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# **Behavior-Based Model of Clavicle Motion for Simulating Seated Reaches**

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# Behavior-Based Model of Clavicle Motion for Simulating Seated Reaches

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## ABSTRACT

A major limitation of ergonomic analyses with current digital human models (DHM) is the speed and accuracy with which they can simulate worker postures and motions. Ergonomic analysis capabilities of DHM would be significantly improved with the addition of a fast, deterministic, accurate movement simulation model for the upper extremities. This paper describes the development of an important component of such a model. Motion data from twelve men and women performing one-handed, push-button reaches in a heavy truck seat were analyzed to determine patterns of motion of the clavicle relative to the thorax. Target direction and reach distance were good predictors clavicle segment motion, particularly for fore-aft clavicle motion.

## INTRODUCTION

Upper-extremity reach simulations are one of the most common ergonomic analyses applied to both industrial workstations and automobile interiors. Although it is possible to conduct such simulations without using inverse kinematics (Park et al. 2004, Faraway 1997), other algorithms use inverse kinematics to choose joint angles that will place the hand in the desired location with respect to the torso. Ideally, an IK algorithm will be accurate, fast, and deterministic. The accuracy of a posture is determined by its similarity to postures assumed by similar-size people performing the simulated task. Fast algorithms are desirable so that ergonomic problems can be identified, adjustments can be made, and new trials can be run in a relatively short period of time. For most purposes, the algorithm should be deterministic, returning identical outputs when exercised with the same inputs. Previously published human upper-extremity IK algorithms have been lacking in at least one of these criteria.

One approach to creating upper-extremity IK models is to utilize robotics techniques, including differential inverse kinematics and optimization (Zhang and Chaffin 2000, Zhang et al. 1998, Jung et al. 1995, Farrell et al. 2005). These models address the kinematic redundancy

of the upper extremity by minimizing one of many possible cost functions, including torque change (Uno et al. 1989), muscular energy (Alexander 1997), and work (Soechting et al. 1995). The researchers who have developed these techniques have reported plausible results, but these methods are not in general use in commercial human figure models.

In part, the lack of acceptance of these techniques is due to the limitations of differential inverse kinematics and optimization for human posture and motion prediction. The algorithms tend to be slow in obtaining solutions, especially when applied to complex, redundant linkages like the human arm. Even when fast methods are available, optimization approaches are limited by the generality of the cost functions, and typically produce path-dependent results that can result in inaccuracy.

Motion within the shoulder complex is often not included in inverse kinematics algorithms for the upper extremities (Tolani et al. 2000). The lack of shoulder motion compromises the fidelity of the posture and motion simulation, particularly for the extreme reaches that are of greatest interest for ergonomics.

Human figure models often use a single claviscapular segment to represent the mobility between the sternum and humerus, rather than including separate components for the clavicle and scapula. The current analysis follows this approach, using a single segment between the sternoclavicular and glenohumeral joints. When necessary for detailed shoulder modeling, the motion of a claviscapular segment can be decomposed into separate clavicle and scapula motions (Dickerson 2004; de Groot et al. 2001). Moreover, it is difficult experimentally to track the three-dimensional motion of the scapula.

New motion simulation methods developed in the Human Motion Simulation laboratory at the University of Michigan employ a *behavior-based* approach to upper-extremity motion simulation. The method uses inverse-kinematics as part of the algorithm, solving the

redundancy problem using statistical models based on measurements of human behavior during task performance. This paper describes the development of a statistical model to predict the change in orientation of a claviscapular segment in reaches.

## METHODS

### Linkage Definition

At the level of detail needed for the current analysis, the shoulder complex can be considered from a kinematic perspective to be composed of four body segments and the joints that connect them, as shown in Figure 1. The thorax segment of the torso (ribcage) is connected to the clavicle at the sternoclavicular joint. The clavicle connects with the scapula at the acromioclavicular joint, and the scapula connects to the humerus at the glenohumeral joint. The current analysis models the orientation of a virtual claviscapular link connecting the sternoclavicular and glenohumeral joints.

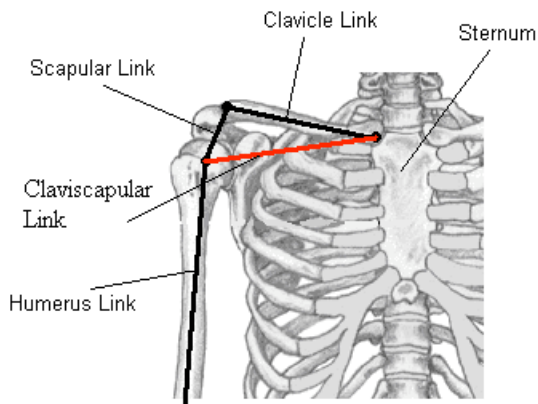


Figure 1. The joint links the in shoulder complex

### Data Collection

Human motion data were collected in the University of Michigan Human Motion Simulation Laboratory using a truck seat mounted on a motorized, rotating platform. The participants reached towards a push-button target located on a rotating apparatus capable of horizontal and vertical motion. In addition, the angle of the button-mounting box could be rotated around a horizontal axis. The combined motion of the push-button target and the motorized seat enabled the target to be located anywhere within the participant's reach envelope. The entire system was under computer control, so that a specific target location in a seat-centered coordinate system could be obtained automatically. Figure 2 shows the experimental setup.

Each participant was tested using approximately 100 target locations distributed throughout the right-hand reach envelope. After receiving a visual signal, the

participant performed a right-handed reach to the target, pressed the button for two seconds with their index finger, and returned to the home position.

Targets were distributed across six radial planes and five vector directions with respect to horizontal. Figure 3 shows the sampling planes with respect to the seat H-point and centerline. The target locations were scaled using initial measurements of each participant's maximum vertical, lateral, and forward reach. The scaling was designed to place about 5 percent of the reach target locations beyond the participant's maximum. Target locations were concentrated in the outer regions of the reach envelope where torso motion was necessary to complete the reach. Because the steering wheel interfered with forward reaches, the origin for the sampling vectors on the -30, 0, and 30-degree planes (see top view in Figure 6) was at shoulder height, rather than at H-point height.



Figure 2. Participant seated in the rotating truck seat reaching towards the push-button target.

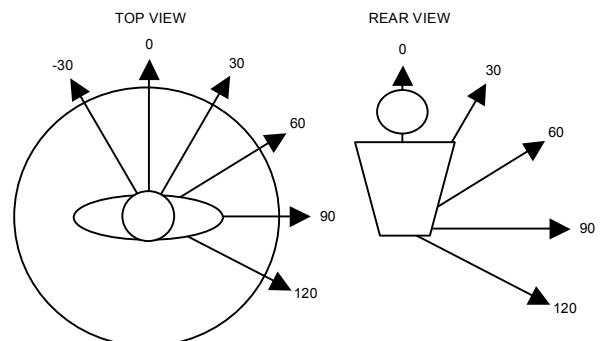


Figure 3. Target location vectors. Angles in degrees.

### Motion Capture

Participant motions were recorded using the electromagnetic Flock of Birds (FOB) system (Ascension Technologies). Each sensor reports both position and orientation, so all six degrees of freedom for a body

segment can theoretically be monitored with a single sensor. However, relative movement between the sensor and body segment can compromise the accuracy of the data. Sensors were placed on the sacrum, the left and right anterior-superior iliac spines (ASIS) of the pelvis, the forehead, on the shoulder superior to the right acromion process of the scapula, and on the lateral arm immediately proximal to the elbow.

Immediately prior to testing, an FOB sensor attached to a probe was used to record the locations of landmarks on the participant's head, thorax, pelvis, and right arm. All of the FOB sensors were sampled simultaneously with the probe sensor so that the locations of the landmarks with respect to the coordinate systems of the associated FOB sensors could be determined. These landmarks were used to reference the FOB sensor locations to anatomically based coordinate systems for each body segment using relationships described in Reed et al. (1999).

The acromioclavicular joint location was estimated to lie 1.5 cm above and 1.5 cm lateral to the suprasternale landmark. The glenohumeral joint location was estimated to lie 5 cm below the acromion landmark with the participant seated upright with the humerus vertical below the acromion. The glenohumeral joint location was tracked by assuming a constant location in the coordinate system of the FOB sensor on the acromion. The sternoclavicular joint location was similarly tracked using the FOB sensor on the sternum. The elbow joint location was estimated to lie 2.5 cm medial to the lateral humeral epicondyle landmark, and was tracked using the FOB sensor affixed to the arm just proximal to the elbow.

Data were sampled from each sensor at 25 Hz during the motion. Data were obtained from six men and six women stratified on stature to span the range from 154 cm to 194 cm. All participants were young adults ranging in age from 22 to 28 years. Participants with low body mass index (median 21.2 kg/m<sup>2</sup>, maximum 25 kg/m<sup>2</sup>) were selected to facilitate placement of the sensors and tracking of the underlying skeletal structures. Consequently, the sample is not suitable for estimating the range of movements that would be observed in a larger sample more representative of the driving population but may be adequate for quantifying the features of typical seated reach motions.

### Coordinate Systems and Angle Definitions

For this investigation, the angular deviations of the claviscapular and humerus segments were taken with respect to a thorax-fixed coordinate system. The Z axis of the coordinate system is parallel to the line connecting the estimated locations of the T12/L1 and C7/T1 joints, positive in the inferior direction. The X axis is perpendicular to the Z axis and directed laterally,

positive to the right. The Y direction was obtained in the resting seated posture by the cross product of the vectors joining T12/L1, the C7 surface landmark, and the suprasternale landmark. The X axis is positive forward, as shown in Figure 4. The origin point of the thorax coordinate system was located at the right sternoclavicular joint for purposes of the current analysis.

The claviscapular segment orientation was calculated in the thorax coordinate system. A vector was constructed from the estimated right sternoclavicular joint location to the estimated glenohumeral joint location. The angle of this vector with respect to the thorax XY (transverse) plane was termed the claviscapular elevation angle, positive above the XY plane. The angle of the projection of the claviscapular vector into the transverse plane with respect to the Y axis was defined as the claviscapular azimuth angle, positive rearward of the Y axis. The average resting posture was -18 degrees azimuth and -8 degrees elevation.

A second coordinate system parallel to the thorax coordinate system was located at the estimated location of the glenohumeral joint in the terminal posture of each reach. The target location was calculated in this coordinate system using the same definitions of azimuth and elevation used for the claviscapular segment. Hence, targets above the shoulder location had positive elevation angles, and targets forward of the frontal plane of the thorax had negative azimuth angles.

The reach vector length was measured from the glenohumeral joint center to the push button target at the final frame of each reach motion. The length of the vector was scaled by dividing by the largest value for this dimension recorded for each subject and termed *scaled reach distance*.

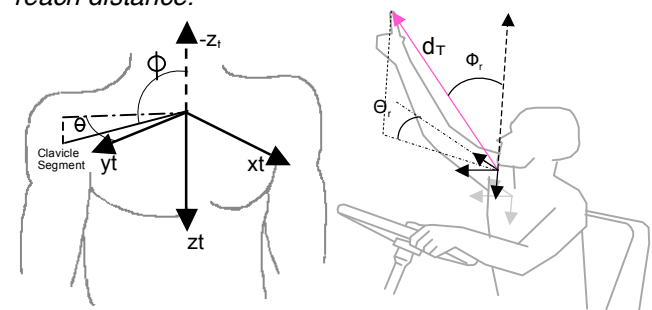


Figure 4. The thorax coordinate system along with the angle convention used for the displacements of the clavicle and humerus segments (left), and the reach distance definitions (right).

### Statistical Analysis

The two dependent measures of interest were the *changes* in claviscapular segment azimuth and elevation with respect to the thorax between the start and end of the trial. Predicting the change in claviscapular segment orientation, rather than the

observed value, removes variability due to initial posture, makes the results more robust to potential errors in locating the joint centers, and makes the results easier to apply to figure models.

A stepwise linear regression analysis was performed to determine which factors were useful predictors of shoulder joint motion relative to the torso during upper-extremity reaches. The predictors were all measured at the end of the trial in the thorax coordinate system. Potential predictors included the azimuth and elevation of the target, azimuth and elevation of the humerus, scaled target distance, and two-way interactions among these factors. The stepwise regression was performed using  $p=0.25$  to enter and  $p=0.10$  to leave, after which factors were manually selected to obtain a parsimonious model with an adjusted  $R^2$  value within 0.02 of the maximum value obtainable. Only factors that were statistically significant with  $p<0.01$  were included in the statistical models.

## RESULTS

### Change in Claviscapular Segment Azimuth

Figure 5 shows the change in clavicle azimuth as a function of target azimuth with respect to the thorax in the terminal posture. The  $R^2$  value for a linear regression with this single predictor was 0.79. No combination of additional factors raised the adjusted  $R^2$  value more than 0.02, so the following single-factor model was used:

$$\Delta\text{Azimuth} = -30.5 + 0.540 \text{ TarAz},$$

$$R^2 = 0.79, \text{ RMSE} = 12.4$$

where  $\Delta\text{Azimuth}$  is the change in claviscapular segment angle with respect to the thorax in degrees, positive forward of directly lateral; and  $\text{TarAz}$  is the target azimuth in degrees in the thorax coordinate system (positive forward of directly lateral). The RMSE (root mean square error) of 12.4 degrees indicates that considerable residual variance remains.

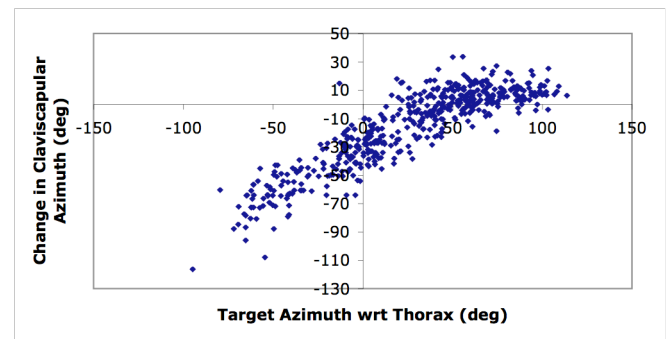


Figure 5. Change in clavicle azimuth angle with respect to the thorax as a function of the final target location azimuth with respect to the glenohumeral joint location expressed in the thorax coordinate system. Negative values on the vertical axis indicate movement of the glenohumeral joint forward from its resting position.

One interesting observation from Figure 5 is that the claviscapular segments tends to move forward (negative azimuth change) in reaches that are directly lateral to the thorax. Because the clavicle is angled slightly rearward in a normal resting posture, angling the clavicle forward increases reach distance. The effect was not significantly related to scaled reach distance in this dataset.

### Change in Claviscapular Segment Elevation

Claviscapular segment elevation was significantly related to the target location, with higher target elevation relative to the thorax in the terminal posture producing larger increases in claviscapular segment orientation. Figure 6 shows the change in claviscapular segment orientation as a function of target direction. The plot shows an increase in variance with increasing target elevation. Examination of the data from each participant showed that this trend occurred in most participants' data and did not result from compositing disparate trends.

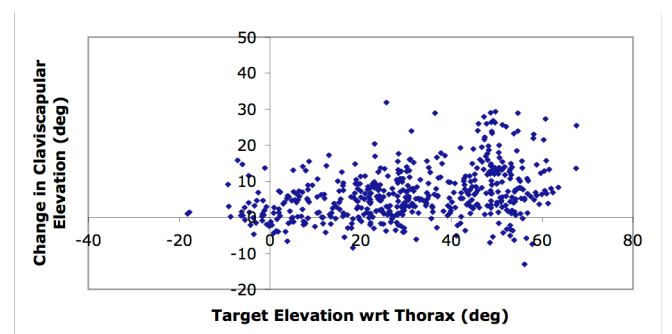


Figure 6. Change in claviscapular segment elevation during the reach as a function of terminal target elevation with respect to the thorax coordinate system.

Regression analysis was used to develop a statistical model based on target elevation, target azimuth, and scaled target distance.

$$\Delta\text{Elevation} = -14.4 - 0.025 \text{ TarAz} + 0.128 \text{ TarEl} + 19.9 \text{ SRD}, R^2_{\text{adj}} = 0.23, \text{RMSE} = 6.3$$

where  $\Delta\text{Elevation}$  is the change in the elevation of the claviscapular segment with respect to the transverse plane of the thorax in degrees, positive upward; TarAz is the target azimuth in degrees in the thorax coordinate system (positive forward of directly lateral); TarEl is the target elevation angle in degrees relative to the transverse plane of the thorax (positive upward); and SRD is the scaled reach distance calculated by expressing the target distance from the glenohumeral joint as a fraction of the maximum distance from the index fingertip to the glenohumeral joint (i.e., with the elbow straight).

Although the model is statistically significant ( $p < 0.001$ ), the relatively weak relationships are reflected in the small  $R^2$  value. Because the data do not conform to some of the standard assumptions of the linear regression model (constant residual variance, in particular) this model should be interpreted with caution. Overall, increasing the elevation of the target in the thorax coordinate system, or increasing its distance, increases the change in claviscapular segment elevation. Increasing the target azimuth angle (moving the target further rearward relative to directly lateral to the thorax) decreases the amount of claviscapular segment elevation.

## DISCUSSION

### Summary

Data on human performance can be used to improve the accuracy of human posture and motion simulations. In the current analysis, data on shoulder posture in seated one-hand reaches were used to quantify the change in orientation of a virtual claviscapular segment connecting the sternum and humerus during seated, one-hand, push-button reaches. The data analysis showed that changes in the azimuth angle of this segment, corresponding to clavicle motion in a transverse plane of the thorax, producing generally fore-aft movement of the glenohumeral joint, was well predicted by the location of the target with respect to the thorax. In contrast, clavicle elevation was not closely related to the potential predictors, although target location and distance did have statistically significant effects. Participants appeared to have variable strategies for using clavicle elevation to complete the reaches.

## Applications

The statistical models in this paper can be used as part of degree-of-freedom-reduction strategies to permit fast, deterministic inverse kinematics. Give a target location with respect to the current glenohumeral joint location, a new claviscapular segment posture is computed and applied to the figure. Because this posture change alters the reference glenohumeral joint location, the calculation is iterated until the incremental change is below some desired threshold. In practice, no more than three iterations are needed to achieve millimeter accuracy.

Although the models were developed using data for the right upper extremity, they could reasonably be applied to the left upper extremity until left-side data are available. Only sign changes are required in the equations to mirror the behavior

## Limitations

The current analysis is limited by the range of test conditions and the relatively small number of participants. The analysis was scaled to eliminate effects of body dimensions and no residual effects of body dimensions were observed. The effects of variability in resting posture were eliminated by modeling the change in segment angle, rather than absolute angle. This also facilitates the application of the results to human figure models with different neutral shoulder postures. However, the relatively homogeneous participant pool limits the ability to estimate population variability in the behavior.

Tracking the orientation of body segments in realistic task scenarios is challenging, particularly in the shoulder area. The estimate of glenohumeral joint location used a constant offset from the acromion landmark and assumed that the electromagnetic sensor remained in a fixed relationship to the scapula during the motion. These assumptions were almost certainly violated to varying extents during reaches, but the consequences for the analysis cannot readily be determined. Between-subject errors in glenohumeral joint estimation are probably not important, because the dependent measures were changes in angle, not absolute angles. Changes in the actual offset between the glenohumeral joint location and the electromagnetic tracking sensor would be more important and would affect primarily the elevation measure, due to the way the tissue under the sensor moves during reaches. Future studies could use manual digitization of palpated body landmarks to reduce these errors, although such a time-consuming measurement process would greatly reduce the number of trials that could be performed and call into question the naturalness of the behavior in extreme reaches.

The most significant limitation of these findings is that participants performed only a single, low-force hand task. Participants pushed a button with the index finger

for approximately two seconds at the end of each reach. The force vector was directed approximately through the shoulder joint, so shoulder moments resulted primarily from the effects of body segment mass. Tasks involving higher hand forces and other force directions might produce different behavior and should be examined in future research.

## CONCLUSIONS

To our knowledge, this is the first effort to characterize claviscapular segment motion in a realistic task. Previous efforts have focused on measurements in non-task postures (e.g., de Groot and Brand, 2001). The data show a strong relationship between reach direction and the fore-aft motion of the glenohumeral joint, but the elevation of the shoulder during reaches is more difficult to predict. The statistical models in this paper can be used to improve the accuracy of reach simulations in digital human figure models. Future work should examine the effects of hand forces on these relationships.

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