2003-01-2216

Assessing the Validity of Kinematically Generated Reach Envelopes for Simulations of Vehicle Operators

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ABSTRACT

Assessments of reach capability using human figure models are commonly performed by exercising each joint of a kinematic chain, terminating in the hand, through the associated ranges of motion. The result is a reach envelope determined entirely by the segment lengths, joint degrees of freedom, and joint ranges of motion. In this paper, the validity of this approach is assessed by comparing the reach envelopes obtained by this method to those obtained in a laboratory study of men and women. Figures were created in the Jack human modeling software to represent the kinematic linkages of participants in the laboratory study. Maximum reach was predicted using the software's kinematic reach-envelope generation methods and by interactive manipulation. Predictions were compared to maximum reach envelopes obtained experimentally. The findings indicate that several changes to the normal procedures for obtaining maximum reach envelopes for seated tasks are needed. Accurate prediction of maximum seated reach requires consideration of balance and pelvis mobility, neither of which is closely linked to joint range of motion. Sufficient ranges of motion in the shoulder and torso are also needed to represent postures near maximum reach.

INTRODUCTION

Maximum reach capability is an important consideration in the design of seated workstations. For most of the history of human-factors engineering, operator reach capability has been represented using graphical representations of statistical models based on laboratory measurements. In one widely cited study, Kennedy (1964) presented the results of a study of the maximum reach capability of U.S. Air Force pilots wearing belt restraints on the torso. The data were presented as planar curves positioned relative to the seating reference point within which 95 percent of the tested subjects could reach. SAE Recommended Practice J287 presents three-dimensional surfaces within which 95 percent of drivers are predicted to be able to reach. These surfaces are based on a study of drivers seated in three different vehicle mockups (Hammond and Roe, 1972). SAE J287 is widely used in the design of passenger cars and light trucks.

During the past decade, software models of the human body have become increasingly important for vehicle interior design. Human modeling tools, such as RAMSIS, Jack, and SafeWork, are used to simulate the interaction of humans and vehicle interiors. The software tools provide the human factors engineer with the ability to simulate a vehicle occupant reaching to controls or other targets by articulating the joints of a virtual human. For many vehicle interior analyses, these simulations, based on the kinematics and posture of a human figure model, are used instead of statistical reach models.

In typical application, the range within which an occupant can reach (reach envelope) is obtained by iterating each joint of the upper extremity, from the sternoclavicular joint to the wrist, through its range of motion. Analytical methods have also been developed to calculate the surfaces defining the reach envelope (Abdel-Malek et al. 2001). Previous studies have examined the validity of reach simulations for pilots with fixed-length torso restraints (e.g., Green and Hilby 1999).

However, belt restraints in modern road vehicles are commonly equipped with emergency locking retractors (ELR). An ELR allows the belt to spool under light tension until the vehicle undergoes a level of acceleration that might be associated with a crash. With this type of belt system, the belt does not substantially restrain the occupant's torso during normal reaching activities. Hence, a vehicle occupant's reach envelope is determined by torso mobility in addition to upper extremity dimensions and range of motion.

In the current study, maximum reach envelopes from a pilot study of seated reaches were used to assess the validity of kinematically generated reach assessments in the Jack human figure model. Because preliminary results showed large discrepancies between the reach envelopes obtained in Jack and those observed with the experiment participants, this paper uses a qualitative evaluation of terminal postures from near-maximal reaches to recommend improvements to human-modeling procedures for estimating seated reach capability.

METHODS

Data for maximal and submaximal seated reaches were obtained from a study conducted at the University of Michigan's Human Motion Simulation (HUMOSIM) laboratory. Details of the experimental methods are found in Reed et al. (2003). Testing was conducted using mockups of heavy truck, passenger car, and industrial workspaces. Figure 1 shows a participant completing a reach in the heavy truck mockup. A computer-controlled target positioning apparatus was used to place a push-button target at a wide range of locations within the participant's right-hand reach envelope. The participant reached to the target, pressed the button for two seconds, and returned to a home position. Optical targets and electromagnetic sensors were attached to landmarks on the participant to track the motion using methods reported previously (Park et al. 1999, Chaffin et al. 1999)

Figure 1. Laboratory setup, showing the optical and electromagnetic markers used to track motions and the computer-controlled target-positioning apparatus.

The kinematic data were analyzed to compute joint locations that produce a representation of the participant's body as a kinematic linkage. These data were used in the Jack human modeling software to scale figures to match the participants' linkage dimensions. The terminal postures from selected maximal reaches were mapped onto the Jack figures to compare with those produced by interactive manipulation.

Maximum reach envelopes were obtained from the laboratory data by a process described in Reed et al. (2003). The participant rated the difficulty of each of over 200 reach trials to targets distributed throughout and just beyond the right-hand reach envelope. Participants rated maximal attainable reaches as 10 on a 10-point scale. Unattainable reaches were coded as 11. Maximum reach envelopes were calculated from these data by interpolating to find locations for which the difficulty rating was predicted to be 10.5 and fitting smooth functions in spherical coordinates. These empirically derived maximum reach envelopes were compared to those obtained by kinematic manipulation of the Jack figures that had previously been scaled to match the participant's body linkages.

RESULTS

Figure 2 shows a Jack figure scaled to match the measured kinematic linkage for one study participant. Three reach envelopes are shown. The innermost envelope was generated in Jack by tracing the right fingertip location as the right upper extremity was manipulated, starting at the right sternoclavicular joint. The middle envelope was created similarly, but with the mobility beginning at the L5/S1 joint. The outermost envelope is the maximum reach envelope obtained in testing with this participant. The focus of the current analysis is on the sources of the discrepancies between these three envelopes.

Note that to simplify the graphical presentation of the reach envelopes, restrictions due to self-collision and interference with the environment (for example, restrictions on forward reach due to the steering wheel) are not included. The analysis focuses on upward and lateral reaches in a coronal plane, for which these restrictions are not important.

The two kinematically generated reach envelopes are similar for reaches up and to the right, because torso mobility does not add much reach distance in that direction. The effect of torso mobility is largest for reaches to the side. Figure 3 shows a posture with the figure reaching to the right with torso mobility down to L5/S1 included, illustrating the additional reach distance obtained when the torso is allowed to flex, bend, and twist. However, this reach envelope is still substantially smaller than the observed envelope.

Analysis of the kinematics of the study participants showed two important differences compared to the terminal postures in Figures 2 and 3. First, the study participants rolled their pelves on the seat to obtain greater reach distance. Figure 4 shows the large increase in lateral reach distance that is obtained by rolling the pelvis.

Figure 2. Illustration of posture on boundary of maximum reach envelope generated using mobility starting at the sternoclavicular joint (innermost envelope).

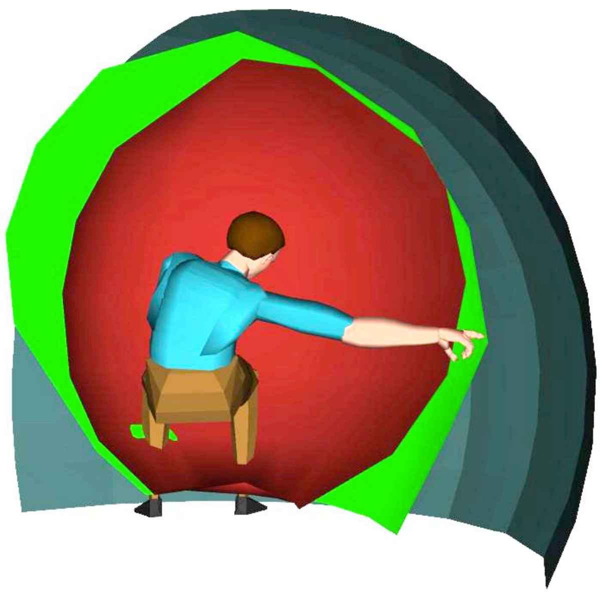

Figure 3. Illustration of posture on boundary of maximum reach envelope generated using mobility from starting at the waist.

Figure 4. Expansion of reach capability obtained by rolling the pelvis (compare with Figure 3).

Second, the study participants showed considerably more range of motion in the shoulder, particularly at the sternoclavicular joint, than is provided by Jack in its default configuration. In Figure 5, the joint limits at the sternoclavicular joint have been relaxed to better approximate the kinematics observed in the laboratory study. Combining torso mobility with pelvis roll and increased range-of-motion at the sternoclavicular joint results in a reach capability that closely approximates that which was observed in the laboratory, although the change in the shoulder motion introduced some graphical anomalies in the figure.

Figure 5. Expansion of reach capability obtained by rolling pelvis and releasing limits at sternoclavicular joint to better approximate the observed (outermost) reach envelope.

DISCUSSION

The analysis in this paper used the Jack human model, but the results of this study indicate that any figure model that relies on kinematics and joint limits to obtain maximum seated reaches for conditions typical of civilian road vehicles will give predictions that are likely to be substantially in error. The shoulder-mobility problems documented above are due in part to deficiencies in the construction of the shoulder joints in Jack, but the majority of the discrepancy between the observed maximum reach capability and that predicted by the model is associated with pelvis rotation.

The study participants used pelvis rotation to substantially increase their reach distances. The effect was observed for all reach directions, even for vertical reaches. In vertical reaches, the participants tilted their pelves to the left to elevate their right shoulders. As illustrated above, rolling the pelvis toward a lateral reach provided a large increase in distance. Pelvis postures at maximum reach do not appear to be determined primarily by joint ranges of motion (at the hips, for example). Rather, the pelvis and torso postures are limited by the balance requirements of the task. In this study, participants held a steering wheel or table with their left hands while performing the right-hand reaches. Analyses of forces exerted at the hands and under the seat indicate that the people use a combination of a shift in seated position (obtained by rolling the pelvis) and counterbalance force at the hand to maintain control of their posture in extreme reaches (Parkinson et al. 2002).

The fact that pelvis rotation in maximal seated reaches is constrained by balance rather than joint range of motion means that a strictly kinematic approach to predicting maximum reach capability is not likely to be accurate. Instead, a model that accounts for balance-maintenance behavior is needed. Such a model could use an empirically derived motion prediction or could involve static or dynamic biomechanical calculations of balance requirements.

The current analysis suggests that kinematic methods for generating seated reach envelopes that do not include pelvis motion are likely to be conservative; the true maximum reach envelopes are probably larger, as illustrated above. Reach targets within these envelopes are very likely to be reachable by people who match the simulated figures in size and seating position. However, the conservative solution is inadequate when a control must be placed beyond the (apparent) reach envelope. Based on the current analyses, and perhaps intuitively, the human factors analyst will know that people can in fact reach beyond the reach envelopes typically generated by human models. But, lacking information about how much greater actual reach capability will be, a quantitative analysis of the suitability of a design requiring near-maximal reaches cannot be conducted.

Contemporary use of the J287 reach curves is instructive in this regard. Most vehicle designers currently use the reach curves obtained with fixed-length, highly restrictive torso belts that effectively represent reach capability without torso motion. Of course, they are well aware that modern restraint systems allow substantial torso mobility, but experience has shown that controls located within the more-restrictive curves are generally reachable by a large percentage of the driving population with acceptable difficulty. In effect, curves that represent maximum reach for a restrictive condition are used to approximate comfortable reach for a less restrictive condition. As with the conservative, kinematically generated reach envelopes, this approach has generally been effective, particularly for passenger cars.

However, the ongoing increase in the number of in-vehicle controls, particularly in commercial vehicles, is exposing the problems with this approach. With a large number of controls to be placed and a limited area within the traditional design curves (or within envelopes generated kinematically using human models) some controls must be placed in zones that are “unreachable” according to the design tools that are currently used. Once beyond the current zones, no information is available on the relative reachability of various potential control locations.

Most users of digital human models will attempt to overcome these limitations by kinematic manipulations of the figure, much as those represented above. However, lacking quantitatively valid models of postures and motions for extreme reaches, the results may not be useful. For example, a user of a digital human model is unlikely to guess the correct amount of lateral pelvis rotation when simulating a lateral reach.

Two solutions are needed. First, human figure models used for vehicle interior design should include functionality for accurate prediction of postures and motions in near-maximal seated reaches, including pelvis mobility and consideration of balance requirements. Second, SAE J287 should be upgraded to accurately represent the reach capabilities of drivers in modern vehicles with current belt restraints. Because maximum reach envelopes are not sufficient for optimizing control layouts, an updated J287 should include a model that predicts the difficulty of submaximal reaches.

ACKNOWLEDGMENTS

This research was sponsored by the University of Michigan Automotive Research Center and by the partners of the Human Motion Simulation (HUMOSIM) program at the University of Michigan. HUMOSIM partners include DaimlerChrysler, Ford, General Motors, International Truck and Engine, United States Postal Service, U.S. Army Tank-Automotive and Armaments Command, and Lockheed Martin.

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