[angle/(2 Pi)-Floor[angle/(2 Pi)]];  
test]
```

(*Calc Prediction Error*)

```
calcError[i_Integer]:=  
Module[{  
},  
predictError=Sqrt[(newprediction[[2,1]]-inputObserved[[i,9]])^2+  
  (newprediction[[2,2]]-inputObserved[[i,10]])^2+  
  (newprediction[[2,3]]-inputObserved[[i,15]])^2];  
predictError  
]
```

(*Minimization Function*)

(*Modules for Posture calculation*)

Off[spell1];

(*INVERSE KINEMATIC FUNCTIONS*)

(*Rotation and Translation Definitions MJD 3/93*)

```
Tx[alpha_]={{1,0,0,0},{0,Cos[alpha],-Sin[alpha],0},  
  {0,Sin[alpha],Cos[alpha],0},{0,0,0,1}};
```

```
Ty[phi_]={{Cos[phi],0,Sin[phi],0},{0,1,0,0},  
  {-Sin[phi],0,Cos[phi],0},{0,0,0,1}};
```

```

Tz[theta_]={ { Cos[theta],-Sin[theta],0,0},
             { Sin[theta],Cos[theta],0,0}, {0,0,1,0},{0,0,0,1}};
Ttrans[dx_,dy_,dz_]={ {1,0,0,dx},{0,1,0,dy},{0,0,1,dz},{0,0,0,1}};
(*Defn of Atan2*)
Atan2[y_,x_]=If[x>0 &&y>=0, ArcTan[y/x],
               If[x<0 &&y>=0, Pi-ArcTan[y/Abs[x]],
               If[x<0 &&y<0, Pi+ArcTan[Abs[y]/Abs[x]],
               If[x>0 &&y<0, 2 Pi-ArcTan[Abs[y]/x],
               If[x==0 &&y<0, (Pi (3/2)),
               If[x==0 &&y>0, Pi/2 ]]]];

gxp[xx_Integer,theta_List] :=
Module[{ },
  Sin[thetasum[xx,theta]] gy[[xx]]
];
gyp[xx_Integer,theta_List] :=
Module[{ },
  Cos[thetasum[xx,theta]] gy[[xx]]
];
thetasum[xx_,theta_List]:=
Module[{ },
  Sum[theta[[i]],{i,1,xx}]
];

(*INPUT FOR MODEL*)
inputData[l_List,anthro_List,ankle_List]:=
Module{
  },
(*Data for joint torque calculations*)
(*weight lifted*)
fx = 0;fy = -45.1;
gy = {-anthro[[3]]*0.086,-anthro[[3]]*0.200, -anthro[[3]]*0.584,
      -anthro[[3]]*0.056, -anthro[[3]]*0.046};
xa=ankle[[1]];
ya=ankle[[2]];

lc = {l[[1]]*0.567,l[[2]]*0.567,l[[3]]*0.396,l[[4]]*0.436,l[[5]]*0.43};
wyh = 0.028 (-anthro[[3]]);
wyb = 0.028 (-anthro[[3]]);
{xheel, yheel} = {ankle[[1]]-anthro[[4]], ankle[[2]]-anthro[[6]]};
{xball, yball} = {ankle[[1]]+anthro[[5]], ankle[[2]]-anthro[[6]]};
footlength=anthro[[4]]+anthro[[5]];
(* For calculating Max strength*)
adjust={ {0.1913,0.1005},{0.2126,0.1153},{0.2845,0.1495},
         {0.4957,0.2485},{0.1304,0.0871},{0.0977,0.0516},
         {0.1429,0.0851},{0.0898,0.0603},{0.0816,0.0489}};
]

(*ANGLES *)
angles[l_List,phi_,xh_,yh_]:=
Module[{theta1,theta2,theta3,theta4,theta5,

```

```
theta4a,theta3p,k1,k2,k3,k4,xep,yep,xhp,yhp,cosht2,alpha,cosht4),
```

```
(*Calculate the elbow point*)
```

```
xe=xhand-l[[5]] Cos[phi];  
ye=yhand-l[[5]] Sin[phi];  
yhp=yh-ya;  
xhp=xh-xa;  
xep=xe-xh;  
yep=ye-yh;
```

```
(*Solution for theta1 and theta2 *)
```

```
cosht2=(xhp^2+yhp^2-l[[1]]^2-l[[2]]^2)/(2 l[[1]] l[[2]]);  
  
(If[Abs[cosht2]>1,theta1=Return[99];];  
  
theta2=Atan2[(1-cosht2^2)^0.5,cosht2];  
  
k1=l[[1]] + l[[2]] Cos[theta2];  
k2=l[[2]] Sin[theta2];  
theta1=Atan2[yhp,xhp]-Atan2[k2,k1];
```

```
(*Solution for theta3 and theta4 *)
```

```
cosht4 = (xep^2+yep^2-l[[3]]^2-l[[4]]^2)/(2 l[[3]] l[[4]]);  
(If[Abs[N[cosht4]]>1,theta1=Return[99];];  
theta4a=Atan2[(1-cosht4^2)^0.5,cosht4];  
  
k3=l[[3]] + l[[4]] Cos[theta4a];  
k4=l[[4]] Sin[theta4a];  
  
theta3p=N[Atan2[yep,xep]+Atan2[k4,k3]];  
If[repet=="yes",theta3p=N[Atan2[yep,xep]-Atan2[k4,k3]]];  
  
alpha=N[Atan2[yep-(l[[3]] Sin[theta3p]),xep-(l[[3]] Cos[theta3p])];  
theta4=alpha + (2 Pi - theta3p);  
  
theta3 = N[theta3p + 2 Pi - (theta1+theta2)];
```

```
(*Calculate theta 5 *)
```

```
theta5=phi-(theta1+theta2+theta3+theta4);)  
If[theta1==99,theta2=99;theta3=99;theta4=99;theta5=99];
```

```
{theta1,theta2,theta3,theta4,theta5}
```

```
]
```

```
(*FORCE AT EACH JOINT*)
```

```
jointForce[theta_List] :=  
Module[{fx6,fy6,fx5,fy5,fx4,fy4,  
fx3,fy3,fx2,fy2,fx1,fy1,fx0,fy0},
```

```

fx6 = Cos[thetasum[5,theta]] fx + Sin[thetasum[5,theta]] fy;
fy6 = -Sin[thetasum[5,theta]] fx + Cos[thetasum[5,theta]] fy;
fx5 = gxp[5,theta] + fx6;
fy5 = gyp[5,theta] + fy6;

```

```

fx4 = gxp[4,theta] + Cos[theta[[5]]] fx5 - Sin[theta[[5]]] fy5;
fy4 = gyp[4,theta] + Sin[theta[[5]]] fx5 + Cos[theta[[5]]] fy5;
fx3 = gxp[3,theta] + Cos[theta[[4]]] fx4 - Sin[theta[[4]]] fy4;
fy3 = gyp[3,theta] + Sin[theta[[4]]] fx4 + Cos[theta[[4]]] fy4;
fx2 = gxp[2,theta] + Cos[theta[[3]]] fx3 - Sin[theta[[3]]] fy3;
fy2 = gyp[2,theta] + Sin[theta[[3]]] fx3 + Cos[theta[[3]]] fy3;
fx1 = gxp[1,theta] + Cos[theta[[2]]] fx2 - Sin[theta[[2]]] fy2;
fy1 = gyp[1,theta] + Sin[theta[[2]]] fx2 + Cos[theta[[2]]] fy2;
fx0 = Cos[theta[[1]]] fx1 - Sin[theta[[1]]] fy1;
fy0 = Sin[theta[[1]]] fx1 + Cos[theta[[1]]] fy1;

```

```

{fx1,fx2,fx3,fx4,fx5,fx6,fy1,fy2,fy3,fy4,fy5,fy6}

```

```

]

```

(*JOINT TORQUE *)

(*This calculates the torques in all the joints (1..6)*)

```

jointTorque[theta_List,l_List,lc_List,fxForce_List,fyForce_List]:=

```

```

Module[

```

```

{fx6,fy6,fx5,fy5,fx4,fy4,fx3,fy3,fx2,fy2,fx1,fy1,fx0,fy0,
torque0,torque1,torque2,torque3,torque4,torque5},

```

```

torque5 = lc[[5]] gyp[5,theta] + l[[5]] fyForce[[6]];

```

```

torque4 =torque5+ lc[[4]] gyp[4,theta] + l[[4]] (Sin[theta[[5]]] fxForce[[5]] +
Cos[theta[[5]]] fyForce[[5]]);

```

```

torque3 =torque4+ lc[[3]] gyp[3,theta] + l[[3]] (Sin[theta[[4]]] fxForce[[4]] +
Cos[theta[[4]]] fyForce[[4]]);

```

```

torque2 =torque3+ lc[[2]] gyp[2,theta] + l[[2]] (Sin[theta[[3]]] fxForce[[3]] +
Cos[theta[[3]]] fyForce[[3]]);

```

```

torque1 =torque2+ lc[[1]] gyp[1,theta] + l[[1]] (Sin[theta[[2]]] fxForce[[2]] +
Cos[theta[[2]]] fyForce[[2]]);

```

```

torque0 = torque1;

```

```

{torque0,torque1,torque2,torque3,torque4,torque5}

```

```

]

```

(*CALC MAX TORQUE AT EACH JOINT*)

```

maxJointTorque[theta_List,gender_Integer,alltorque_List]:=

```

```

Module[{ MaxElbow,MaxTshoulder,MaxThip,MaxTknee,MaxTankle
},
If[alltorque[[5]]>0,
  MaxElbow=(336.29+1.544*(Pi-theta[[5]])
            -0.0085(Pi-theta[[5]]^2-0.5(theta[[4]]-
Pi))adjust[[1,gender]];,
  MaxElbow=(264.153-0.575*(Pi-theta[[5]])
            -0.425(theta[[4]]-Pi)adjust[[2,gender]]);
If[alltorque[[4]]>0,
  MaxTshoulder=(227.338+0.525*(Pi-theta[[5]])
                -0.296*(theta[[4]]-Pi)adjust[[3,gender]];,
  MaxTshoulder=(204.562-0.099*(theta[[4]]-Pi)adjust[[4,gender]]);
If[alltorque[[3]]>0,
  MaxThip=(-820.21+34.29(theta[[3]]-Pi)
           -0.11426(theta[[3]]-Pi)^2)adjust[[5,gender]];,
  MaxThip=(3338.1-15.711(theta[[3]]-Pi)
           +0.04626(theta[[3]]-Pi)^2)adjust[[6,gender]]);
If[alltorque[[2]]>0,
  MaxTknee=(1091.9+0.0996(Pi-theta[[2]])+0.17308(Pi-theta[[2]]^2
              -0.00097(Pi-theta[[2]]^3)adjust[[7,gender]];,
  MaxTknee=(-94.437+6.3672(Pi-theta[[2]]^2)adjust[[8,gender]]);

  MaxTankle=(3356.8-18.4*theta[[1]])adjust[[9,gender]];
{ MaxTankle,MaxTknee,MaxThip,MaxTshoulder,MaxElbow }

```

(*BALANCE *)

```

balance[theta_List,fxForce_List,fyForce_List,torque0_]:=
Module[{ torqueh,torqueb,fxh,fyh,fxb,fyb },

  (* If torqueh>0 then the person will tip backwards*)
  fxh = Cos[theta[[1]]] fxForce[[1]] - Sin[theta[[1]]] fyForce[[1]];
  fyh = Sin[theta[[1]]] fxForce[[1]] + Cos[theta[[1]]] fyForce[[1]];
  torqueh = N[torque0 + (Abs[xheel-xa] fyh)
  - (anthro[[6]] fxh) + 0.44*footlength*wyl];

  (* If torqueb<0 then the person will tip forwards *)
  torqueb = N[torque0 - (Abs[xball-xa] fyh)
  - (anthro[[6]] fxh) - 0.56*footlength*wyl];
  {torqueh,torqueb}
]

```

(*Note: retry is used to calculate the other posture
if the elbow is behind the hip*)

```

minFunct[xyphi_List]:=
Module[{ theta,fxForce,fxForce,fyForce,alltorque,torque0,
  ttorque0,ttorque,ball,heel,totalbalance,maxJoint,
  percenttorque,percentChosen,ansr,retry
},

```

```

xh=xyphi[[1]];
yh=xyphi[[2]];
phi=xyphi[[3]];
firstansr=99999;
gender=anthro[[1]];

Do[
ansr={99999};
If[retry==1,
    repet="no",repet="yes"];
theta=angles[l,phi,xh,yh];

(*Test for Range of Motion
 *to see if ankle is feasible 29<theta1<153*)
If[(checkAngle[N[theta[[1]]]<(29/360)) &&
    (checkAngle[N[theta[[1]]]>(153/360))),
    ansr={111111,111111,111111};];

(*Test Hip for Range of Motion -50<theta3<180*)
If[(checkAngle[N[theta[[3]]]>(50/360)) &&
    (checkAngle[N[theta[[3]]]<(180/360))),
    ansr={333333,333333,333333};];

(*Test Shoulder for Range of Motion 120<theta4<370*)
If[(checkAngle[N[theta[[4]]]<(120/360)) &&
    (checkAngle[N[theta[[4]]]>(10/360))),
    ansr={444444,444444,444444};];

(*Test to see if posture is has a feasible elbow angle*)
If[Sin[theta[[5]]]<0,
    ansr={555555,555555,555555};];

(*Test to see if it is any feasible posture at all*)
If[N[theta[[1]]]==99,ansr={98989,98989,98989};];

If[ansr=={99999},
fxForce=jointForce[theta];
fxForce=Table[fxForce[[i]],{i,1,6}];
fyForce=Table[fxForce[[i]],{i,7,12}];

alltorque = jointTorque[theta,l,lc,fxForce,fyForce];
torque0=alltorque[[1]];
ttorque=Sum[Abs[alltorque[[i]]],{i,1,5}];
{heel,ball}=balance[theta,fxForce,fyForce,torque0];
(*Print[heel," ",ball];*)
If[(heel>0) || (ball<0),
    ttorque=9999;totalbalance=9999;percentChosen=9999,
    totalbalance=Abs[Abs[heel]-Abs[ball]];
];

```

```

If[hypoth==2,
    maxJoint=maxJointTorque[theta,gender,alltorque];
    percenttorque=Table[Abs[alltorque[[i]]/maxJoint[[i]],{i,1,5}];
    percentChosen=Last[Sort[percenttorque]];
];

If[(heel>0),ttorque=9998;totalbalance=9998;percentChosen=9998];
If[(ball<0),ttorque=9999;totalbalance=9999;percentChosen=9999];

ansr={ttorque,N[percentChosen],totalbalance};
]; (*End of If[ansr<98000]*)

If[retry==1,firstansr=ansr,
    If[(ansr[[hypoth]]>firstansr[[hypoth]]),ansr=firstansr;];];

,{retry,1,2}]; (*End of Do statement*)

repet="no";

{ansr[[hypoth]]}
]

(*Modules for Nelder and Mead*)
stepThree[functall_List,xbar_List,functxhat_List,gamma_Real
    ]:=
Module[{xe, functxe,functmax,functnewall
    },

    xe=xbar+gamma*(xhat-xbar);
    functxe=minFunct[xe];
    (*Step THREE*)
    If[functxhat[[1]]>functxe[[1]],
        functmax={functxe,xe},
        functmax={functxhat,xhat}];
    functnewall=Take[Sort[Append[functall,functmax]],{1,4}];
    functnewall
    ]

stepFour[functall_List,xbar_List,functxhat_List,
    xhat_List,functmax_List,beta_Real]:=
Module[{functxprime,x2prime,functx2prime,xnew,
    functnewall,functnewmax
    },

    If[(Last[Drop[Sort[functall],-1]][[1,1]]>=functxhat[[1]]),
        functnewmax={functxhat,xhat};
        functnewall=Join[Take[Sort[functall],{1,3}],{functnewmax}];
        (* else Step FIVE*)

        functxprime=First[Sort[{functxhat,xhat},functmax]];
        x2prime=xbar+beta*(functxprime[[2]]-xbar);

```

```

            functx2prime=minFunct[x2prime];
            If[functx2prime[[1]]>functxprime[[1,1]],
                xnew=Table[
                    functall[[i,2]]+0.5*(functmin[[2]]-functall[[i,2]]),
                    {i,1,4}];
                functnewall={{ minFunct[xnew[[1]]],xnew[[1]],
                    { minFunct[xnew[[2]]],xnew[[2]]}
                    ,{ minFunct[xnew[[3]]],xnew[[3]]}
                    ,{ minFunct[xnew[[4]]],xnew[[4]]} };
                (*else*)
                functnewmax={ functx2prime,x2prime };

    functnewall=Take[Sort[Append[functall,functnewmax]],{1,4}];
];
];

]
]

```

(*Find Starting Points for Search*)

```

startPoints[l_List,xhand_Real,yhand_Real,ankle_List]:=
Module[{ phitryout,c,psy,delta,zeta,xend2,xend1,xtryoutLeft,ytopLeft,
ybottomLeft,xtryoutRight,ytopRight,ybottomRight,allpoints
},
    phitryout={ -1.5,-1.0,-0.5,0.0,0.5,1.0,1.5 };
    allpoints={ };
    adjustment=0.0;
    testpnts={ 9999 };
    While[(testpnts[[1]]>9997),
        allpoints={ };
        Do[
            (phi=phitryout[[i]];
                xe=xhand-l[[5]] Cos[phi];
                ye=yhand-l[[5]] Sin[phi];
                xa=ankle[[1]];
                ya=ankle[[2]];

                c=((xa-xe)^2+(ya-ye)^2)^0.5;
                If[Abs[l[[1]]+l[[2]]-c]>l[[3]]+l[[4]],,
                    psy =ArcCos[(((l[[1]]+l[[2]))^2+c^2-(l[[3]]+l[[4]))^2)/
                        (2*(l[[1]]+l[[2])) c)];

                    delta =ArcTan[(ye-ya)/(xe-xa)];

                    (*point end2*)
                    zeta=delta-psy;
                    xend2=(l[[1]]+l[[2])) Cos[zeta] + xa;

                    (*point end1*)

```



```

zeta=delta+psy;
xend1=(l[[1]]+l[[2]]) Cos[zeta] + xa;

xtryoutLeft= -(1-adjustment) ((xend2-xend1)/2) + ((xend1+xend2)/2);
ytopLeft = Sqrt[(l[[1]]+l[[2]])^2-(xtryoutLeft-xa)^2]+ya-0.001;
ybottomLeft = -Sqrt[(l[[3]]+l[[4]])^2-(xtryoutLeft-xe)^2]+ye+0.001;

AppendTo[allpoints,{ minFunct[{ xtryoutLeft,ytopLeft,phi }],{ xtryoutLeft,ytopLeft,
phi },

minFunct[{ xtryoutLeft,ybottomLeft,phi }],{ xtryoutLeft,ybottomLeft,phi } }];

xtryoutRight= (0.5-adjustment) ((xend2-xend1)/2) + ((xend1+xend2)/2);
ytopRight = Sqrt[(l[[1]]+l[[2]])^2-(xtryoutRight-xa)^2]+ya- 0.001;
ybottomRight = -Sqrt[(l[[3]]+l[[4]])^2-(xtryoutRight-xe)^2]+ye+ 0.001;

AppendTo[allpoints,{ minFunct[{ xtryoutRight,ytopRight,phi }],{ xtryoutRight,ytop
Right,phi },

minFunct[{ xtryoutRight,ybottomRight,phi }],{ xtryoutRight,ybottomRight,phi } }];
)
,{i,1,7}];
startingpnts=Take[Sort[Partition[Flatten[allpoints],4],4],4];
testpnts=First[startingpnts];
adjustment=adjustment+0.1;

If[adjustment>0.1,Print[adjustment,"-adjust",testpnts]];

];
startingpnts
]

(*The NM Search*)
setUp[l_List,xhand_Real,yhand_Real,ankle_List,hypoth_Integer]:=
Module[{
},
(*Choose hypothesis where 1: torque., 2: percenttorque
* 3: totalbalance*)
alpha=0.5; (*reflection coefficient*)
gamma=1.4; (*expansion coefficient*)
beta=1.4; (*positive contraction coefficient*)
error=5;
stop=0;
answer={{999},{99,99,99}};
incrmnt={0.1,0.05,0.01};
marker=0;

If[trial==lasttrial,

```

```

marker=1;
startingfunc=Table[Flatten[{ minFunc[laststartfunc[[i,2]],laststartfunc[[i,2]]}],{i
,1,4}];
(*Check to see if these points are feasible*)

If[First[Sort[startingfunc]][[1]]>997,startingfunc=startPoints[l,xhand,yhand,ankl
e]];marker=0;,
(*Calculate new starting Points*)
startingfunc=startPoints[l,xhand,yhand,ankle];
];
x=Table[Table[startingfunc[[j,i]],{i,2,4}],{j,1,4}];
funcall=Table[{ startingfunc[[i,1]],x[[i]]},{i,1,4}];

beginfunc=funcall;
comparex=x;

lasttrial=trial;

maxmarker=0;
lastanswer={ {999},{99,99,99} };
]

postureSoln[l_List,xhand_Real,yhand_Real,ankle_List,hypoth_Integer] :=
Module[{
},
setUp[l,xhand,yhand,ankle,hypoth];

While[(marker<4),
If[lastanswer[[1,1]]==answer[[1,1]],
marker=marker+1;incr=incrmnt[[marker]];];
change=incr*{ {0,0,0},{1,0,0},{-1,0,0},{0,1,0},{0,-1,0},{0,0,1},{0,0,-1} };
lastanswer=answer;
Print["increment-",incr];

Do[
If[k==1,,
x=Table[comparex[[j]]+change[[k]],{j,1,4}]; (*Change plane*)
funcall={ { minFunc[x[[1]],x[[1]]},{ minFunc[x[[2]],x[[2]]}
,{ minFunc[x[[3]],x[[3]]},{ minFunc[x[[4]],x[[4]]} };
];

(*If[k==1,Print[funcall]];*)

sortfunc=Sort[funcall];
funcmax=Last[sortfunc];
funcmin=First[sortfunc];
previous=99999;
i=0;

```

```

While[(previous-(functmax[[1,1]]-functmin[[1,1]])>0.1 &&(i<3)),
previous=functmax[[1,1]]-functmin[[1,1]];
i=i+1;

(*The actual search*)
xbar=Sum[functall[[j,2]],{j,1,4}]/4;
xhat=xbar+alpha*(xbar-functmax[[2]]);
functxhat=minFunct[xhat];

If[functmin[[1,1]]>functxhat[[1]],
  functall=stepThree[functall,xbar,functxhat,gamma],
  functall=stepFour[functall,xbar,functxhat,xhat,functmax,beta];
];

sortfunct=Sort[functall];
functmax=Last[sortfunct];
functmin=First[sortfunct];

(*Print[i,functmin];*)

]; (*Return to While statement*)
If[functmin[[1,1]]<answer[[1,1]],answer=functmin];

,{k,1,7}];
Print["ans",answer];
functmax=Last[Sort[beginfunct]];
If[(functmax[[1,1]]>=9999) || (maxmarker<3),
  maxmarker=maxmarker+1;
  functall=Append[Drop[Sort[beginfunct],-
1],answer];,
  functall=Append[Drop[Sort[beginfunct],1],answer];
];

x=Table[functall[[j,2]],{j,1,4}];
beginfunct=functall;
comparex=x;
If[(lastanswer[[1,1]]==answer[[1,1]]) && (marker==3),marker=4];
If[(lastanswer[[1,1]]!=answer[[1,1]]) && (Apply[Plus,Abs[lastanswer[[2]]-
answer[[2]]])<0.0003),

  marker=marker+1;

  If[marker<4,incr=incrmnt[[marker]]];];
]; (*First While loop*)
laststartfunct=functall;
answer
]
(* Gender {1,2}, Stature (m), Weight (Kg),

```

* ankle to heel (m),ankle to toe (m), ankle to floor (m)
 *)

```
anthropometry=
{{1, 1.744, 69.9*9.80665, 0.058, 0.227, 0.085},
{1, 1.815, 80.6*9.80665, 0.067, 0.254, 0.107},
{1, 1.884, 83.8*9.80665, 0.071, 0.234, 0.102},
{1, 1.711, 67.4*9.80665, 0.077, 0.220, 0.105},
{1, 1.761, 81.6*9.80665, 0.042, 0.220, 0.087},
{1, 1.851, 83.9*9.80665, 0.075, 0.218, 0.085},
{1, 1.842, 71.1*9.80665, 0.086, 0.237, 0.092},
{1, 1.889, 81.3*9.80665, 0.073, 0.244, 0.100},
{2, 1.690, 56.8*9.80665, 0.06, 0.203, 0.100},
{2, 1.683, 49.5*9.80665, 0.039, 0.216, 0.055},
{2, 1.649, 66.1*9.80665, 0.049, 0.216, 0.088},
{2, 1.713, 67.0*9.80665, 0.066, 0.207, 0.074},
{2, 1.661, 54.6*9.80665, 0.052, 0.212, 0.058},
{2, 1.642, 48.2*9.80665, 0.052, 0.201, 0.081},
{2, 1.642, 55.7*9.80665, 0.063, 0.217, 0.059},
{2, 1.548, 55.1*9.80665, 0.057, 0.189, 0.083}};
```

(*Read Data*)

```
subjAnswers[subj_Integer]:=
  Module[{
    },
  begofTrials={1,1,1};
  endofTrials={32,32,32};
  inputFile = StringJoin["AlgorInput_",ToString[subj],".DAT"];

  inputAlgor= Sort[ReadList[inputFile,Number,RecordLists -> True]];
  observedFile=StringJoin["PosObserved_",ToString[subj],".DAT"];
  inputObserved= Sort[ReadList[observedFile,Number,RecordLists -> True]];
  outFile = StringJoin["PredictOut_",ToString[subj],".DAT"];
  lasttrial=999;
  anthro=anthropometry[[subj]];
  predictions={};
  outData={};

  Do[

  Do[
  xhand=inputAlgor[[a,5]];
  yhand=inputAlgor[[a,6]];
  l=Table[inputAlgor[[a,j]],{j,7,11}];
  ankle={inputAlgor[[a,3]],inputAlgor[[a,4]]};
  trial=inputAlgor[[a,1]];
  observe={inputObserved[[a,9]],inputObserved[[a,10]],inputObserved[[a,15]]};

  inputData[1,anthro,ankle];
  Print[a," ",hypoth," ",inputObserved[[a,1]]," ",inputObserved[[a,2]],
```

```

" (" ,xhand," ,yhand,")");
(*Print[minFunct[observe],observe];*)
newprediction=postureSoln[l,xhand,yhand,ankle,hypoth];
AppendTo[predictions,newprediction];
AppendTo[outData,Flatten[Join[{hypoth,inputObserved[[a,1]],inputObserved[[a,2]]}
, newprediction,{minFunct[observe],observe,calcError[a]}]]];

,{a,begofTrials[[hypoth]],endofTrials[[hypoth]]};

writeMatrix[StringJoin[outFile,"-",ToString[hypoth]],outData];

,{hypoth,1,3}];
]

```

APPENDIX B: Calculations for Forces and Moments at Each Joint

B.1 Introduction to calculation of force and moments

The following solution for calculating forces and moments is adapted from Byun (1991). Table B.1 describes the variables that were used for the calculations and is shown in Figure B.1.

TABLE B.1 Description of variables used in force and moment calculations.

	${}^i\mathbf{f}_i = \begin{bmatrix} {}^i\mathbf{f}_x \\ {}^i\mathbf{f}_y \\ 0 \end{bmatrix}$
	is the force at joint i due to external forces and link mass.
	${}^i\mathbf{n}_{i+1}$ is the moment applied to joint i by link i+1.
	${}^i\mathbf{n}_i$ is the total moment at joint i.
	${}^i\mathbf{P}_{C_i}$ is the 3 x 1 position vector locating the center of mass of link i relative to joint i.
	${}^i\mathbf{P}_{i+1}$ is the position vector locating reference frame (i+1) with respect to reference frame (i).
	l_{ci} : Center of mass of link length i. Defined as distance from joint i.

The balance equations of static forces and moments can be written as:

$${}^i\mathbf{n}_i = {}^i\mathbf{n}_{i+1} + {}^i\mathbf{P}_{C_i} \times {}^i\mathbf{g}_i + {}^i\mathbf{P}_{i+1} \times {}^i\mathbf{f}_{i+1} \quad (\text{B.1})$$

$${}^i\mathbf{f}_i = {}^i\mathbf{g}_i + {}^i\mathbf{f}_{i+1}. \quad (\text{B.2})$$

All the forces and moments must be transformed to reference frame (i) relative to reference frame (i+1) using a rotation matrix:

$${}^i\mathbf{n}_i = \mathbf{R}_{i+1}^i {}^{i+1}\mathbf{n}_{i+1} + {}^i\mathbf{P}_{C_i} \times {}^i\mathbf{g}_i + {}^i\mathbf{P}_{i+1} \times \mathbf{R}_{i+1}^i {}^{i+1}\mathbf{f}_{i+1} \quad (\text{B.3})$$

$${}^i\mathbf{f}_i = {}^i\mathbf{g}_i + \mathbf{R}_{i+1}^i {}^{i+1}\mathbf{f}_{i+1}. \quad (\text{B.4})$$

The torque is then described as a scalar by the following:

$$\tau_i = ({}^i\mathbf{n}_i)^t \hat{\mathbf{z}}_i \quad (\text{B.5})$$

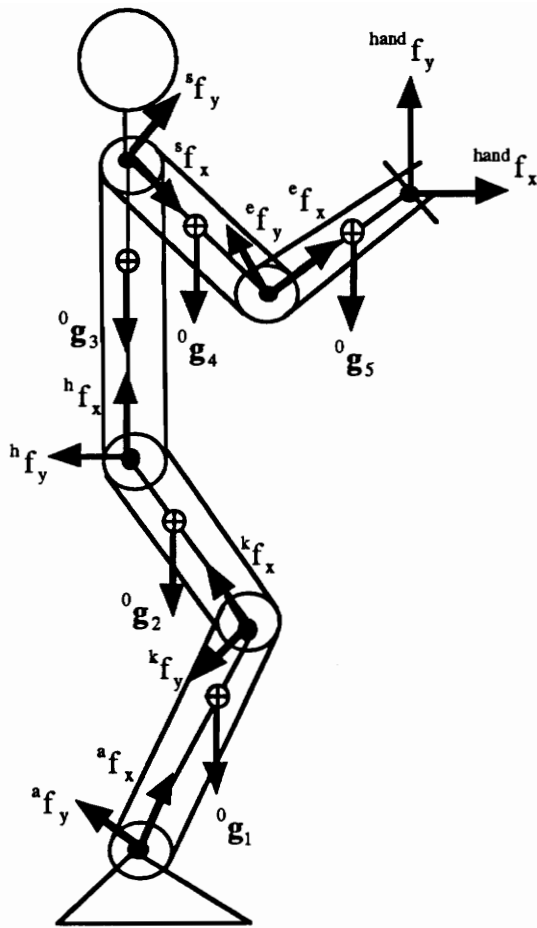


Figure B.1 Definition of forces on body.

where

$${}^i\hat{\mathbf{z}}_i = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (\text{B.6})$$

Thus the rotation matrix describing from (0) reference frame to i reference frame is:

$$\mathbf{R}_i^0 = \mathbf{R}_1^0 \mathbf{R}_2^1 \dots \mathbf{R}_i^{i-1} = \begin{bmatrix} C_{12\dots i} & -S_{12\dots i} & 0 \\ S_{12\dots i} & C_{12\dots i} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (\text{B.7})$$

and the rotation matrix for i to 0 is:

$$\mathbf{R}_0^i = [\mathbf{R}_i^0]^{-1} = \begin{bmatrix} C_{12\dots i} & S_{12\dots i} & 0 \\ -S_{12\dots i} & C_{12\dots i} & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (\text{B.8})$$

The load at the hand is described as:

$${}^0\mathbf{f}_{\text{hand}} = \begin{bmatrix} \text{external } f_x \\ \text{external } f_y \\ 0 \end{bmatrix}. \quad (\text{B.9})$$

So the force at the hand in the hand reference frame is:

$${}^{\text{hand}}\mathbf{f}_{\text{hand}} = \mathbf{R}_0^{\text{hand}} {}^0\mathbf{f}_{\text{hand}} = \begin{bmatrix} C_{12345} \text{external } f_x + S_{12345} \text{external } f_y \\ -S_{12345} \text{external } f_x + C_{12345} \text{external } f_y \\ 0 \end{bmatrix} = \begin{bmatrix} \text{hand } f_x \\ \text{hand } f_y \\ 0 \end{bmatrix}. \quad (\text{B.10})$$

The weight of link i in the 0 reference frame is:

$${}^0\mathbf{g}_i = \begin{bmatrix} 0 \\ {}^i g_y \\ 0 \end{bmatrix}. \quad (\text{B.11})$$

The weight at link i in the ith reference frame is:

$${}^i \mathbf{g}_i = \mathbf{R}_0^i {}^0 \mathbf{g}_i = \begin{bmatrix} S_{12\dots i} & \mathbf{g}_i \\ C_{12\dots i} & \mathbf{g}_i \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} {}^i \mathbf{g}_x \\ {}^i \mathbf{g}_y \\ 0 \end{bmatrix} \quad (\text{B.12})$$

B.2 Calculations of moments and forces at each joint

Since the external forces are at the hand, there is no moment at the hands (${}^{\text{hand}} \mathbf{n}_{\text{hand}}$).

The following are the calculation of forces and moments at the elbow, shoulder, hip, knee, ankle and base (0).

Elbow:

$${}^e \mathbf{n}_e = \mathbf{R}_{\text{hand}}^e {}^{\text{hand}} \mathbf{n}_{\text{hand}} + {}^e \mathbf{P}_{C_e} \times {}^5 \mathbf{g}_5 + {}^e \mathbf{P}_{\text{hand}} \times \mathbf{R}_{\text{hand}}^e {}^{\text{hand}} \mathbf{f}_{\text{hand}} \quad (\text{B.13})$$

$$= \begin{bmatrix} l_{c5} \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} {}^5 \mathbf{g}_x \\ {}^5 \mathbf{g}_y \\ 0 \end{bmatrix} + \begin{bmatrix} l_5 \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} {}^e \mathbf{f}_x \\ {}^e \mathbf{f}_y \\ 0 \end{bmatrix} \quad (\text{B.14})$$

$$= \begin{bmatrix} 0 \\ 0 \\ l_{c5} {}^5 \mathbf{g}_y + l_5 {}^{\text{hand}} \mathbf{f}_y \end{bmatrix} \quad (\text{B.15})$$

$$\boldsymbol{\tau}_e = ({}^e \mathbf{n}_e)^t {}^5 \hat{\mathbf{z}}_5 = \begin{bmatrix} 0 & 0 & l_{c5} {}^5 \mathbf{g}_y + l_5 {}^{\text{hand}} \mathbf{f}_y \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (\text{B.16})$$

$$= l_{c5} {}^5 \mathbf{g}_y + l_5 {}^{\text{hand}} \mathbf{f}_y \quad (\text{B.17})$$

$${}^e \mathbf{f}_e = {}^5 \mathbf{g}_5 + \mathbf{R}_{\text{hand}}^e {}^{\text{hand}} \mathbf{f}_{\text{hand}} = \begin{bmatrix} {}^5 \mathbf{g}_x + {}^{\text{hand}} \mathbf{f}_x \\ {}^5 \mathbf{g}_y + {}^{\text{hand}} \mathbf{f}_y \\ 0 \end{bmatrix} = \begin{bmatrix} {}^e \mathbf{f}_x \\ {}^e \mathbf{f}_y \\ 0 \end{bmatrix} \quad (\text{B.18})$$

Shoulder:

$${}^s \mathbf{n}_s = \mathbf{R}_e^s {}^e \mathbf{n}_e + {}^s \mathbf{P}_{C_s} \times {}^4 \mathbf{g}_4 + {}^s \mathbf{P}_e \times \mathbf{R}_e^s {}^e \mathbf{f}_e \quad (\text{B.19})$$

$$= \begin{bmatrix} 0 \\ 0 \\ \tau_e + l_{c4} {}^4\mathbf{g}_y + l_4(S_5 {}^e\mathbf{f}_x + C_5 {}^e\mathbf{f}_y) \end{bmatrix} \quad (\text{B.20})$$

$$\tau_s = ({}^s\mathbf{n}_s)^t {}^4\hat{\mathbf{z}}_4 = \tau_e + l_{c4} {}^4\mathbf{g}_y + l_4(S_5 {}^e\mathbf{f}_x + C_5 {}^e\mathbf{f}_y) \quad (\text{B.21})$$

$${}^s\mathbf{f}_s = {}^4\mathbf{g}_4 + \mathbf{R}_e {}^e\mathbf{f}_e = \begin{bmatrix} {}^4\mathbf{g}_x + C_5 {}^e\mathbf{f}_x - S_5 {}^e\mathbf{f}_y \\ {}^4\mathbf{g}_y + S_5 {}^e\mathbf{f}_x + C_5 {}^e\mathbf{f}_y \\ 0 \end{bmatrix} = \begin{bmatrix} {}^s\mathbf{f}_x \\ {}^s\mathbf{f}_y \\ 0 \end{bmatrix} \quad (\text{B.22})$$

Hip:

$${}^h\mathbf{n}_h = \mathbf{R}_i {}^h\mathbf{n}_i + {}^h\mathbf{P}_{C_i} {}^3\mathbf{g}_3 + {}^h\mathbf{P}_i \mathbf{R}_i {}^h\mathbf{f}_i \quad (\text{B.23})$$

$$= \begin{bmatrix} 0 \\ 0 \\ \tau_s + l_{c3} {}^3\mathbf{g}_y + l_3(S_4 {}^s\mathbf{f}_x + C_4 {}^s\mathbf{f}_y) \end{bmatrix} \quad (\text{B.24})$$

$$\tau_h = ({}^h\mathbf{n}_h)^t {}^3\hat{\mathbf{z}}_3 = \tau_s + l_{c3} {}^3\mathbf{g}_y + l_3(S_4 {}^s\mathbf{f}_x + C_4 {}^s\mathbf{f}_y) \quad (\text{B.25})$$

$${}^h\mathbf{f}_h = {}^3\mathbf{g}_3 + \mathbf{R}_i {}^h\mathbf{f}_i = \begin{bmatrix} {}^3\mathbf{g}_x + C_4 {}^s\mathbf{f}_x - S_4 {}^s\mathbf{f}_y \\ {}^3\mathbf{g}_y + S_4 {}^s\mathbf{f}_x + C_4 {}^s\mathbf{f}_y \\ 0 \end{bmatrix} = \begin{bmatrix} {}^h\mathbf{f}_x \\ {}^h\mathbf{f}_y \\ 0 \end{bmatrix} \quad (\text{B.26})$$

Knee:

$${}^k\mathbf{n}_k = \mathbf{R}_h {}^k\mathbf{n}_h + {}^k\mathbf{P}_{C_h} {}^2\mathbf{g}_2 + {}^k\mathbf{P}_h \mathbf{R}_h {}^k\mathbf{f}_h \quad (\text{B.27})$$

$$= \begin{bmatrix} 0 \\ 0 \\ \tau_h + l_{c2} {}^2\mathbf{g}_y + l_2(S_3 {}^h\mathbf{f}_x + C_3 {}^h\mathbf{f}_y) \end{bmatrix} \quad (\text{B.28})$$

$$\tau_k = ({}^k\mathbf{n}_k)^t {}^2\hat{\mathbf{z}}_2 = \tau_h + l_{c2} {}^2\mathbf{g}_y + l_2(S_3 {}^h\mathbf{f}_x + C_3 {}^h\mathbf{f}_y) \quad (\text{B.29})$$

$${}^k\mathbf{f}_k = {}^2\mathbf{g}_2 + \mathbf{R}_h {}^k\mathbf{f}_h = \begin{bmatrix} {}^2\mathbf{g}_x + C_3 {}^h\mathbf{f}_x - S_3 {}^h\mathbf{f}_y \\ {}^2\mathbf{g}_y + S_3 {}^h\mathbf{f}_x + C_3 {}^h\mathbf{f}_y \\ 0 \end{bmatrix} = \begin{bmatrix} {}^k\mathbf{f}_x \\ {}^k\mathbf{f}_y \\ 0 \end{bmatrix} \quad (\text{B.30})$$

Ankle:

$${}^a\mathbf{n}_a = \mathbf{R}_k^a \mathbf{n}_k + {}^a\mathbf{P}_{C_k} \times {}^a\mathbf{g}_a + {}^a\mathbf{P}_k \times \mathbf{R}_k^a \mathbf{f}_k \quad (\text{B.31})$$

$$= \begin{bmatrix} 0 \\ 0 \\ \tau_k + l_{c1} {}^1g_y + l_1 (S_2 {}^k f_x + C_2 {}^k f_y) \end{bmatrix} \quad (\text{B.32})$$

$$\tau_a = ({}^a\mathbf{n}_a)^{11} \hat{\mathbf{z}}_1 = \tau_k + l_{c1} {}^1g_y + l_1 (S_2 {}^k f_x + C_2 {}^k f_y) \quad (\text{B.33})$$

$${}^a\mathbf{f}_a = {}^1\mathbf{g}_1 + \mathbf{R}_k^a \mathbf{f}_k = \begin{bmatrix} {}^1g_x + C_2 {}^k f_x - S_2 {}^k f_y \\ {}^1g_y + S_2 {}^k f_x + C_2 {}^k f_y \\ 0 \end{bmatrix} = \begin{bmatrix} {}^a f_x \\ {}^a f_y \\ 0 \end{bmatrix} \quad (\text{B.34})$$

At coordinate base (0):

$${}^0\mathbf{n}_0 = \mathbf{R}_a^0 {}^a\mathbf{n}_a + {}^0\mathbf{P}_{C_a} {}^0\mathbf{g}_0 + {}^0\mathbf{P}_a \mathbf{R}_a^0 {}^a\mathbf{f}_a \quad (\text{B.35})$$

$$= \begin{bmatrix} 0 \\ 0 \\ \tau_a \end{bmatrix} \quad (\text{B.36})$$

$$\tau_0 = ({}^0\mathbf{n}_0)^{10} \hat{\mathbf{z}}_0 = \tau_a \quad (\text{B.37})$$

$${}^0\mathbf{f}_0 = {}^0\mathbf{g}_0 + \mathbf{R}_a^0 {}^a\mathbf{f}_a = \begin{bmatrix} {}^0g_x + C_1 {}^a f_x - S_1 {}^a f_y \\ {}^0g_y + S_1 {}^a f_x + C_1 {}^a f_y \\ 0 \end{bmatrix} = \begin{bmatrix} {}^0 f_x \\ {}^0 f_y \\ 0 \end{bmatrix} \quad (\text{B.38})$$

B.3 Balance Equations

An important assumption is that a human chooses a posture without falling down. Kerk (1992) investigated the stability of postures by looking at the predicted torque at the ball and heel of the feet. This thesis used calculations from Byun (1991) who modified Kerk's equations into matrices. Figure B.2 describes the variables for the calculations in this section. The assumption is that if the amount of torque at the heel or ball exceeds a certain limit then the body is not static and is falling either forwards or backwards.

B.3.1 Calculations for the torque at the heel of the foot

So continuing on from equation B.38, the force at the heel is calculated.

$${}^{\text{heel}}\mathbf{f}_{\text{heel}} = {}^{\text{heel}}\mathbf{g}_{\text{heel}} + \mathbf{R}_0^{\text{heel}} \times {}^0\mathbf{f}_0 = \begin{bmatrix} 0 \\ {}^{\text{foot}}\mathbf{g}_y \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_1^a f_x - S_1^a f_y \\ S_1^a f_x + C_1^a f_y \\ 0 \end{bmatrix} \quad (\text{B.39})$$

$$= \begin{bmatrix} C_1^a f_x - S_1^a f_y \\ {}^{\text{foot}}\mathbf{g}_y + S_1^a f_x + C_1^a f_y \\ 0 \end{bmatrix} \quad (\text{B.40})$$

If the human falls backwards, the reaction force at the ball will be zero and all the weight will be supported at the heel. To test if a human is falling backwards, the model calculates the torque at heel while assuming that there is no reaction force at the ball. The model defines the human as falling backwards if the torque at the heel is greater than zero. If the torque is less than zero then the human is not falling backwards and the assumption that there is no reaction force at the ball is incorrect.

Kerk (1992) found that the center of pressure for the heel is about 40% of the distance from the ankle joint center to the posterior-most point of the barefoot. The value ${}^{\text{foot}}\mathbf{g}_y$ is the weight of the foot. The following calculations of the torque at the heel assume that there is no reaction force at the ball of the foot.

$${}^{\text{heel}}\mathbf{g}_{\text{heel}} = \begin{bmatrix} 0 \\ {}^{\text{foot}}\mathbf{g}_y \\ 0 \end{bmatrix} \quad (\text{B.41})$$

$$\tau_0 = ({}^0\mathbf{n}_0)^t {}^0\hat{\mathbf{z}}_0 = \tau_a \quad (\text{B.42})$$

$${}^{\text{heel}}\mathbf{n}_{\text{heel}} = \mathbf{R}_0^{\text{heel}} {}^0\mathbf{n}_0 + {}^{\text{heel}}\mathbf{P}_{C_{\text{foot}}} \times {}^{\text{heel}}\mathbf{g}_{\text{heel}} + {}^{\text{heel}}\mathbf{P}_0 \times \mathbf{R}_0^{\text{heel}} {}^0\mathbf{f}_0$$

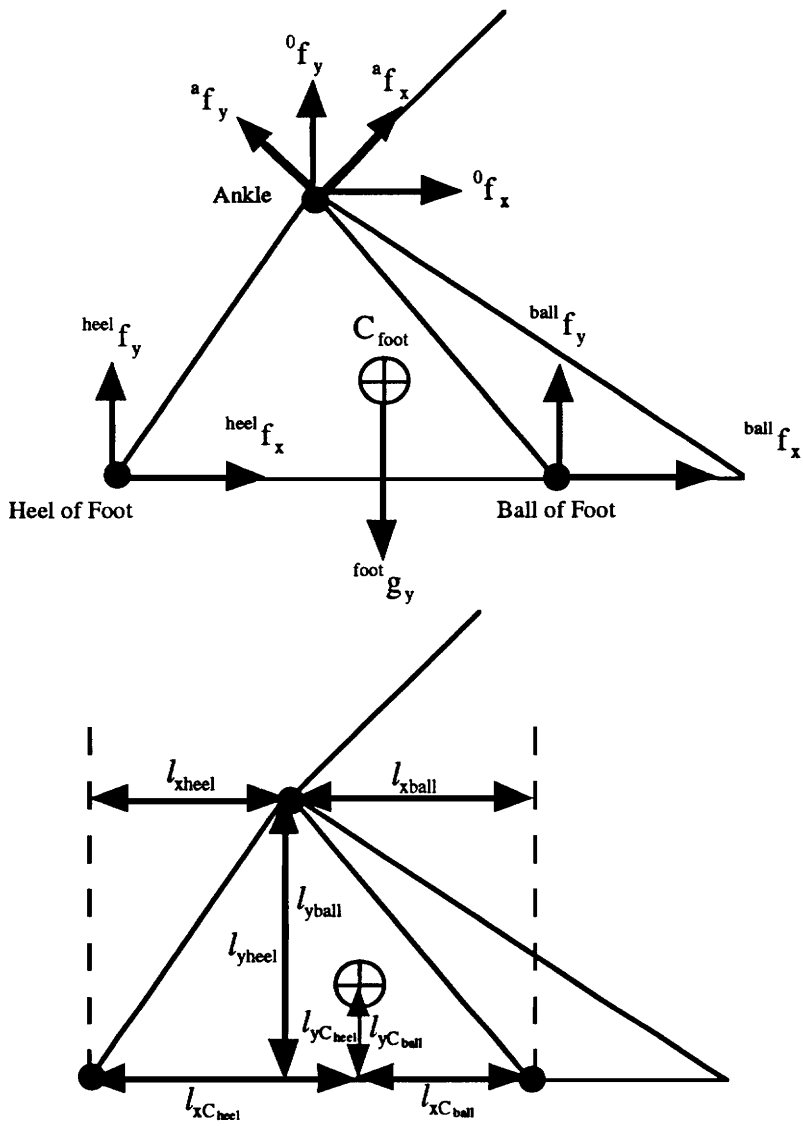


Figure B.2 Forces at the foot.

$$= \begin{bmatrix} 0 \\ 0 \\ \tau_0 + l_{x\text{heel}}(S_1^a f_x + C_1^a f_y) - l_{y\text{heel}}(C_1^a f_x - S_1^a f_y) + l_{xC\text{heel}}^{\text{foot}} g_y \end{bmatrix} \quad (\text{B.43})$$

where ${}^{\text{heel}}\mathbf{P}_0 = \begin{bmatrix} l_{x\text{heel}} \\ l_{y\text{heel}} \\ 0 \end{bmatrix}$, and (B.44)

$${}^{\text{heel}}\mathbf{P}_{C_{\text{foot}}} = \begin{bmatrix} l_{xC\text{heel}} \\ l_{yC\text{heel}} \\ 0 \end{bmatrix} \quad (\text{B.45})$$

so: $\tau_{\text{heel}} = ({}^{\text{heel}}\mathbf{n}_{\text{heel}})^t {}^{\text{heel}}\hat{\mathbf{z}}_{\text{heel}}$

$$= \tau_0 + l_{x\text{heel}}(S_1^a f_x + C_1^a f_y) - l_{y\text{heel}}(C_1^a f_x - S_1^a f_y) + l_{xC\text{heel}}^{\text{foot}} g_y \quad (\text{B.46})$$

As discussed above, if $\tau_{\text{heel}} \leq 0$, it is assumed that the body will not tip over backwards.

B.3.2 Calculations for the torque at the ball of the foot

Kerk (1992) found that the center of pressure for the heel is about 130% of the distance from the ankle joint center to the ball of the foot. The following calculations of the torque at the ball assume that there is no reaction force at the heel of the foot:

$${}^{\text{ball}}\mathbf{g}_{\text{ball}} = \begin{bmatrix} 0 \\ {}^{\text{foot}}g_y \\ 0 \end{bmatrix} \quad (\text{B.47})$$

$$\begin{aligned} {}^{\text{ball}}\mathbf{f}_{\text{ball}} = {}^{\text{ball}}\mathbf{g}_{\text{ball}} + \mathbf{R}_0^{\text{ball}0} \mathbf{f}_0 &= \begin{bmatrix} 0 \\ {}^{\text{foot}}g_y \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_1^a f_x - S_1^a f_y \\ S_1^a f_x + C_1^a f_y \\ 0 \end{bmatrix} \\ &= \begin{bmatrix} C_1^a f_x - S_1^a f_y \\ {}^{\text{foot}}g_y + S_1^a f_x + C_1^a f_y \\ 0 \end{bmatrix} \end{aligned} \quad (\text{B.48})$$

$$\begin{aligned}
{}^{\text{ball}}\mathbf{n}_{\text{ball}} &= \mathbf{R}_0^{\text{ball } 0} \mathbf{n}_0 + {}^{\text{ball}}\mathbf{P}_{C_{\text{foot}}} \times {}^{\text{ball}}\mathbf{g}_{\text{ball}} + {}^{\text{ball}}\mathbf{P}_0 \times \mathbf{R}_0^{\text{ball } 0} \mathbf{f}_0 \\
&= \begin{bmatrix} 0 \\ 0 \\ \tau_0 + l_{\text{xball}}(S_1^a f_x + C_1^a f_y) - l_{\text{yball}}(C_1^a f_x - S_1^a f_y) + l_{\text{x}C_{\text{ball}}}{}^{\text{foot}}\mathbf{g}_y \end{bmatrix} \quad (\text{B.49})
\end{aligned}$$

$${}^{\text{ball}}\mathbf{P}_0 = \begin{bmatrix} l_{\text{xball}} \\ l_{\text{yball}} \\ 0 \end{bmatrix} \quad (\text{B.50})$$

$${}^{\text{ball}}\mathbf{P}_{C_{\text{foot}}} = \begin{bmatrix} l_{\text{x}C_{\text{ball}}} \\ l_{\text{y}C_{\text{ball}}} \\ 0 \end{bmatrix} \quad (\text{B.51})$$

$$\begin{aligned}
\tau_{\text{ball}} &= ({}^{\text{ball}}\mathbf{n}_{\text{ball}})^t {}^{\text{ball}}\hat{\mathbf{z}}_{\text{ball}} \\
&= \tau_0 + l_{\text{xball}}(S_1^a f_x + C_1^a f_y) - l_{\text{yball}}(C_1^a f_x - S_1^a f_y) + l_{\text{x}C_{\text{ball}}}{}^{\text{foot}}\mathbf{g}_y \quad (\text{B.52})
\end{aligned}$$

If $\tau_{\text{ball}} \geq 0$, it is assumed that the body will not tip over forwards.

APPENDIX C: Procedure for Finding a Starting Simplex

This appendix describes how the algorithm chooses starting points. Since there will be many searches on many different functions each person has different characteristics (objective function), a procedure was developed to determine the optimal solution for any function.

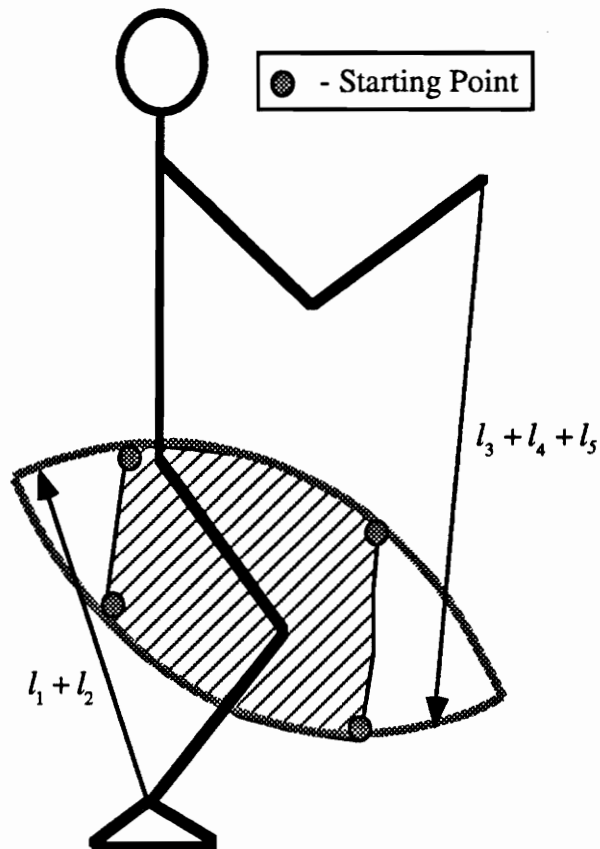


Figure C.1 Feasible solution set. Note in this figure that the hip position must be in the shaded area. (Outside of this area, the human will fall down or dislocate a joint)

The search starts by choosing points in the corners of the shaded area as shown in Figure C.1 (four hip positions) at four forearm orientations at $\phi = -1.5, -1.0, -0.5, 0.0, 0.5, 1.0,$ and 1.5 for a total of 28 points. The starting points are designated as the four points with the smallest value.

Because this is a nonconvex function it is possible to get a local answer which is not equal to the global answer. To make sure that the local minimum is the same as global minimum, the simplex that is searched is shifted in six directions:

$$((d,0,0), (-d,0,0), (0,d,0), (0,-d,0), (0,0,d), (0,0,-d))$$

where d is the distance that the simplex is shifted. Figure C.2 shows two of the six simplices.

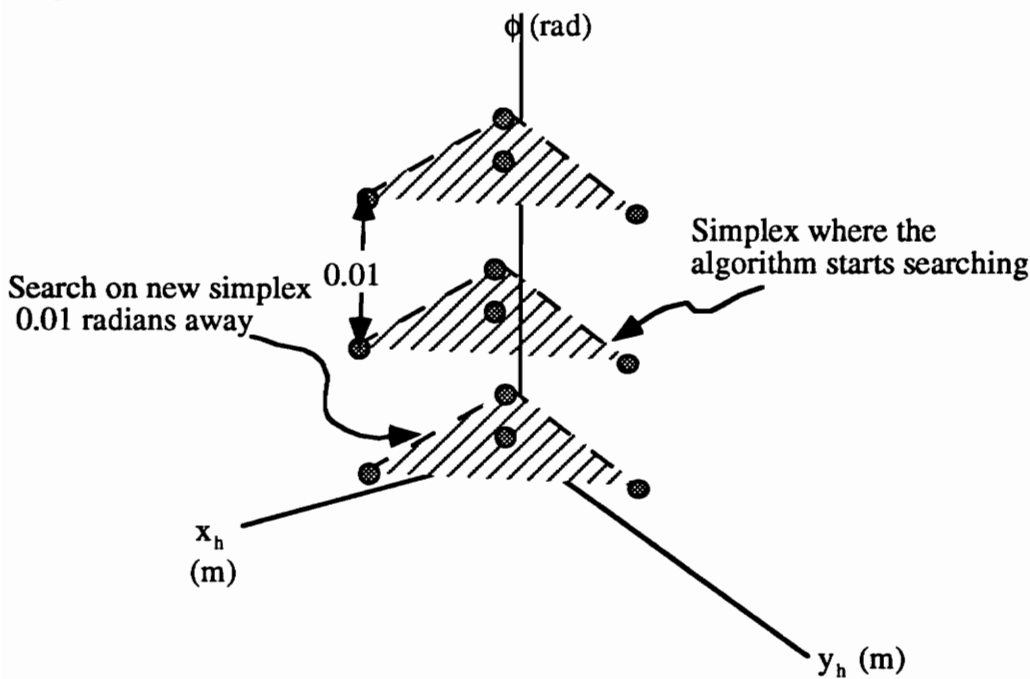


Figure C.2 Examples of two simplex shifts from original position.

At first, the search is at an increment of 0.1 ($d=0.1$). If after the seven searches (the original search and the six in the other directions) a new minimum has been found, the new minimum replaces the maximum point of the original four starting points. The search continues until the search cannot improve the minimum. At this point in the search, it is

highly likely that the current solution is less than 0.1 m from the optimal minimum. The search is continued with shifts of $d=0.05$ and then $d=0.01$ from the original simplex. At this point in the search, it is highly likely that the current solution is less than 0.01 m from the optimal minimum. The error of 0.01 m is defined as acceptable and the search stops.

One important factor in defining a starting simplex is to make sure the points are not too far apart and more importantly that they are not too close to each other. Determining this can be very difficult for each situation. After testing the seven simplexes, if a new minimum is found then this point replaces a point in the starting simplex and the above is performed again. The following rules are used to determine which points are replaced:

- 1) If one of the four points in the simplex is not feasible then they are replaced by points which are feasible.
- 2) Once the top three postures have been replaced, the next improved answer replaces the minimum. For the rest of the search if a new minimum is found, the previous minimum from the simplex is replaced.

APPENDIX D: Missing Point Calculation Mathematica 2.1 Program

(*Calc Miss Points*)

(*Defn of Atan2*)

```
Atan2[y_,x_]=If[x>0 &&y>=0, ArcTan[y/x],  
              If[x<0 &&y>=0, Pi-ArcTan[y/Abs[x]],  
              If[x<0 &&y<0, Pi+ArcTan[Abs[y]/Abs[x]],  
              If[x>0 &&y<0, 2 Pi-ArcTan[Abs[y]/x],  
              If[x==0 &&y<0, (Pi (3/2)),  
              If[x==0 &&y>0, Pi/2 ]]]];
```

(*Read Files*)

```
readFiles[subj_Integer]:=
```

```
Module[{  
},
```

(*DEFINE FILE NAMES*)

```
jointFile = StringJoin["PosObserved_",ToString[subj],".DAT"];
```

```
posFile = StringJoin["POST_",ToString[subj],".DAT"];
```

(*READ DATA*)

```
jointData= ToExpression[ReadList[jointFile,Word,RecordLists -> True]];
```

```
posData= ReadList[posFile,Word,RecordLists -> True];
```

```
posData= ToExpression[Table[posData[[i]],{i,2,224}]];
```

```
rad=Pi/180;
```

```
]
```

(*Calculate Missing Point Modules*)

(*x1=x2-l1 Cos[theta1]

y1=y2-l1 Sin[theta1]*)

```
missOne[theta1_List,link1_List,trial_Integer]:=
```

```
Module[{x1,y1},
```

```
x1=jointData[[trial,11]]-link1*Cos[theta1];
```

```
y1=jointData[[trial,12]]-link1*Sin[theta1];
```

```
Print["1-",N[x1],N[y1]];
```

```
]
```

(*x2=x1+l1 Cos[theta1]

y2=y1+l1 Sin[theta1]*)

```
missTwo[theta1_List,link1_List,trial_Integer]:=
```

```
Module[{x2,y2
```

```
},
```

```
x2=jointData[[trial,13]]+link1*Cos[theta1];
```

```
y2=jointData[[trial,14]]+link1*Sin[theta1];
```

```
Print["2-",N[x2],N[y2]];
```

```
]
```

(*x3=x2+l2 Cos[theta1+theta2]

y3=y2+l2 Sin[theta1+theta2]*)

```
missThree[alpha2_List,link2_List,trial_Integer]:=
```

```

Module[{x3,y3
    },

theta2=Pi-alpha2;
theta1=Atan2[(jointData[[trial,12]]-jointData[[trial,14]]),
             (jointData[[trial,11]]-jointData[[trial,13]])];
x3=jointData[[trial,11]]+link2*Cos[theta1+theta2];
y3=jointData[[trial,12]]+link2*Sin[theta1+theta2];
Print["3-",N[x3],N[y3]];
]
(*x4=x5+l4 Cos[phi+alpha5]
  y4=y5+l4 Sin[phi+alpha5]*)

missFour[alpha5_List,link4_List,trial_Integer]:=
Module[{x3,y3
    },

phi=Atan2[(jointData[[trial,4]]-jointData[[trial,6]]),
           (jointData[[trial,3]]-jointData[[trial,5]])];
x4=jointData[[trial,5]]+link4*Cos[phi+alpha5];
y4=jointData[[trial,6]]+link4*Sin[phi+alpha5];
Print["4-",N[x4],N[y4]];
]
missOneandTwo[theta1_List,alpha2_List,link1_List,link2_List,trial_Integer]:=
Module[{x1,y1,x2,y2
    },

theta2=Pi-alpha2;
x2=posData[[{(trial-1)*7+3,4}]-link2*Cos[theta1+theta2];
y2=posData[[{(trial-1)*7+3,6}]-link2*Sin[theta1+theta2];

x1=x2-link1*Cos[theta1];
y1=y2-link1*Sin[theta1];

Print["1-",N[x1],",",N[y1]];
Print["2-",N[x2],",",N[y2]];
]
missOneandThree[theta1_List,alpha2_List,link1_List,link2_List,trial_Integer]:=
Module[{x3,y3,x1,y1
    },

theta2=Pi-alpha2;
x1=jointData[[trial,11]]-link1*Cos[theta1];
y1=jointData[[trial,12]]-link1*Sin[theta1];

x3=jointData[[trial,11]]+link2*Cos[theta1+theta2];
y3=jointData[[trial,12]]+link2*Sin[theta1+theta2];

Print["1-",N[x1],",",N[y1]];
Print["3-",N[x3],",",N[y3]];
]

```

```

missTwoandThree[theta1_List,alpha2_List,link1_List,link2_List,trial_Integer]:=
Module[{x3,y3,x2,y2
},

theta2=Pi-alpha2;
x2=jointData[[trial,13]]+link1*Cos[theta1];
y2=jointData[[trial,14]]+link1*Sin[theta1];

x3=x2+link2*Cos[theta1+theta2];
y3=y2+link2*Sin[theta1+theta2];

Print["2-",N[x2],",",N[y2]];
Print["3-",N[x3],",",N[y3]];
]
missOneTwoThree[theta1_List,alpha2_List,alpha3_List,link1_List,link2_List,link3_List,trial_Integer]:=
Module[{x3,y3,x2,y2
},
theta3=alpha3+Pi;
theta2=Pi-alpha2;
x3=posData[[{(trial-1)*7+4,4}]-link3*Cos[theta1+theta2+theta3];
y3=posData[[{(trial-1)*7+4,6}]-link3*Sin[theta1+theta2+theta3];

x2=x3-link2*Cos[theta1+theta2];
y2=y3-link2*Sin[theta1+theta2];

x1=x2-link1*Cos[theta1];
y1=y2-link1*Sin[theta1];

Print["1-",N[x1],",",N[y1]];
Print["2-",N[x2],",",N[y2]];
Print["3-",N[x3],",",N[y3]];
]
(* Key
missOne[theta1,link1,trial]
missTwo[theta1,link1,trial]
missThree[alpha2,link2,trial]
missFour[alpha5,link4,trial]
missOneandTwo[theta1,alpha2,link1,link2,trial]
missOneandThree[theta1,alpha2,link1,link2,trial]
missTwoandThree[theta1,alpha2,link1,link2,trial]
missOneTwoThree[theta1,alpha2,alpha3,link1,link2,link3,trial]

*)
readFiles[1];
missTwo[{45*rad},{0.376},12]
2-{0.282872}{0.282872}

```


**APPENDIX E: Examples of Predicted Postures compared with
Observed Postures**

TABLE E.1 Studentized t test. * denotes p values below 0.0001.

Subject	Criterion	Hand Position	p	Subject	Criterion	Hand Position	p
1	TT	(0.3,1.2)	0.0001*	5	TT	(0.3,1.2)	0.0001*
	TT	(0.3,0.5)	0.0001*		TT	(0.3,0.5)	0.0006
	TT	(Max,1.2)	0.0001*		TT	(Max,1.2)	0.0001*
	TT	(Max,0.5)	0.0001*		TT	(Max,0.5)	0.0001*
	PS	(0.3,1.2)	0.0001*		PS	(0.3,1.2)	0.0001*
	PS	(0.3,0.5)	0.0001*		PS	(0.3,0.5)	0.0001*
	PS	(Max,1.2)	0.0001*		PS	(Max,1.2)	0.0001*
	PS	(Max,0.5)	0.0001*		PS	(Max,0.5)	0.0001*
	B	(0.3,1.2)	0.0001*		B	(0.3,1.2)	0.0001*
	B	(0.3,0.5)	0.0001*		B	(0.3,0.5)	0.0001
	B	(Max,1.2)	0.0001*		B	(Max,1.2)	0.0002
2	TT	(0.3,1.2)	0.0001*	6	TT	(0.3,1.2)	0.0001*
	TT	(0.3,0.5)	0.0001*		TT	(0.3,0.5)	0.0001*
	TT	(Max,1.2)	0.0001*		TT	(Max,1.2)	0.0001*
	TT	(Max,0.5)	0.0001*		TT	(Max,0.5)	0.0001*
	PS	(0.3,1.2)	0.0002		PS	(0.3,1.2)	0.0001*
	PS	(0.3,0.5)	0.0001*		PS	(0.3,0.5)	0.0001*
	PS	(Max,1.2)	0.0001*		PS	(Max,1.2)	0.0001*
	PS	(Max,0.5)	0.0001*		PS	(Max,0.5)	0.0001*
	B	(0.3,1.2)	0.0003		B	(0.3,1.2)	0.0004
	B	(0.3,0.5)	0.0001*		B	(0.3,0.5)	0.0001*
	B	(Max,1.2)	0.0001*		B	(Max,1.2)	0.0001*
3	TT	(0.3,1.2)	0.0001*	7	TT	(0.3,1.2)	0.0001
	TT	(0.3,0.5)	0.0001*		TT	(0.3,0.5)	0.0001*
	TT	(Max,1.2)	0.0001*		TT	(Max,1.2)	0.0001*
	TT	(Max,0.5)	0.0001*		TT	(Max,0.5)	0.0001*
	PS	(0.3,1.2)	0.0004		PS	(0.3,1.2)	0.0001*
	PS	(0.3,0.5)	0.0001*		PS	(0.3,0.5)	0.0001*
	PS	(Max,1.2)	0.0001*		PS	(Max,1.2)	0.0001*
	PS	(Max,0.5)	0.0001*		PS	(Max,0.5)	0.0001*
	B	(0.3,1.2)	0.0001*		B	(0.3,1.2)	0.0001
	B	(0.3,0.5)	0.0001*		B	(0.3,0.5)	0.0001*
	B	(Max,1.2)	0.0001*		B	(Max,1.2)	0.0001*
4	TT	(0.3,1.2)	0.0001*	8	TT	(0.3,1.2)	0.0001*
	TT	(0.3,0.5)	0.0001*		TT	(0.3,0.5)	0.0001*
	TT	(Max,1.2)	0.0001*		TT	(Max,1.2)	0.0001*
	TT	(Max,0.5)	0.0001*		TT	(Max,0.5)	0.0001*
	PS	(0.3,1.2)	0.0001*		PS	(0.3,1.2)	0.0001*
	PS	(0.3,0.5)	0.0001*		PS	(0.3,0.5)	0.0001*
	PS	(Max,1.2)	0.0001*		PS	(Max,1.2)	0.0001*
	PS	(Max,0.5)	0.0001*		PS	(Max,0.5)	0.0001*
	B	(0.3,1.2)	0.0001*		B	(0.3,1.2)	0.0001*
	B	(0.3,0.5)	0.0001*		B	(0.3,0.5)	0.0001*
	B	(Max,1.2)	0.0001*		B	(Max,1.2)	0.0001*
B	(Max,0.5)	0.0001*	B	(Max,0.5)	0.0001*		

TABLE E.1 Continued.

Subject	Criterion	Hand Position	p	Subject	Criterion	Hand Position	p
9	TT	(0.3,1.2)	0.0001*	13	TT	(0.3,1.2)	0.0001*
	TT	(0.3,0.5)	0.0001*		TT	(0.3,0.5)	0.0001*
	TT	(Max,1.2)	0.0001*		TT	(Max,1.2)	0.0001*
	TT	(Max,0.5)	0.0001*		TT	(Max,0.5)	0.0001*
	PS	(0.3,1.2)	0.0001*		PS	(0.3,1.2)	0.0164
	PS	(0.3,0.5)	0.0001*		PS	(0.3,0.5)	0.0001*
	PS	(Max,1.2)	0.0001*		PS	(Max,1.2)	0.0001*
	PS	(Max,0.5)	0.0001*		PS	(Max,0.5)	0.0001*
	B	(0.3,1.2)	0.0001*		B	(0.3,1.2)	0.0001*
	B	(0.3,0.5)	0.0001*		B	(0.3,0.5)	0.0001*
	B	(Max,1.2)	0.0001*		B	(Max,1.2)	0.0001*
10	TT	(0.3,1.2)	0.0001*	14	TT	(0.3,1.2)	0.0001*
	TT	(0.3,0.5)	0.0001*		TT	(0.3,0.5)	0.0001*
	TT	(Max,1.2)	0.0001*		TT	(Max,1.2)	0.0001*
	TT	(Max,0.5)	0.0001*		TT	(Max,0.5)	0.0001*
	PS	(0.3,1.2)	0.0001*		PS	(0.3,1.2)	0.0001*
	PS	(0.3,0.5)	0.0001*		PS	(0.3,0.5)	0.0001*
	PS	(Max,1.2)	0.0001*		PS	(Max,1.2)	0.0001*
	PS	(Max,0.5)	0.0001*		PS	(Max,0.5)	0.0001*
	B	(0.3,1.2)	0.0001*		B	(0.3,1.2)	0.0001*
	B	(0.3,0.5)	0.0001*		B	(0.3,0.5)	0.0001*
	B	(Max,1.2)	0.0001*		B	(Max,1.2)	0.0001*
11	TT	(0.3,1.2)	0.0001*	15	TT	(0.3,1.2)	0.0001*
	TT	(0.3,0.5)	0.0001*		TT	(0.3,0.5)	0.0001*
	TT	(Max,1.2)	0.0001*		TT	(Max,1.2)	0.0001*
	TT	(Max,0.5)	0.0001*		TT	(Max,0.5)	0.0001*
	PS	(0.3,1.2)	0.0322		PS	(0.3,1.2)	0.0203
	PS	(0.3,0.5)	0.0001*		PS	(0.3,0.5)	0.0001*
	PS	(Max,1.2)	0.0001*		PS	(Max,1.2)	0.0001*
	PS	(Max,0.5)	0.0001*		PS	(Max,0.5)	0.0001*
	B	(0.3,1.2)	0.0001*		B	(0.3,1.2)	0.0001*
	B	(0.3,0.5)	0.0001*		B	(0.3,0.5)	0.0001*
	B	(Max,1.2)	0.0001*		B	(Max,1.2)	0.0001*
12	TT	(0.3,1.2)	0.0001*	16	TT	(0.3,1.2)	0.0001*
	TT	(0.3,0.5)	0.0001*		TT	(0.3,0.5)	0.0001*
	TT	(Max,1.2)	0.0002		TT	(Max,1.2)	0.0001*
	TT	(Max,0.5)	0.0001*		TT	(Max,0.5)	0.0001*
	PS	(0.3,1.2)	0.0001*		PS	(0.3,1.2)	0.0001*
	PS	(0.3,0.5)	0.0001*		PS	(0.3,0.5)	0.0001*
	PS	(Max,1.2)	0.0001*		PS	(Max,1.2)	0.0001*
	PS	(Max,0.5)	0.0001*		PS	(Max,0.5)	0.0001*
	B	(0.3,1.2)	0.0004		B	(0.3,1.2)	0.0001*
	B	(0.3,0.5)	0.0001*		B	(0.3,0.5)	0.0001*
	B	(Max,1.2)	0.0001*		B	(Max,1.2)	0.0001*
B	(Max,0.5)	0.0001*	B	(Max,0.5)	0.0001*		

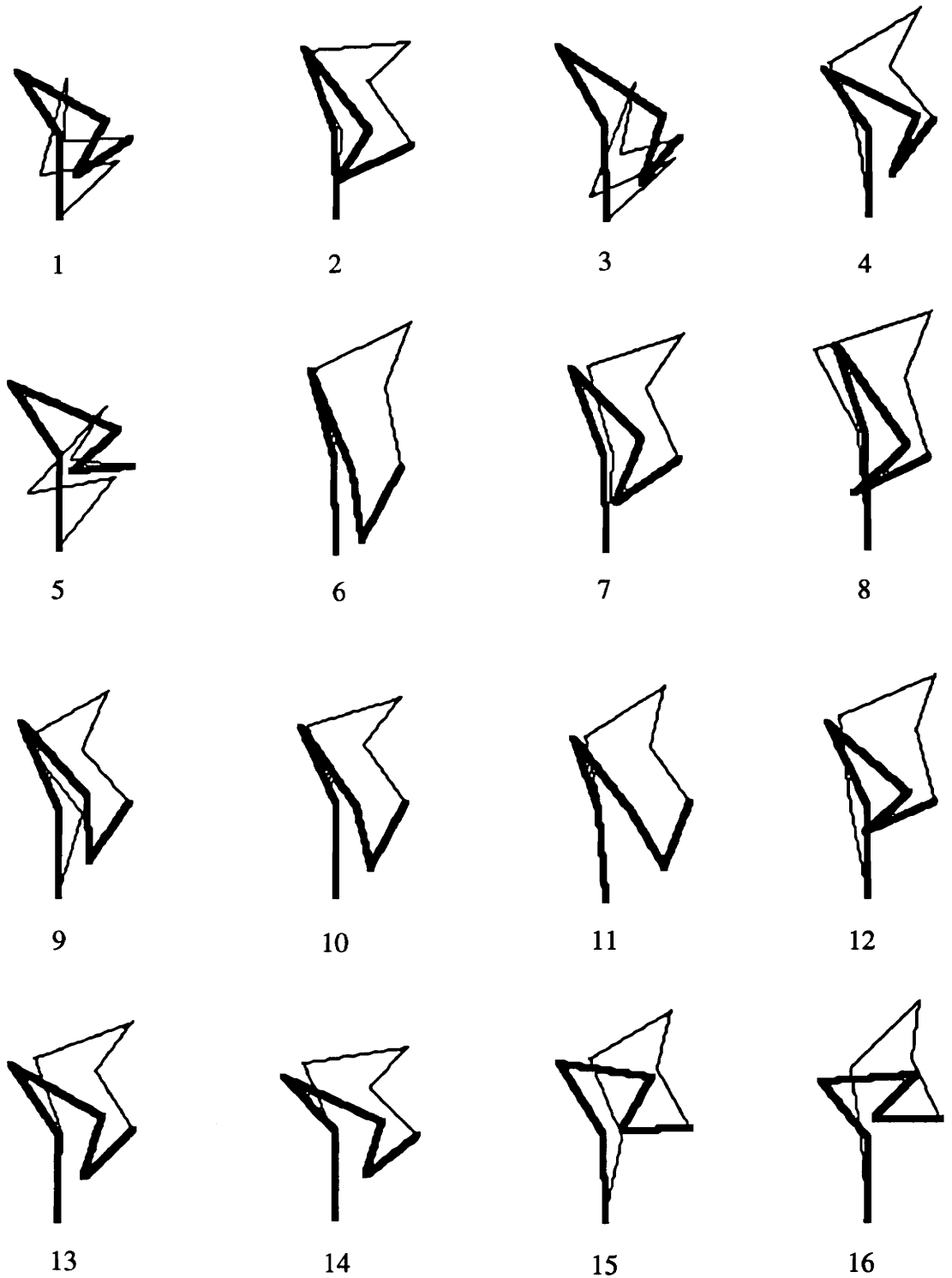


Figure E.1 Total Torque (0.3,0.5). Observed postures (thin lines) compared with predicted postures (thick lines).

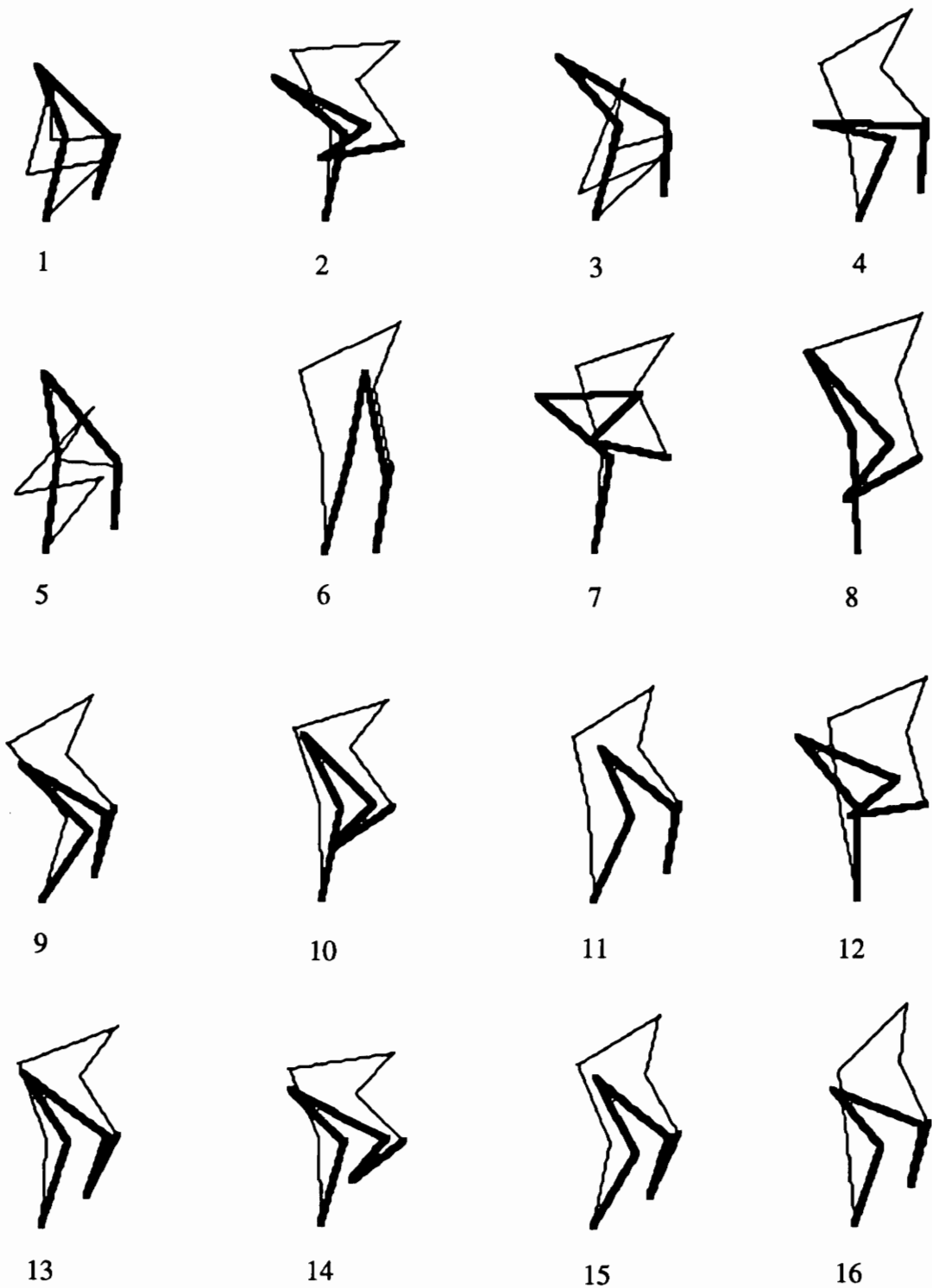


Figure E.2 Percent Torque (0.3,0.5). Observed postures (thin lines) compared with predicted postures (thick lines).

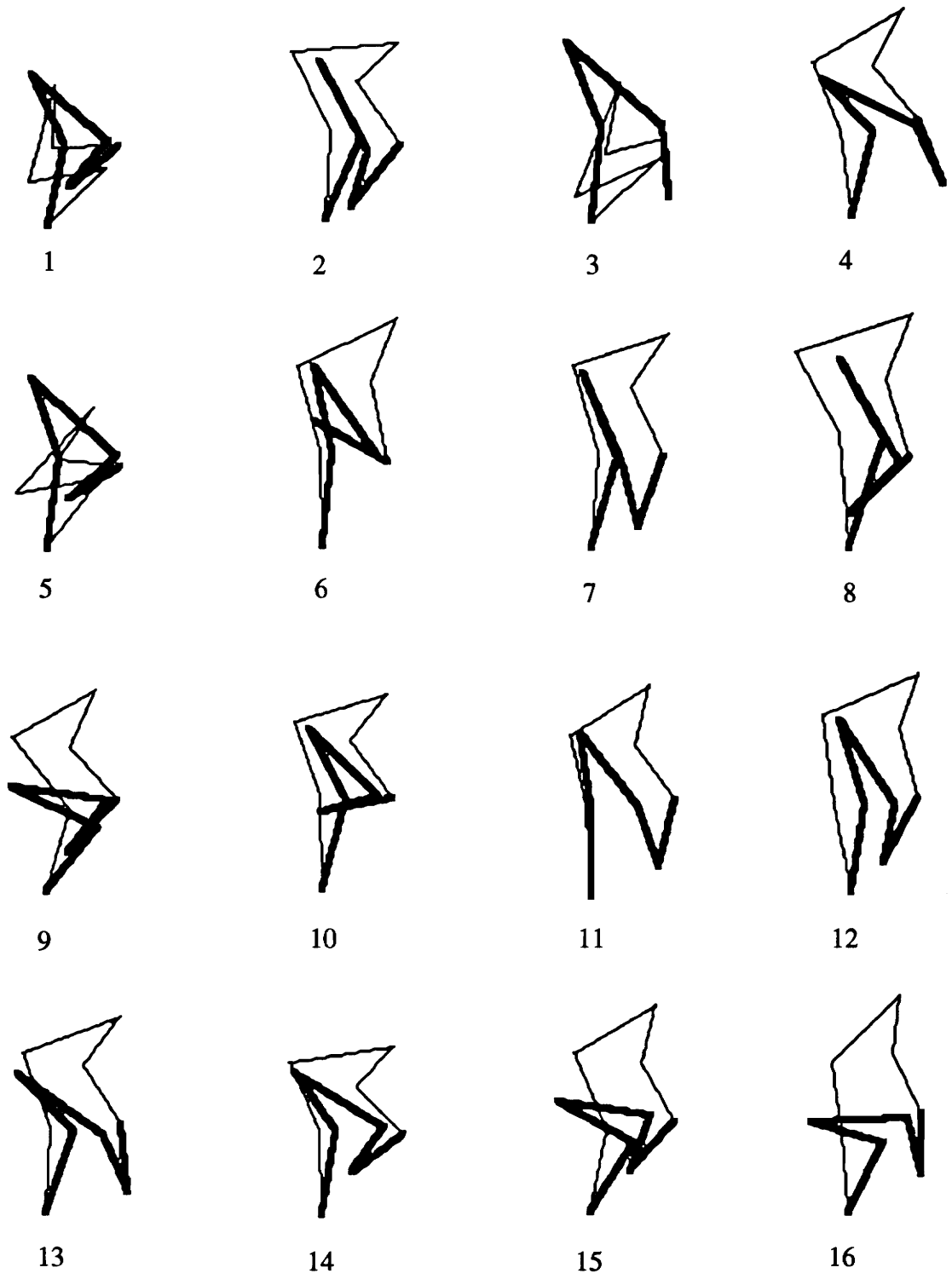
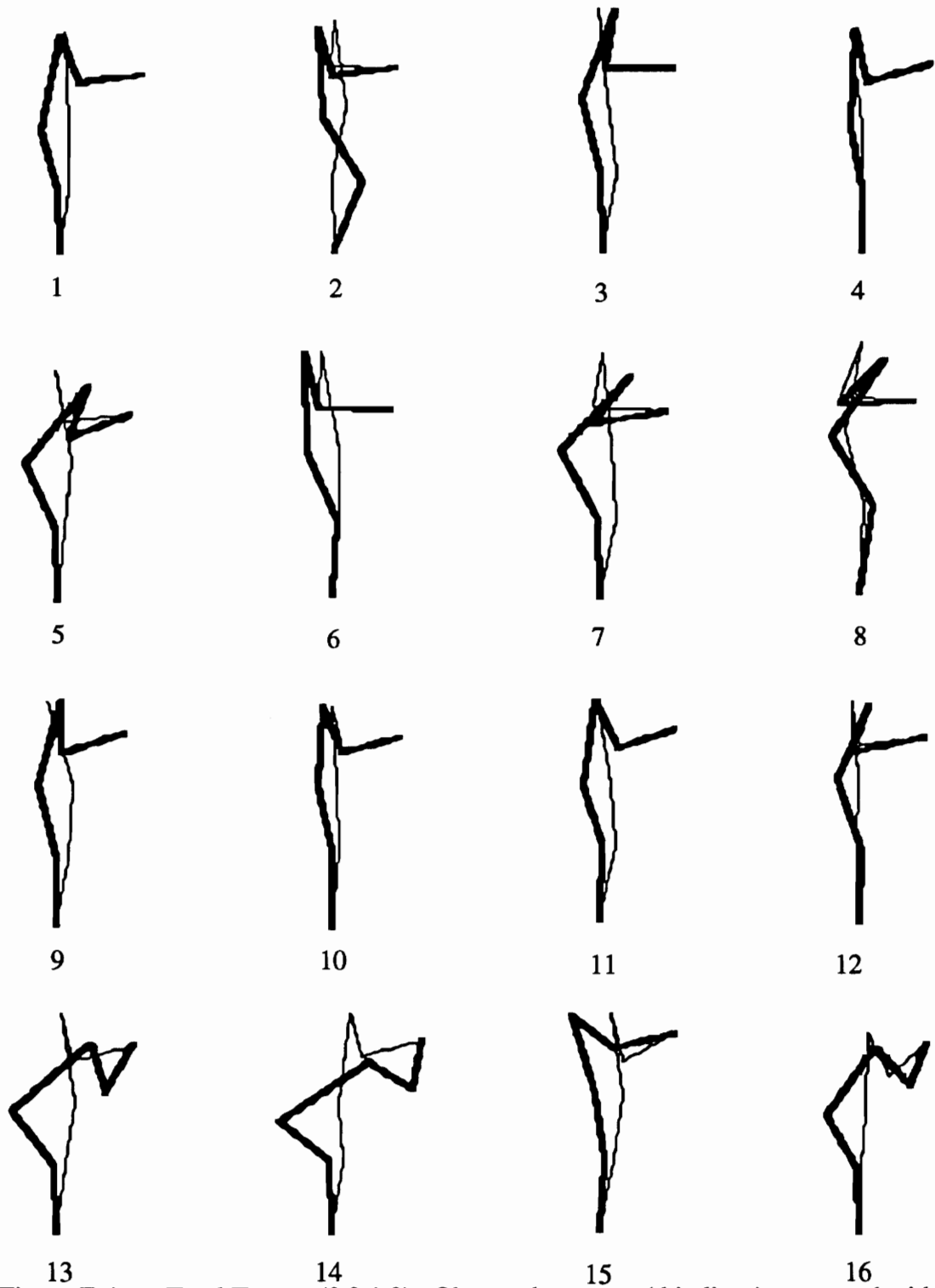


Figure E.3 Balance (0.3,0.5). Observed postures (thin lines) compared with predicted postures (thick lines).



13 14 15 16
 Figure E.4 Total Torque (0.3,1.2). Observed postures (thin lines) compared with predicted postures (thick lines).

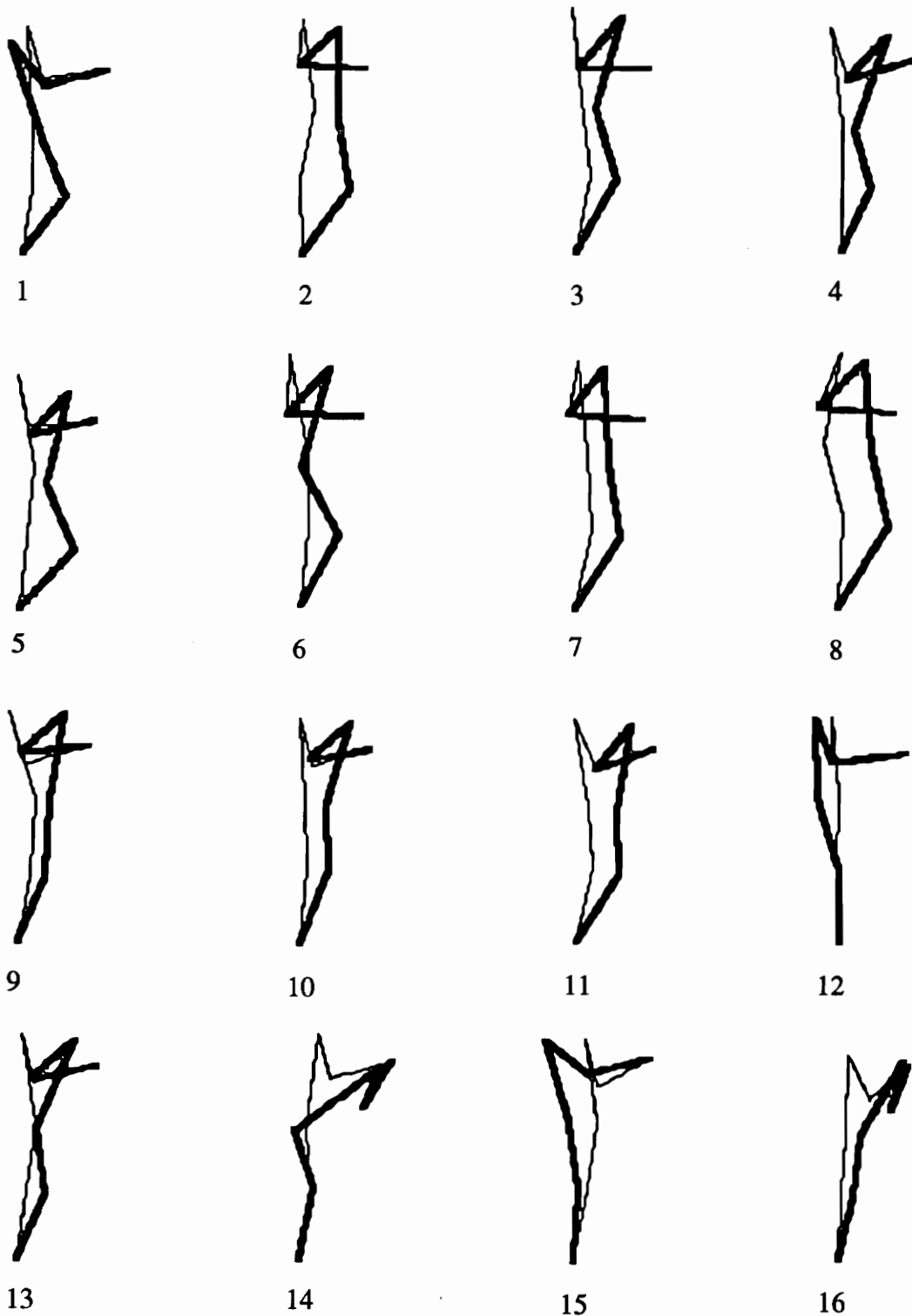
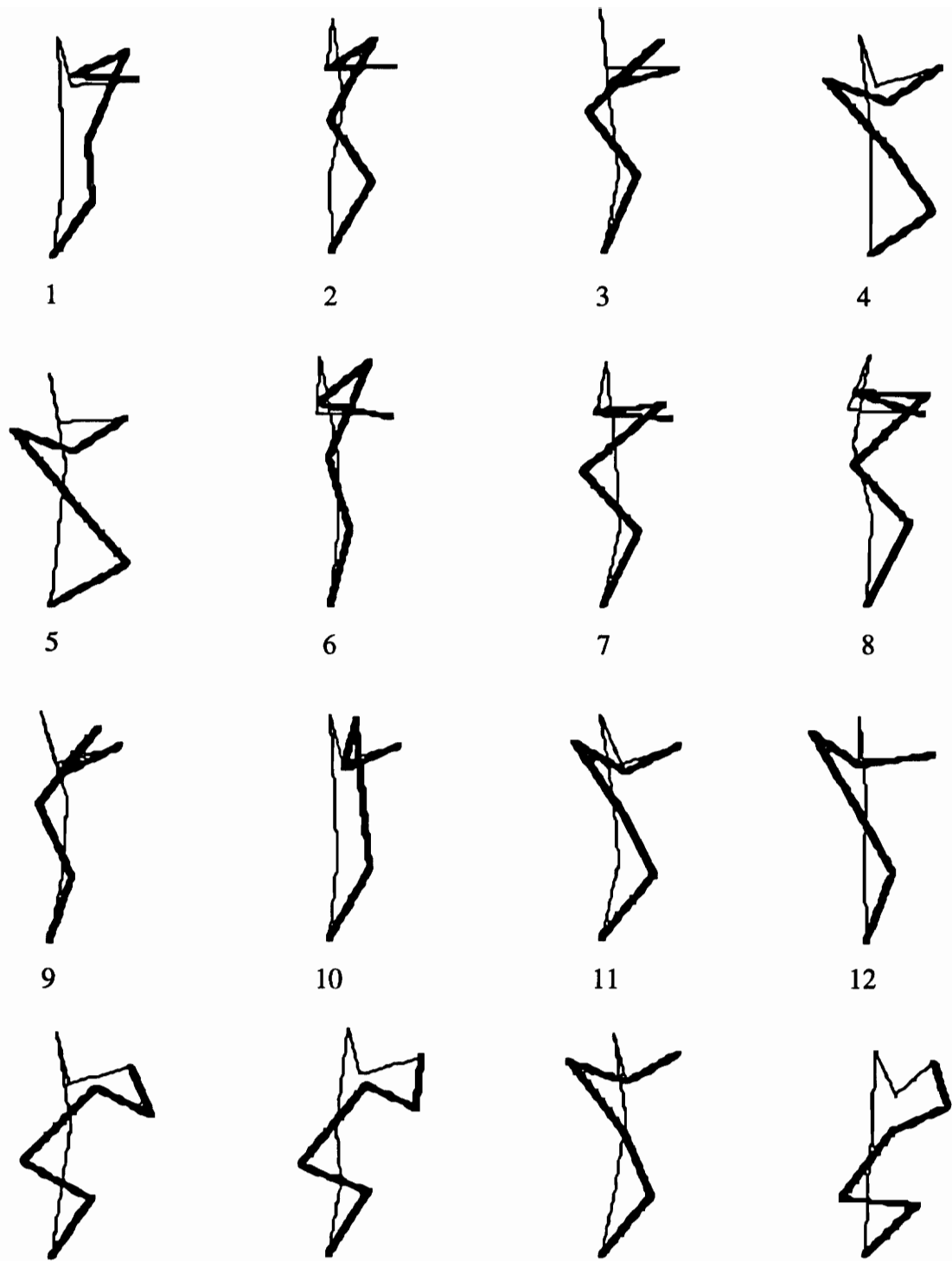


Figure E.5 Percent Torque (0.3,1.2). Observed postures (thin lines) compared with predicted postures (thick lines).



13
 Figure E.6 Balance (0.3,1.2). Observed postures (thin lines) compared with
 14
 15
 16
 predicted postures (thick lines).

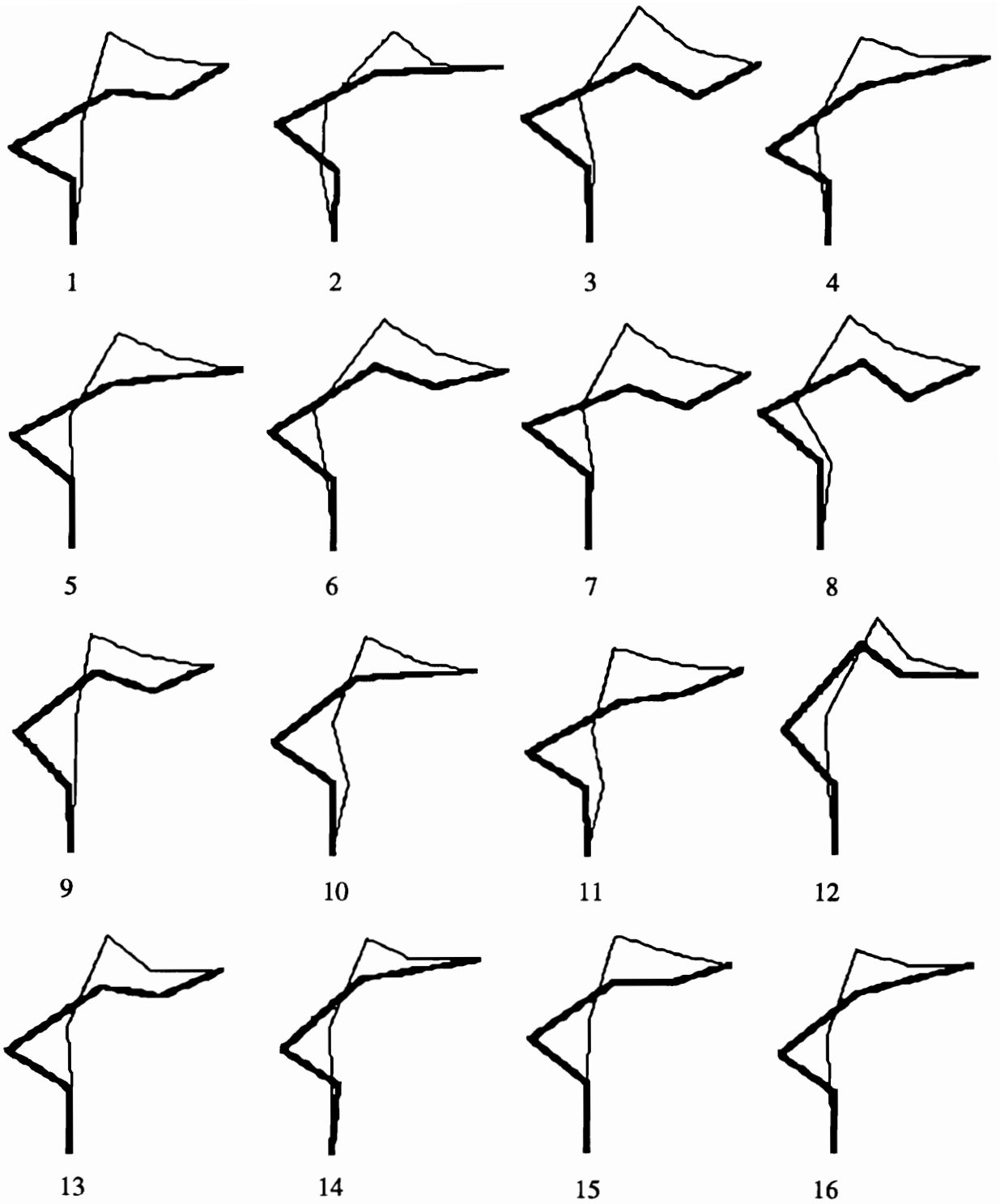


Figure E.7 Total Torque (Max,1.2). Observed postures (thin lines) compared with predicted postures (thick lines).

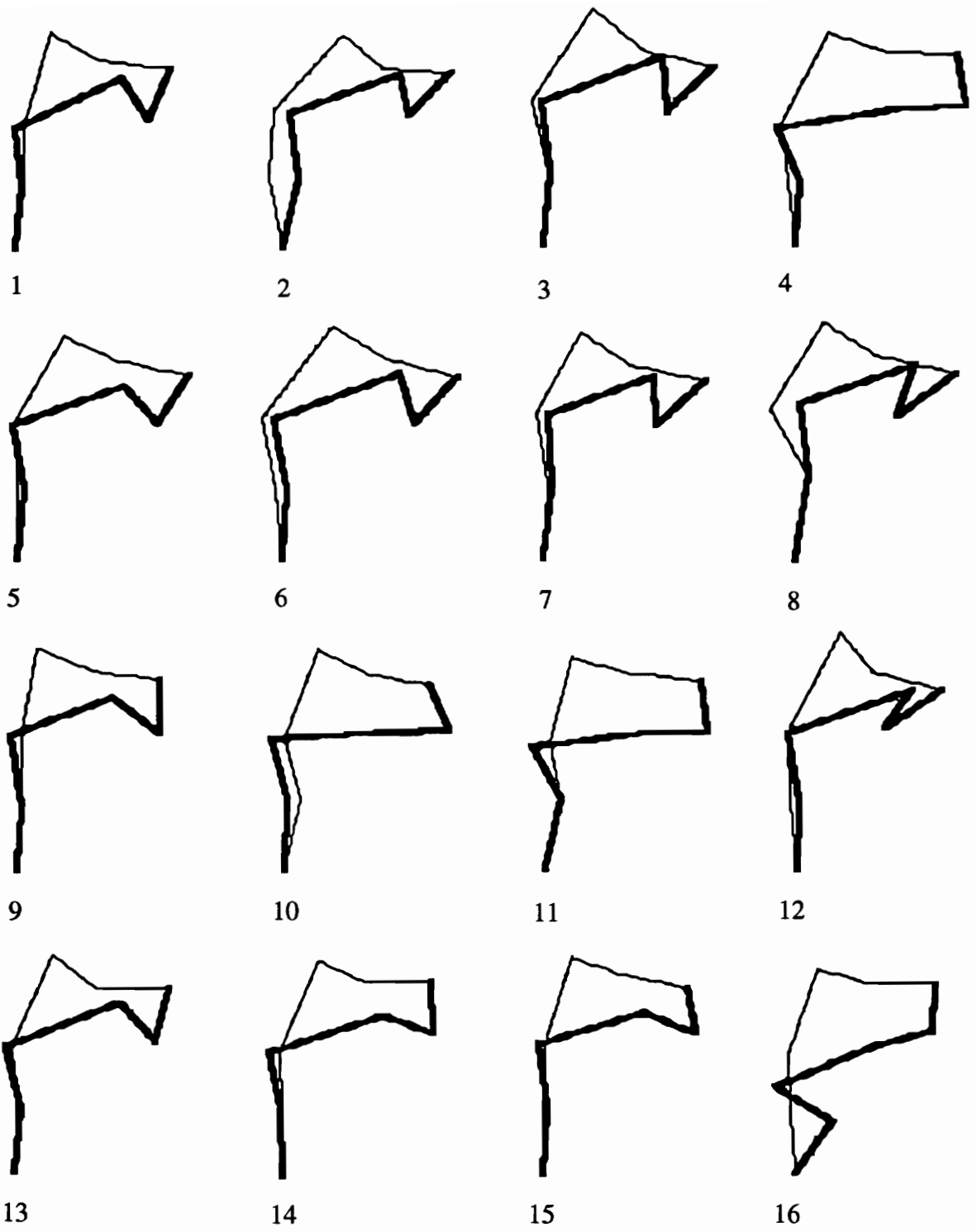


Figure E.8 Percent Torque (Max,1.2). Observed postures (thin lines) compared with predicted postures (thick lines).

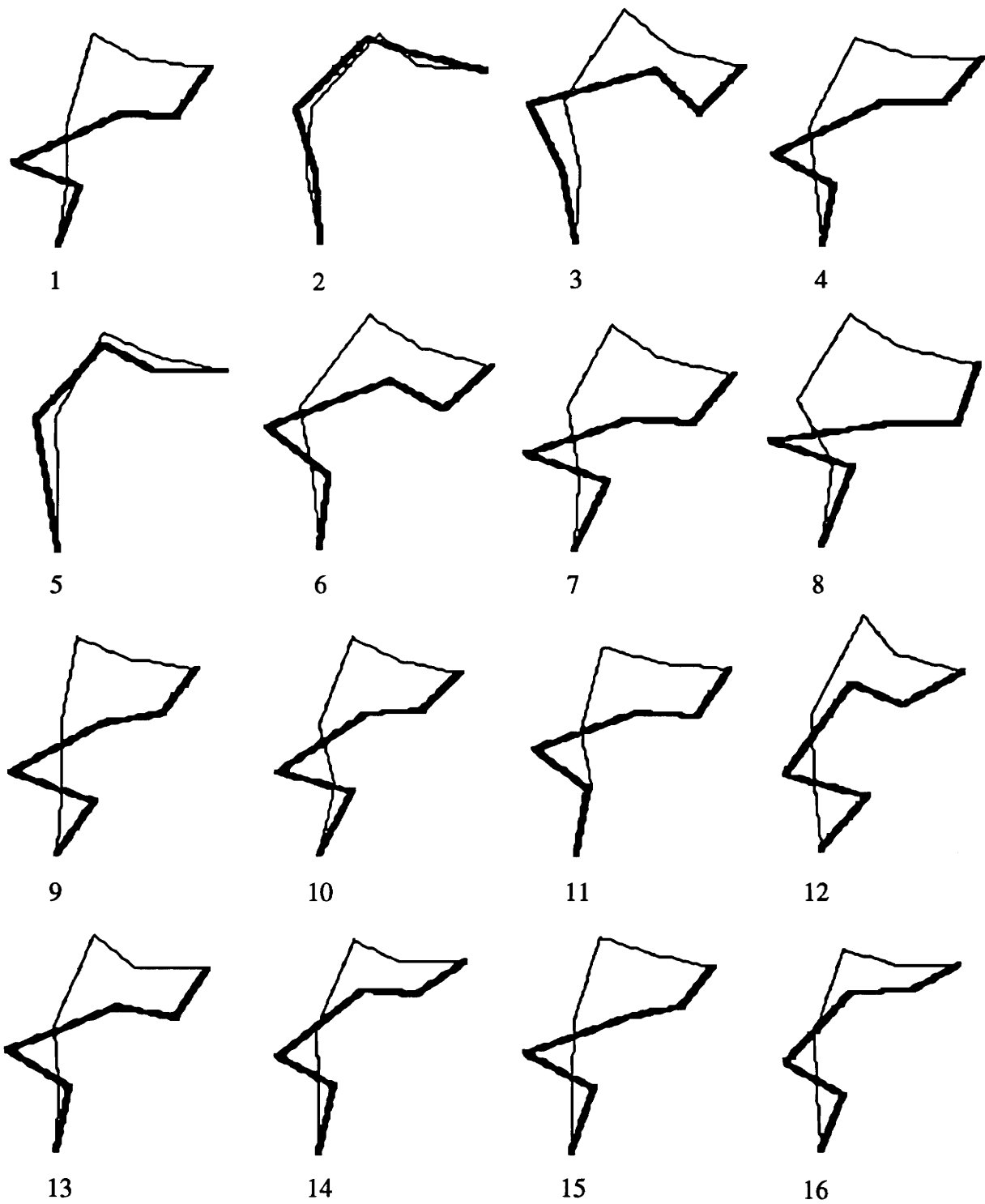


Figure E.9 Balance (Max,1.2). Observed postures (thin lines) compared with predicted postures (thick lines).

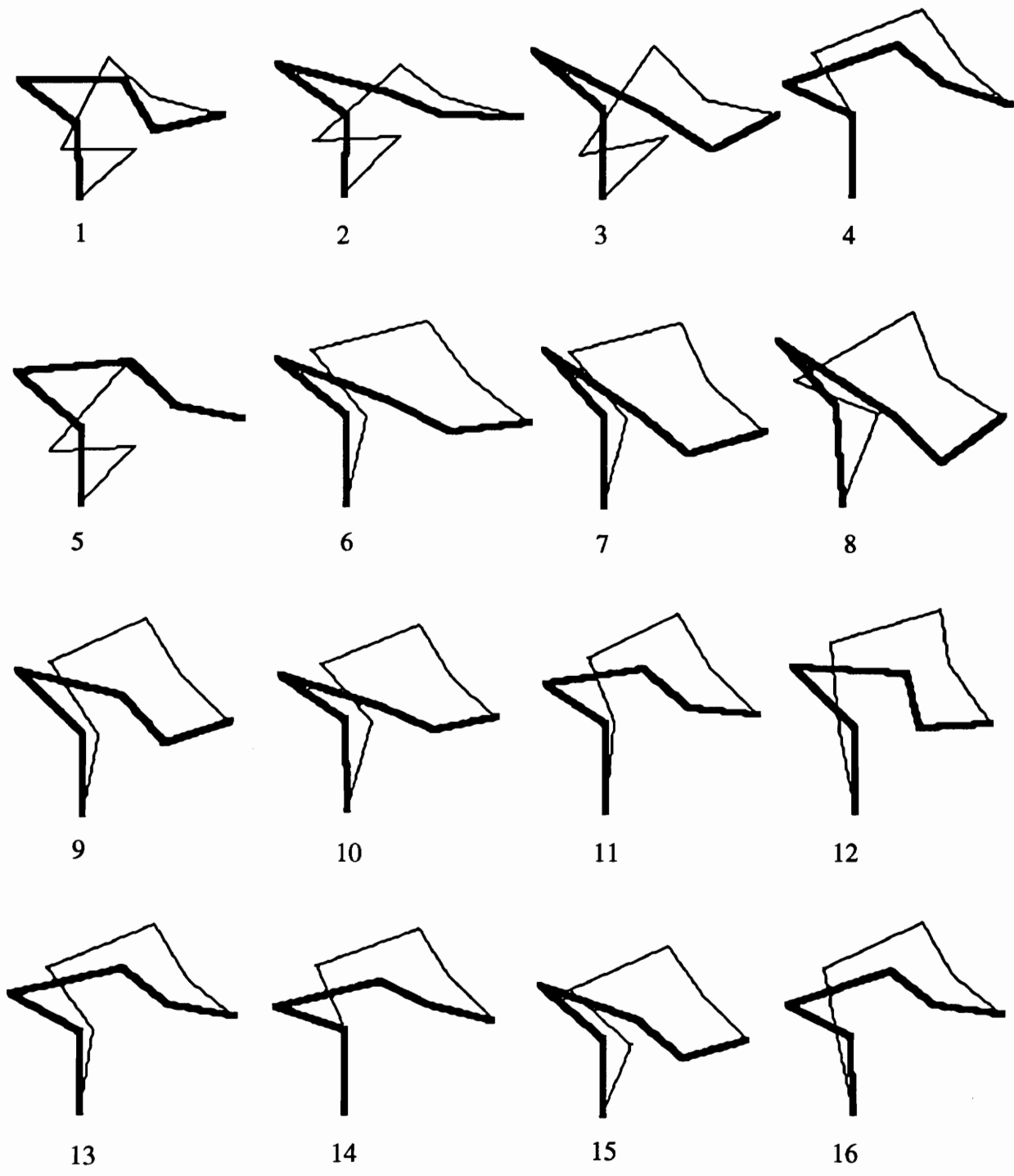


Figure E.10 Total Torque (Max,0.5). Observed postures (thin lines) compared with predicted postures (thick lines).

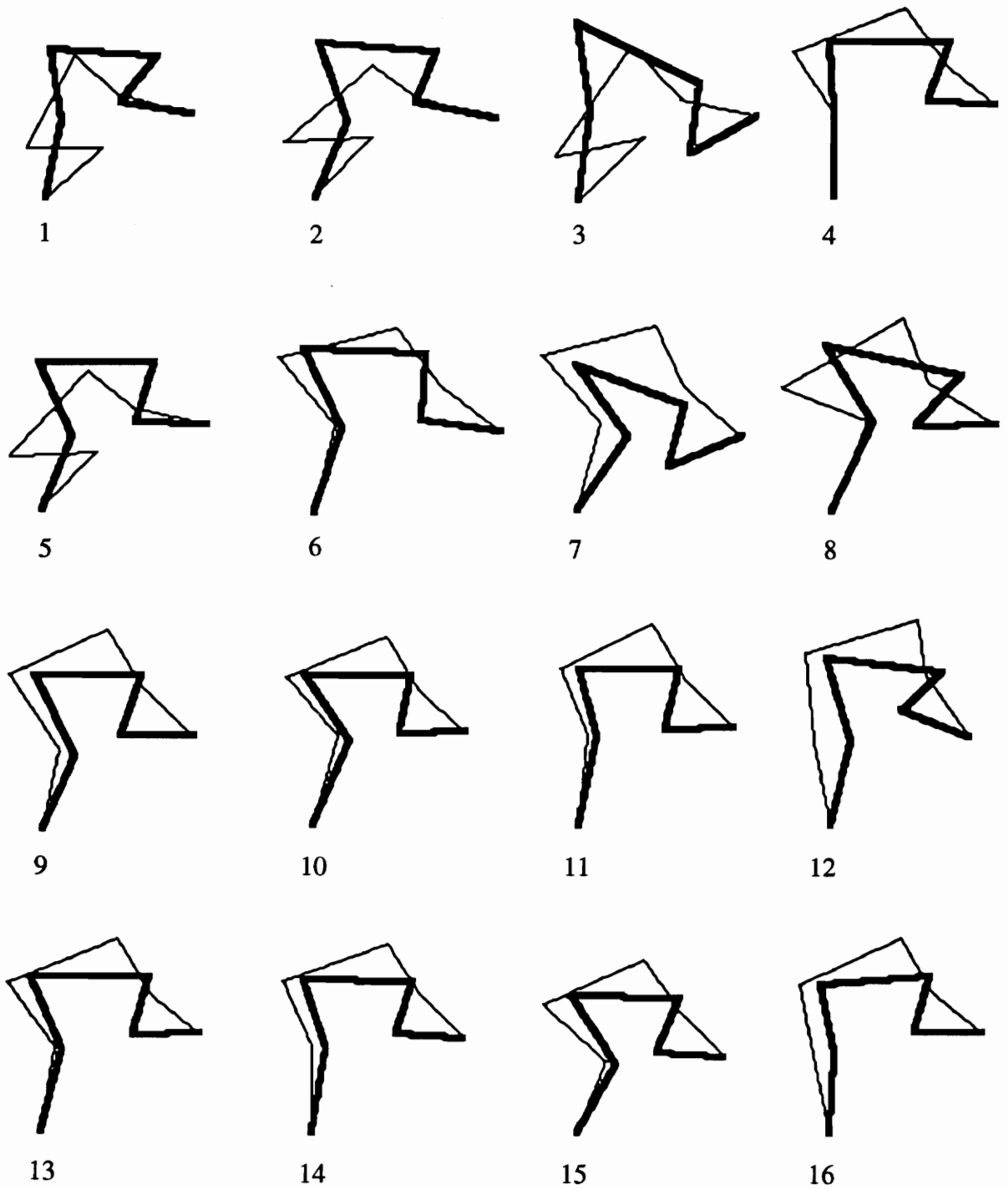


Figure E.11 Percent Torque (Max,0.5). Observed postures (thin lines) compared with predicted postures (thick lines).

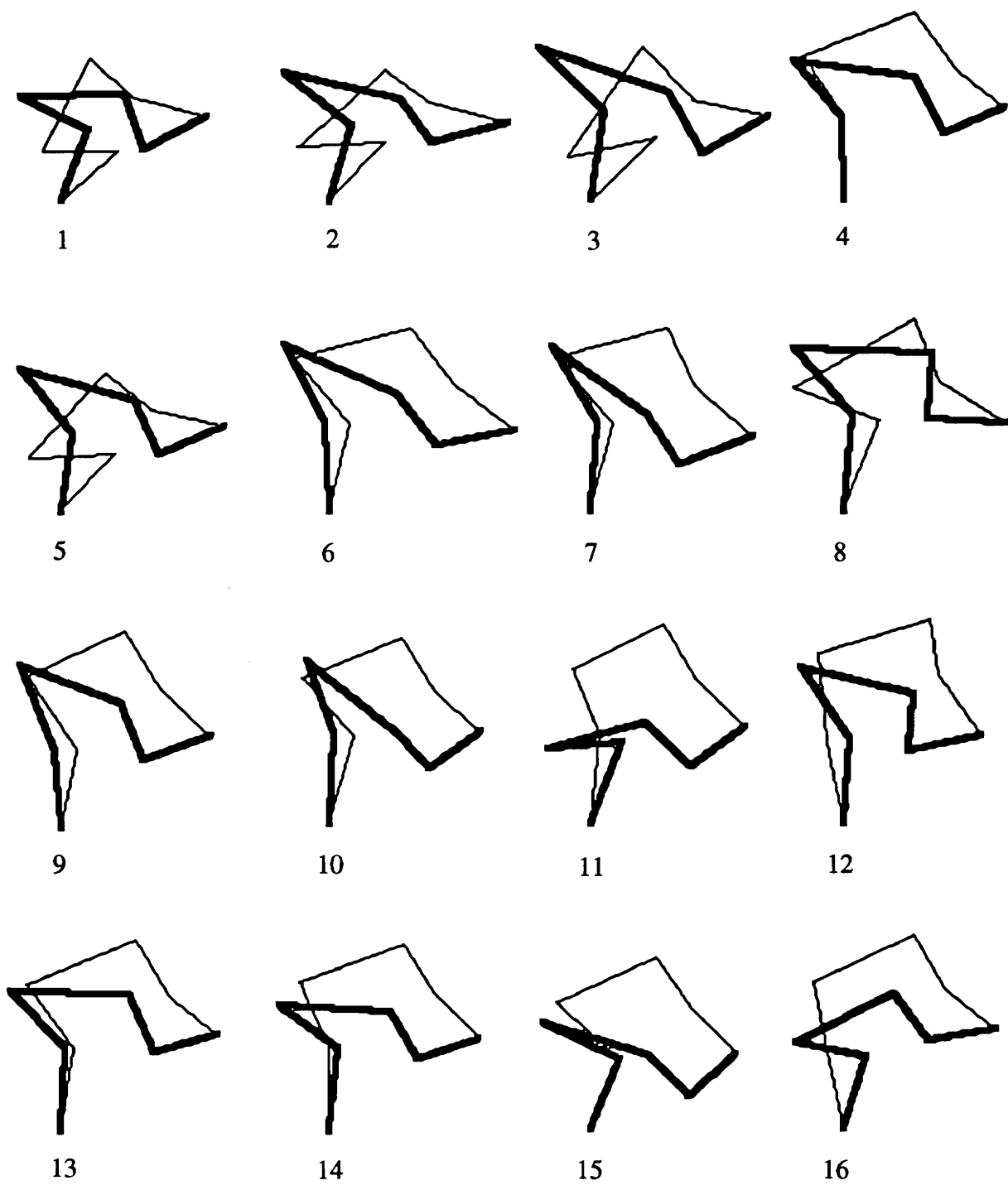


Figure E.12 Balance (Max,0.5). Observed postures (thin lines) compared with predicted postures (thick lines).

**APPENDIX F: Informed Consent Form and Physical Fitness Questionnaire
for Experiment.**

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants of Investigative Projects

I. THE PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study investigating lifting techniques. Further detail about the project will be explained at the end of the experiment.

II. PROCEDURES

You will be asked to hold a 5 kg weight at a determined hand position. The time and conditions required for you to participate in this project is approximately 3 hours consisting of 32 trials. You will be asked to wear both black sweat pants and a sweat shirt which will be provided. Infrared emitting diodes (IREDS) will then be attached to your arms and legs. Then you will be asked to complete approximately 32 lifting tasks. Two minutes of rest will be allowed between trials.

The possible risks or discomfort to you as a participant may be some muscle fatigue and soreness after the completion of the experiment; however, this fatigue should be short-lived and pose no further complication or discomfort to you. There is no risk of electric shock due to the IREDS or any other part of the testing apparatus.

Safeguards that will be used to minimize your risk or discomfort are short lifts with two minutes rest between each trial.

III. BENEFITS OF THIS PROJECT

Your participation in the project will provide the following information that may be helpful. This experiment will address the techniques used for lifting tasks. This type of information can help improve the design of workstations to reduce injury.

No guarantee of benefits has been made to encourage you to participate.

You may receive a synopsis or summary of this research when it is completed. Please leave (or bring back) a self-addressed envelope.

IV. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. At no time will the researchers release the results of the study to anyone other than individuals working on the project without your written consent. The information you provide will have your name removed and only a subject number will identify you during analyses and any written reports of the research.

This experiment will be video taped. These tapes will only be reviewed by Marc Dysart.

V. COMPENSATION

Monetary

For participation in the project you will receive \$5.00 for each hour completed, for a total of \$15.

VI. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time without penalty. If you chose to withdraw, you will be compensated for the portion of the time of the study in which you participated.

There may be circumstances under which the investigator may determine that you should not continue as a subject of this project. These might include fatigue or discomfort. If this occurs, you will be compensated for the portion of the project completed.

VII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for projects involving human subjects at Virginia Polytechnic Institute and State University, by the Department of Industrial and Systems Engineering.

VIII. SUBJECT'S RESPONSIBILITIES

I know of no reason I cannot participate in this study. I have the responsibility to complete the physical fitness questionnaire.

Signature

IX. SUBJECT'S PERMISSION (Tear off at dashed line and give to subject)

I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Should I have any questions about this research or its conduct, I will contact:

Marc J. Dysart, Investigator	231-6053
Dr. Jeffrey Woldstad, Faculty Advisor	231-4927
Chair, Institutional Review Board, Research Division	231-9359

SUBJECT PHYSICAL FITNESS QUESTIONNAIRE

Subject's Name: _____ SSN: _____

Address: _____

Telephone Number: (____) _____

Sex: _____ Date of Birth: _____

Which best describes your present physical condition (circle one):

Poor Fair Good Excellent

Please describe any physical activities you presently participate in on a regular basis:

Sports (name):

_____ : _____ times per week

_____ : _____ times per week

Other (name):

_____ : _____ times per week

_____ : _____ times per week

Have you ever had a hernia (Yes or No)? _____

Have you ever had a back injury (Yes or No)? _____

Have you had any noticeable back pain during the last year (Yes or No)? _____

Have you ever had any joint dislocations, broken bones, or other physical injuries in the last year (Yes or No)? _____

Have you ever had any other serious musculoskeletal injury (Yes or No)? _____

Are you presently taking any medication or drugs (Yes or No)? _____

Do you presently have any physical impairment or injury worth noting (Yes or No)? _____

Can you think of any injury, or illness you might have which could be aggravated by physical activity or participation in this experiment (Yes or No)? _____

If you answered yes to any of the above or have any other remarks you feel are pertinent to your participation, please elaborate in the space below or on the back of this page:

Signature and Date

VITA

Marc James Dysart was born on August 31, 1969 in Paris, France. He received his B.S. in Industrial and Systems Engineering at Virginia Polytechnic Institute and State University in May of 1992. He went on to pursue his graduate work in the Human Factors Engineering Laboratory at Virginia Polytechnic Institute and State University, Blacksburg, Virginia. He is a member of Human Factors and Ergonomics Society, RESNA, and Toastmasters International. He will be working for the Peace Corps in Guinea teaching Mathematics at the secondary level.

A handwritten signature in cursive script that reads "Marc James Dysart". The signature is written in black ink and is positioned above a horizontal line.

Marc James Dysart