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Torso Kinematics in Seated Reaches

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ABSTRACT

Simulations of humans performing seated reaches require accurate descriptions of the movements of the body segments that make up the torso. Data to generate such simulations were obtained in a laboratory study using industrial, auto, and truck seats. Twelve men and women reached to push-button targets located throughout their right-hand reach envelopes as their movements were recorded using an electromagnetic tracking system. The data illustrate complex patterns of motion that depend on target location and shoulder range of motion. Pelvis motion contributes substantially to seated reach capability. On padded seats, the effective center of rotation of the pelvis is often within the seat cushion below the pelvis rather than at the hips. Lumbar spine motions differ markedly depending on the location of the target. A categorization of reach targets into four zones differentiated by torso kinematics is proposed.

INTRODUCTION

Driver reach simulations are among the more common applications of digital human models in the design of vehicle interiors. The analysis is typically concerned with whether controls or other targets can be reached by a sufficient percentage of drivers. Prior to the widespread use of human figure models in CAD, reach analyses were primarily conducted using the reach surfaces in SAE J287 (SAE 2003). The conditions under which the data underlying J287 were gathered (Hammond and Roe 1972) differ substantially from the conditions in current vehicles, particularly in the restraint system design.

J287 provides surfaces within which 95 percent of drivers are expected to be able to reach with different levels of torso restraint. This approach provides the vehicle designer with important information for locating controls, but is not useful for simulating reaches with individual figure models. That is, J287 does not indicate how or how far a person described by a particular set of body dimensions would reach. Current SAE practice also provides no guidance on the perceived difficulty of submaximal reaches or reach kinematics. Work is currently underway to replace the surfaces in J287 with new, more flexible models based on data obtained in conditions representative of current vehicles (Reed et al. 2003a).

Robotics approaches have been used to predict the maximum reach envelope (Abdel-Malek et al. 2002), although actual reach capability is not well predicted by strictly kinematic approaches (Reed et al. 2003b). Regardless, the maximum reach capability is of less practical interest than the kinematics and subjective difficulty with which *submaximal* reaches are performed, because any plausible design for a control will place it within the maximum reach capability of most drivers.

In the absence of standardized approaches to modeling seated reach in vehicles, research teams have developed methods to predict either terminal postures or motions using regression equations (Ryan 1970; Snyder et al. 1972), optimization-based inverse kinematics (Wang and Verriest 1998), analytical inverse kinematics (Jung et al. 1995), optimization-based differential inverse kinematics (Zhang and Chaffin 2000), and functional regression on stretch-pivot parameters (Faraway 2003). Additionally, most human figure models used for ergonomic analysis (e.g., Jack, Safework, and RAMSIS) provide for prediction of reach postures using inverse kinematics. Reach motions are predicted by interpolating between starting and ending postures. A variety of heuristic and optimization-based approaches are used to address the redundancy of the linkage. Interpolation-based inverse-kinematics methods tend to produce distinctly artificial movement patterns because the interpolation methods are not based on human behavior data.

The diversity of approaches to seated reach prediction in commercial human models indicates that none of the previously developed models of seated reach have achieved widespread acceptance. One explanation for the lack of consensus in motion prediction is that no models have been published in a form that can be readily implemented, and hence there is no opportunity for independent validation of the reach prediction in commercial tools. Several detailed posture prediction models for seated reaches have been published (e.g., Synder et al. 1972), but those results are not generalizable to motion. Other models lack sufficient complexity in the torso. For example, the torso is commonly represented by a single link between the hip and shoulder (Jung et al. 1995) or between L5/S1 and the sternoclavicular joint (Zhang and Chaffin 2000). None of the published models predict pelvis motions, which have been found to be important contributors to torso mobility in seated reaches (Reed et al. 2003b).

The current study was conducted to provide the basis for a new model of seated reach motions that would include detailed torso kinematics and would be suitable for most driver reach assessments. The primary objective of the data collection was to record detailed torso kinematics for seated reaches, including six degrees of freedom for both the pelvis and thorax, for submaximal and maximal reaches in a wide range of directions. Previous studies of seated reaches performed in the Human Motion Simulation (HUMOSIM) laboratory at the University of Michigan used fixed targets distributed throughout, for example, the simulated interior of a vehicle, with each participant reaching to the same targets (Zhang and Chaffin 2000). The current study used a computerized target positioning apparatus to allow customization of the target locations for each participant (Reed et al. 2003a), ensuring that each participant would be presented near-maximal targets in a wide range of reach directions.

This paper presents preliminary observations of some salient characteristics of torso motion during seated reaches. Any reasonable simulation method must produce these characteristics, and hence they form a foundation for selecting a simulation approach that has the right balance between complexity and efficiency, an important consideration with any model intended for real-time use (Zhang 2003).

METHODS

Facility and Test Conditions

Testing was conducted in the HUMOSIM laboratory in passenger car, heavy truck, and industrial seats. The test seat is mounted on a motorized, rotating platform. A push-button target is located on a motorized apparatus that can move vertically and horizontally. The angle of the button-mounting box can also be rotated around a horizontal axis. By rotating the seat platform and adjusting the horizontal and vertical target position, the target can be placed anywhere within the participant's reach envelope. The entire system is under computer control, so that a specified target location in a seat-centered coordinate system can be obtained automatically. Figure 1 shows a participant in the test facility.

Each participant was tested in each seat 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.

A target location matrix was constructed with target locations on six radial planes and five vector directions with respect to horizontal. Figure 2 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 the reach difficulty was expected to change more rapidly with increasing distance from the H-point. 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.

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Figure 1. Participant in the test facility, showing rotating seat, computer-controlled target-positioning apparatus, and motion capture hardware.

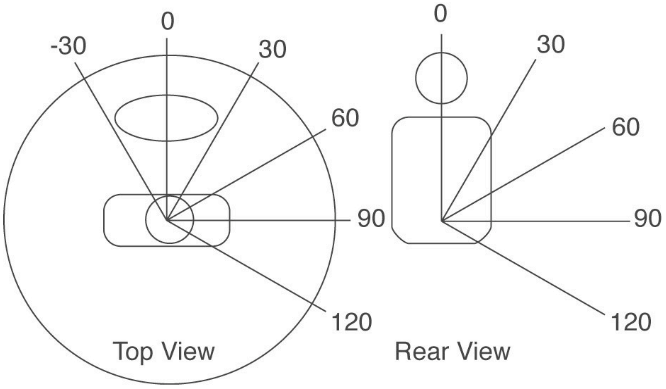


Figure 2. Target location vectors. Angles in degrees.

Motion Capture

Motions were recorded using the electromagnetic Flock of Birds 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. In this study, redundant sensors were used on the thorax and the pelvis to provide better tracking of the skeleton. Sensors were placed on the sacrum and over the left and right anterior-superior iliac spines (ASIS) of the pelvis. The ASIS sensors were intended and used for position data only, since the orientation of the sensors with respect to the pelvis was not maintained during reaching. Sensors were mounted on the sternum and over the T8 spinous process. While the sternum sensor could be mounted securely, the T8 sensor orientation was more affected by movement of the skin and soft tissue, so the T8 sensor was used only to establish, with the sternum sensor, the orientation of the midsagittal plane. Additional sensors were placed on the forehead, 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). For example, the locations of the hip and L5/S1 joints were calculated using data from the probe measurements of the left and right posterior superior iliac spine landmarks and the FOB sensor positions of the FOB sensors at the left and right ASIS, and the position and orientation of the sacrum FOB sensor. The pelvis orientation calculated using the locations of the sacrum and ASIS sensors was compared to the orientation obtained from the sacrum FOB sensor to verify that the pelvis sensors did not shift appreciably with respect to the participant during testing.

Data were sampled from each sensor at 25 Hz during the motion. Joint locations were calculated from the motion data and measured landmark locations, and transformation matrices were calculated for each segment of a linkage system consisting of pelvis, abdomen, thorax, neck, head, right clavicle, and right arm. Note that because data describing six degrees of freedom are available for the pelvis, thorax, and head, the length of the abdomen and neck segments is not fixed in the data, which allows the motion of the lumbar and cervical portions of the spine to be described in ways that are more complex than are provided by one- or two-joint lumbar or neck linkages.

In this paper, torso kinematics are illustrated using a model of the skeleton. The measured scale, positions, and orientations of the pelvis, thorax, clavicle, head, and arm are used to display the associated skeletal segments. The lumbar and cervical spines are interpolated between the adjacent segments to provide visualization of the associated changes in spine contour. The lumbar and cervical spine visualizations should be assessed qualitatively since no data were actually gathered on spine contours in these regions. Similarly, no data were gathered on scapula motion independent of the clavicle, so the scapula in the visualizations moves with the clavicle.

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^2, maximum 25 kg/m^2) 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.

RESULTS

Pelvis Kinematics

Pelvis mobility has been shown to be a key determinant of reach capability for people with the minimal torso constraint produced by safety belts equipped with emergency locking retractors (Reed et al. 2003). When people reach up, forward, or to the side to targets that require torso motion, the pelvis rolls to facilitate the reach. Pelvis motions for several types of reaches are illustrated here. In all cases, we are concerned with targets that require a substantial engagement of the torso.

One important observation from this study is that the pelvis does not generally roll around either the hips or the ischial tuberosities. Relative to a seat surface, seated pelvis motion is rarely centered on the hips, even though changes in torso orientation in human figure models are often based on hip rotation. Rotating around the hips would require that the base of the pelvis shift against the seat, a motion that is not feasible when a significant fraction of the sitter's body weight is borne by the buttocks. On a rigid seat, the center of rotation of the pelvis might be in the area of the ischial tuberosities, since the skin under the buttocks typically remains stationary with respect to the seat while the pelvis rolls inside the skin.

In the current study, participants sat on three padded seats, two of which had relatively thick foam cushions (the truck and car seats). With padding under the buttocks, changes in torso and pelvis orientation cause changes in cushion penetration. Reaching to forward targets that require torso involvement causes the pelvis to roll forward, concentrating pressure under the buttocks as the fraction of the torso weight that is offloaded from the backrest is now over the buttocks. The additional load carried by the pelvis drives the pelvis lower in the seat as it is rolling forward, resulting in a center of rotation that is below and slightly behind the pelvis within the seat cushion.

Figure 3 shows torso kinematics for a high forward reach and Figure 4 shows a low forward/lateral reach. Both reaches were performed in the truck seat. In these reaches to relatively distant targets, the pelvis rolls as the sitter reaches. The deformation of the cushion is seen as the pelvis drops relative to the seat H-point. In both cases the average center of rotation for the pelvis is slightly below the pelvis in the seat cushion.

Lumbar Spine Motion

The data show that torso motion occurs when either (1) the target distance from the starting location of the sternoclavicular joint is larger than the sum of the lengths of the hand, forearm, arm, and clavicle segments, or (2) reach to the target without torso motion would exceed the ranges of motion of one or more upper extremity joints.

The lumbar spine shows complex kinematics during seated reaches that require torso motion. For many reaches with torso involvement, the sternoclavicular joint is at or near the boundary of its range of motion (ROM), so that clavicle and thorax begin to rotate together as a unit. For example, when reaching forward, the thorax rotates contralaterally to allow the clavicle to point toward the front of the body to a greater extent than permitted by the sternoclavicular joint (of course, the ROM at the sternoclavicular joint is effectively determined by the kinematic limitations of the entire shoulder complex and not only locally).

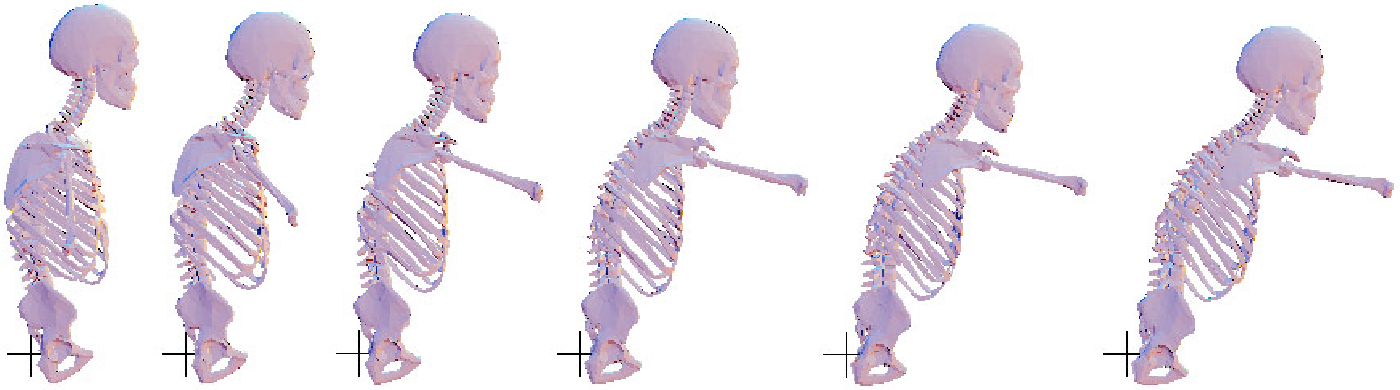


Figure 3. Kinematics for a forward reach in a truck seat showing rotation of the pelvis. Crossed lines indicate the seat H-point.

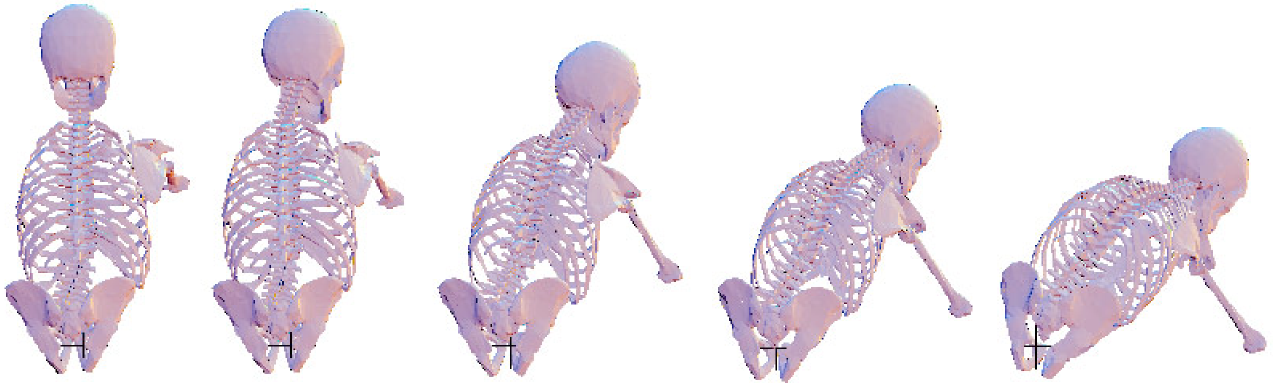


Figure 4. Kinematics for a forward/lateral reach in a truck seat showing rotation of the pelvis. Crossed lines indicate the seat H-point.

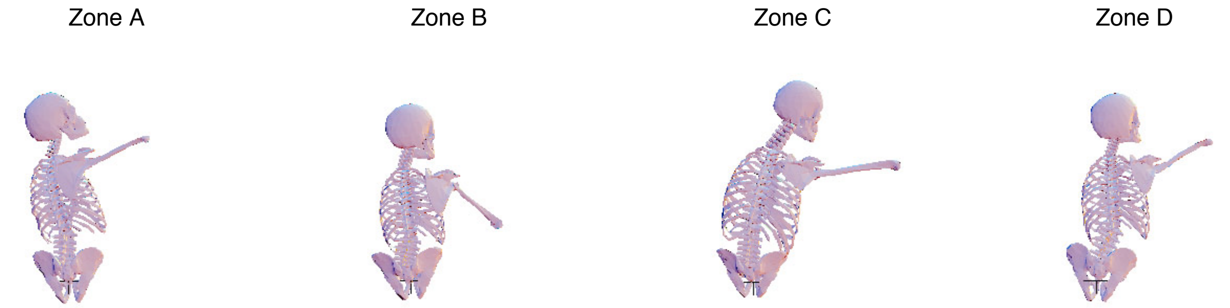
There are four target zones within which torso movements are distinctly different. These zones are illustrated in Figure 5 with representative terminal postures. In zone A, the target is sufficiently close to the sitter that the shoulder ROM prevents the target from being reached without a contralateral movement of the torso. This motion is accomplished by lateral bending and twisting in the lumbar spine, usually without significant pelvis motion. The thorax is moved away from the target and rotated to bring the target closer to the front of the thorax. Since the outer margin of zone A is determined primarily by shoulder range of motion, zone A is located near and particularly behind the shoulder. The external rotation limit of the humerus is commonly the limit that necessitates torso motion in zone-A reaches. In vehicles, seatbelts are often stowed in zone A, necessitating a contralateral motion of the torso to grasp the belt (Ebert and Reed 2002; Monnier et al. 2003) and the console between the front vehicle seats can lie in zone A, particularly for people who choose more-forward seat positions.

In zone B, the target can be reached without torso motion. Within zone B, the humerus does not reach the boundary of the glenohumeral ROM and the target distance from the initial position of the glenohumeral joint does not exceed the combined lengths of the arm, forearm, and hand (with a small amount of additional distance achieved for forward and vertical reaches by clavicle motion without thorax motion). However, the outer limit of zone B, defined by the maximum reach distance without torso motion, may be less than what would be calculated from the total lengths of the upper extremity segments (Delleman et al. 2003). Vehicle designers usually attempt to locate reach targets within zone B for most drivers by using the reach curves in SAE J287 obtained from drivers wearing fixed-length torso restraints. Reaches within zone B receive the lowest difficulty ratings (Reed et al. 2003b).

In zone C, the lumbar spine flexes, bends, and rotates to move the glenohumeral joint in the direction of the target. By definition, there is little or no pelvis motion in zone C, because thorax motion alone is sufficient. The pelvis motion that is observed is due to cushion deflection produced by movements in torso center of mass. The outer margin of zone C is determined by the ROM of the lumbar spine. Zone C reaches are rated as more difficult than zone B reaches.

In zone D, the pelvis is rotated in the direction of the reach, and lumbar spine flexion/bending/rotation is often less than in zone C. That is, the lumbar spine straightens out to increase the distance between the pelvis and the glenohumeral joint.

The changes in lumbar spine motion across the zones can be visualized by examining the terminal postures for forward reaches shown in Figure 5. Zone A is essentially non-existent for forward reaches at chest level, because the shoulder ROM is well oriented for targets directly in front of the body. Zone B spans the range from directly in front of the sitter to a point approximately at the upper (and forward) rim of the steering wheel. In fact, one heuristic criterion used to position steering wheels is that sitters can reach the top of the rim while in zone B, that is, without moving the thorax. As the target is moved further forward, into zone C, lumbar flexion *increases* and lateral bending and twisting of the spine is observed. However, as the target moves into zone D, lumbar spine flexion *decreases* as the pelvis rolls forward. Lateral bending and twisting of the spine remain the same as at the zone C/D margin or increase as the pelvis rotation permits greater movement (the bending and twisting ranges of motion for the lumbar spine are greatest when near the middle of the flexion/extension range of motion). At the maximum reach envelope, the distance from the bottom of the pelvis to the finger tip has been maximally lengthened by extension, lateral bending, and rotation in the lumbar spine, as shown in Figure 6 for a near-maximal overhead reach.



Torso moves away from target to accommodate shoulder range of motion

Minimal torso motion; target can be reached using only clavicle and upper extremity

Lumbar spine flexion/bending/twisting in direction of target but little pelvis motion

Pelvis rolls and lumbar spine moves toward extension to lengthen torso

Figure 5. Illustration of typical terminal postures for reaches to targets in four zones.

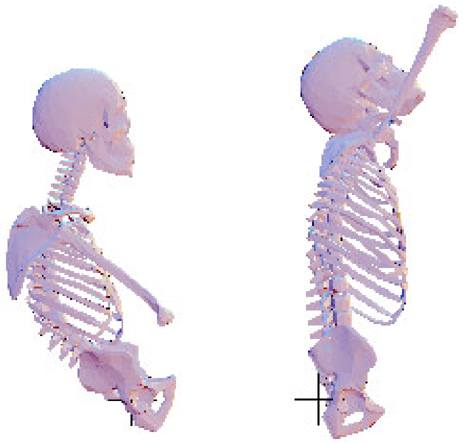


Figure 6. Example of zone-D reach to an overhead target in a car seat (starting posture on left, ending posture on right) illustrating movement of lumbar spine toward extension. Seat H-point location is shown.

DISCUSSION

These data demonstrate that seated reach motion studies require measurement of six degrees of freedom on the pelvis and at least three degrees of freedom on the thorax. Clavicle mobility is also important and must be quantified to obtain an accurate representation of the motion. This suggests that seated reach prediction requires modeling a kinematic chain with a fairly large number of degrees of freedom: 6 (pelvis) + 3 (thorax) + 2 (clavicle) + 3 (shoulder) + 1 (elbow) + 3 (wrist) = 18. For push-button motions, this could be reduced to 15, a number that is still larger than the number of degrees of freedom addressed by most of the previously reported kinematic models of seated reach. Simpler linkages will not be able to reproduce, for example, the transition from zone C to zone D.

Pelvis mobility was found to be an important characteristic of seated reaches, particularly reaches to targets sufficiently distant to be of interest for ergonomic analysis. On padded seats, the pelvis pivots around a moving axis generally located below the pelvis, within the seat cushion. This effective center of rotation is produced by forward/lateral pelvis rolling and increased penetration into the cushion as the weight of the torso is offloaded from the seat back.

Examination of the lumbar spine motion revealed four distinct motion patterns, differentiated by target zone, that must be reproduced in a motion prediction model applicable to seated reaches. The differences in kinematics among the four zones indicate several features of a good motion prediction model:

1. The model must take into account joint ranges of motion, particularly at the shoulder, because the shoulder ROM determines whether a near target will produce zone-A or zone-B behavior in the torso.

2. The model must be capable of identifying the transition between zone C, in which lumbar spine mobility but not pelvis mobility is important, and zone D, in which the pelvis rolls and the lumbar spine flexion/extension can be opposite of that in zone C.

3. The model must be able to produce realistic pelvis kinematics, which has been shown to depend on penetration into the seat and hence seat cushion stiffness.

Reach targets have been divided into zones based on the characteristics of terminal postures in previous work (e.g., Ryan 1970, Jung et al. 1995). The idea that the torso becomes involved only when movements of the distal segments is insufficient is not new (see Delleman et al. 2003 for a review). The current work, however, identifies the importance of the zone A/B and zone C/D transitions, in which the torso motion includes components in a direction opposite from or perpendicular to the reach. Delleman et al. (2003), analyzing terminal postures, showed that the transition from zone B to zone C for lateral reaches occurred prior to reaching the end of the range of motion of the upper extremity. This finding highlights the need for detailed information on torso kinematics for zone C reaches.

Previous work has also shown that lateral and near-lateral maximum seated reaches are balance limited, rather than joint range-of-motion limited (Reed et al. 2003b). Hence, accurate prediction of lateral reach capability and motions requires consideration of balance and the ability of the sitter to generate counterbalancing forces with the contralateral hand (by gripping the steering wheel, for example).

The generality of the observations in this study is limited by the relatively homogenous participant pool. The participants were all young people with low body fat. Older sitters are known to have different maximum reach capability due to balance maintenance limitations (Parkinson et al. 2002) and also may have different reach kinematics (Chaffin et al. 2000). For example, the size of zone A, which is determined by shoulder ROM motion, might be quite different for older sitters. Sitters with higher levels of body fat may also have different reach kinematics. The extensive data gathered in the current study will allow subsequent work with more diverse populations to be conducted more efficiently. Future studies should examine the influence of environmental obstructions, such as the seat back. Even more important will be generalizing the current work to examine the effects of hand orientation and force application at the termination of the reach.

Work is now underway to develop a motion-prediction model for seated reaches that reproduces the behaviors observed in the four reach zones described in this paper. The ultimate goal is to publish a seated reach model in fully implementable form. Such a model will provide an independent validation of the reach models available in commercial digital human modeling tools. Additional data collection will be necessary to assess the generalizability of the model to more diverse populations and to simulate reaches to targets other than push-button controls.

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REFERENCES

Abdel-Malek, K, Yang, J., Brand, R., Tanbour, E., (2001). Towards understanding the workspace of the upper extremities. Technical Paper 2001-01-2095. Society of Automotive Engineers, Inc., Warrendale, PA.

Chaffin, D. B., J. J. Faraway, X. Zhang, and C. Wooley, (2000). Stature, Age, and Gender Effects on Reach Motion Postures, *Human Factors,* 42:3, 408-420.

Delleman, N.J., Huysman, M.A., and Kuijt-Evers, L.F.M. (2003). Postural behavior in static reaching sidewards. Technical Paper 2003-01-2230. SAE International, Warrendale, PA.

Ebert, S.M. and Reed, M.P. (2002). Characterization of Driver Seatbelt Donning Behavior. Technical Paper 2002-01-0783. SAE International, Warrendale, PA.

Faraway, J.J. (2003). Data-based motion prediction. Technical Paper 2003-01-2229. SAE International, Warrendale, PA.

Hammond and Roe (1972). SAE controls reach study. Technical Paper 720199. Society of Automotive Engineers, Inc., Warrendale, PA.

Monnier, G., Wang, X., Verriest, J.P., and Goujon, S. (2003). Simulation of complex and specific task-orientated movements – application to the automotive seat belt reaching. Technical Paper 2003-01-2225. SAE International, Warrendale, PA.

Parkinson, M.B., Chaffin, D.B., and Reed, M.P. (2002). Maintaining Balance in Seated Reaches. Proc. RESNA Annual Conference. Rehabilitation Engineering and Assistive Technology Society of North America, Arlington, VA.

Reed, M.P., Parkinson, M.B., and Klinkenberger, A.L. (2003a). Assessing the validity of kinematically generated reach envelopes for simulations of vehicle operators. Technical Paper 2003-01-2216. SAE International, Warrendale, PA.

Reed, M.P., Parkinson, M.B., and Chaffin, D.B. (2003b). A new approach to modeling driver reach. Technical Paper 2003-01-0587. SAE International, Warrendale, PA.

Reed, M.P., Manary, M.A., and Schneider, L.W. (1999). Methods for measuring and representing automobile occupant posture. Technical Paper 990959. SAE Transactions: Journal of Passenger Cars, Vol. 108.

Ryan, P. W. (1970). Cockpit geometry evaluation, Joint Army-Navy Aircraft Instrumentation Research Report 700201. The Boeing Company, Seattle, WA.

SAE International (2003). Automotive Engineering Handbook. SAE International, Warrendale, PA.

Synder, R.G., Chaffin, D.B., and Schutz, R.K. (1972). Link system of the human torso. Technical Report AMRL-TR071-88. Aeorspace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.

Wang, X. and Verriest, J.P. (1998). A geometric algorithm to predict the arm reach posture for computer-aided ergonomic evaluation. *Journal of Visualization and Computer Animation*, 9:33-47.

Zhang, X. (2001). Biomechanical Realism Versus Algorithmic Effeciency: A Trade-off in Human Motion Simulation and Modeling, *SAE Transactions,* 110:6, 2184-2191.

Zhang, X. and D. Chaffin (2000). A Three-Dimensional Dynamic Posture Prediction Model for Simulating In-Vehicle Seated Reaching Movements: Development and Validation, *Ergonomics,*43:9,1314-1330.