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ABSTRACT

Standing reach envelopes are important tools for the design of industrial and vehicle environments. Previous work in this area has focussed on manikin-based (where a few manikins are used to simulate individuals reaching within the region of interest) and population-based (where data are gathered on many individuals reaching in a constrained environment) approaches. Each of these methods has merits and shortfalls. The current work bridges the manikin- and population-based approaches to assessing reach by creating population models using kinematic simulation techniques driven by anthropometric data. The approach takes into account body dimensions, balance, and postural cost to create continuous models that can be used to assess designs with respect to both maximal and submaximal reaches. Cost is quantified as the degree to which the torso is involved in the reach, since the inclination of the torso is a good measure of lower-back load and may be related to subjective reach difficulty. A simplified planar analysis is presented to illustrate the modeling approach.

INTRODUCTION

Reach assessments were among the earliest uses of digital human models (e.g., Ryan et al., 1970) and are now performed using motion analyses as well as static postures (e.g., Chevalot and Wang, 2004; Chaffin et al., 2000). For industrial task analysis, tasks are evaluated by determining whether workers will be able to reach required hand locations. For vehicle design studies, manikins are used to assess reach to controls. Seated reach capability, particularly in vehicles, has been studied more than standing reach capability, probably because seated postures are generally more constrained (Kennedy, 1964; Stoudt et al., 1970; Bullock, 1974; Asfour et al., 1978; Garg et al., 1982).

Reach capability is limited by body dimensions, but also by joint ranges of motion, balance, and strength for some tasks. Reed et al. (2003) showed that seated reach capability is not primarily limited by ranges of motion, but rather by motivation and the requirement to maintain balance. Parkinson et al. (2006) quantified the limits of balance for seated lateral reaches and applied balance as a design criterion for control placement (Parkinson and Reed, 2006a).

Reach capability is often quantified by envelopes that define a surface within which a person or population of people can reach. The most widely used example is the SAE J287 reach curves for motor vehicles SAE (2006), which define surfaces within which 95% of a particular driver population can reach under certain restraint conditions (Hammond and Roe, 1972). Note that this is not the same as the average surface within which a person who is 95th-percentile by stature (or some other dimension) can reach, but rather reflects the combined effects of body size, posture, and other factors that affect reach capability.

The population approach has been applied to more general task conditions. Standing and seated reach envelopes limited by body dimensions were quantified by Sengupta and Das (2000). The origin for these data was the proximal edge of a table placed immediately in front of participants and raised or lowered to their elbow height. Participants stood or sat with erect torsos and waved an instrumented stylus with their right hands at a range of elevations. Estimates of the 5^{th}, 50^{th}, and 95^{th} percentile reach envelopes for the male and female population were calculated from the resulting data. These data capture the effects of upper-extremity mobility, but do not include the effects of torso mobility, which is a contributor to reach capability in most tasks.

For non-vehicle applications, the prevailing approach for reach assessment is to use boundary manikins (e.g., 5^{th} percentile female and 95^{th} percentile male) to evaluate designs. The joints of the figure are exercised to assess the reach capability based on kinematic limitations. For example, Abdel-Malek et al. (2004) demonstrated a method by which the reach envelopes of any portion of the arm-as-end-effector (i.e., fingers, forearm and hand, arm and hand, etc.) can be calculated using kinematics, but this approach does not take into account behavioral variability and assumes the joint limits are rigidly defined. The limitations of such approaches have been documented (Reed and Flannagan, 2000; Parkinson and Reed, 2006b) and include misleading results and insufficient information from which design decisions can be made. It is important for designers to consider the variability in both anthropometry and capability across the breadth of the user population rather than the envelopes for a few idealized individuals. Yet, manikin-based methods remain popular because well-established population-based models are not available for standing tasks and for varying levels of postural constraint, and because a manikin-based analysis has high face validity.

There are also important limitations to the current population-based models. Current tools, such as the J287 reach envelopes, depict maximum reach capability but do not provide information on how difficult reaches within the envelope will be. Designers need a formulation of the reach capability problem that allows for the integrated consideration of capability and postural "cost", while allowing quantitative statements regarding population accommodation at any particular level of cost. Psychophysical and physiological studies confirm that not all reaches are equivalent. Reed et al. (2003) confirmed that subjective difficulty rises nonlinearly with target distance in seated reaches. Sengupta and Das (2004) studied oxygen uptake, heart rate, and muscle activity levels in three types of reaching tasks. In the first level, participants moved a box horizontally on a table, keeping their torso erect, elbow bent, and forearm horizontal. In the second level of task, the arm was extended. In the third level, the torso was involved, with participants leaning as far as they had strength to (balance requirements were not mentioned). As the rigor of the task was increased, all three metrics also increased. The addition of the torso had the largest effect.

The current work bridges the manikin- and population-based approaches to assessing reach by creating population models using kinematic simulation techniques driven by anthropometric data. The approach takes into account body dimensions, balance, and postural cost to create continuous models that can be used to assess designs with respect to both maximal and submaximal reaches. Cost is quantified as the degree to which the torso is involved in the reach, since the inclination of the torso is a good measure of lower-back load and may be related to subjective reach difficulty. A simplified planar analysis is presented to illustrate the modeling approach.

METHODS

Reach envelopes were calculated for a test population consisting of the anthropometric measures of 1000 randomly selected participants (500 males and 500 females) in the ANSUR (Gordon et al., 1989) study. The terminal reach postures for each member of the population were simulated such that torso angle, range of motion, balance, and anthropometry constraints were respected. The region of interest was stratified into horizontal levels beginning 700 mm above floor level and extending, in 25-mm increments, to 2300 mm above the floor. The minimum and maximum elevations were selected to be well beyond maximum reach boundaries for the shortest and tallest participants in the population while limiting the torso angle with respect to vertical to 60 degrees and maintaining the standing pelvis height.

Reach envelopes were calculated for each set of data (or *person*) in the sample population by simulating a reach along each of the 65 elevations. For each individual, targets higher than the maximum overhead reach, with the torso upright and the shoulder mobility and arm segments all aligned vertically, were considered unreachable. Because the kinematics for low reaches (e.g., reaching to the ground) are dramatically different than those for forward and overhead reaches, a lower bound was imposed on the region of interest. This was selected to be 20 mm below the hip level of the individual being assessed. Other values could certainly be used. All measures (and analysis and results) are relative to the tip of the toe of the individual being simulated.

The simulations were performed using a kinematic linkage modeling reach in the sagittal plane (Figure 1). The linkage consisted of eight segments with joints at the toe, ankle, knee, hip, shoulder (2), upper arm, lower arm, and hand. The foremost point of the foot was set at the origin. The two joints at the shoulder modeled "shoulder mobility"—the amount of extension movement in the shoulder towards the reach target. The segment length representing shoulder mobility was calculated as the difference between two ANSUR measures: *wrist to wall* and *wrist to wall, extended*. These are horizontal measures of the distance between stylion (wrist) and the back wall. One additional ANSUR measure quantifying the *overhead fingertip reach* was culled from the data for each individual. These values were not used to drive the kinematic linkage, but retained for validation of the model.

Segment masses and centers-of-mass were calculated using gender-appropriate parameters from de Leva (1996). The head and neck were assumed to be in-line with the torso. The mass of the head was included in the torso segment, with commensurate adjustments to

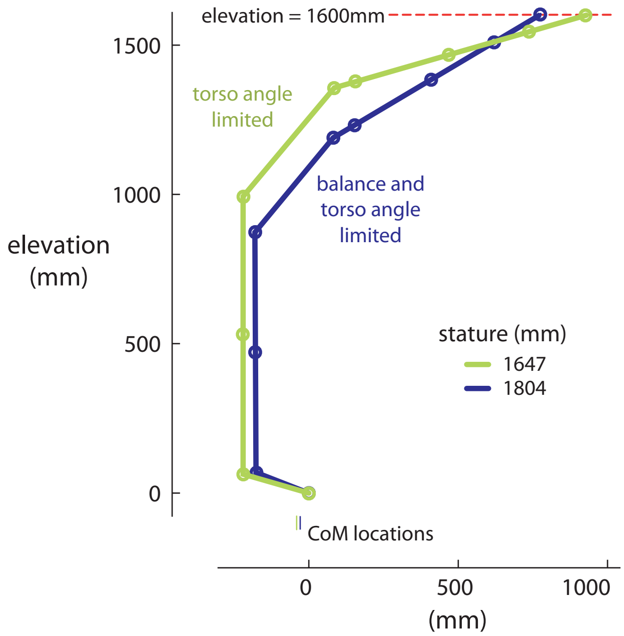

Figure 1: The kinematic linkages for two of the 1000 individuals simulated for this paper. Both are in the maximum reach configuration for an elevation of 1600 mm. The taller individual is limited by the prescribed maximum torso angle of 40 degrees. The shorter is limited by both balance and the maximum torso angle.

the torso CoM using the parallel-axis theorem (Beer and Johnston, 2006).

Sengupta and Das (2004) showed that the degree to which the torso was involved in the reach was a major contributor to the overall physiological “cost”. This is implemented in the current study by quantifying cost as *torso angle*. An acceptable cost is specified for each reach and the figure is posed such that reach is maximized while not exceeding that torso angle. Joint ranges of motion are respected, although they are assumed to be the same across individuals. Additionally, balance must be maintained. The projected CoM was restricted from moving forward of a point 15% posterior of the tips of the toes. The model was parameterized so that this value could be readily specified to accommodate more conservative limits. For example, Holbein and Redfern (1997) found that this value would be as great as 23% for reaches involving materials handling. Given the mass of the torso, its positioning generally drives activity of the balance constraint. When the torso angle was such that the project CoM exceeded the balance limitations, the hips of the participant were adjusted rearward to bring the figure back into balance, resulting in a shortened maximum reach.

For a given maximum torso angle (i.e., a selected maximum cost level), each figure was postured at each of the 65 elevations. The maximum reach for an individual at any given elevation was limited by some combination of torso angle, balance, range of motion, or body dimensions. Figure 1 shows a simulation of two individuals reaching as far as possible on an elevation of 1600mm, with a maximum torso angle of 40 degrees. The reach of the shorter (by stature) individual is limited by balance: due to their particular anthropometry, a torso inclination of 40 degrees puts the individual out of balance. The posture was adjusted by positioning the hip such that the CoM moves back behind the maximum excursion limit. Although this behavior keeps the individual in balance, it reduces their maximum reach. Determining the final posture is an iterative process in which the hip, torso, and arm positions are adjusted so that the CoM is as far forward as possible while keeping the torso at the maximum allowed angle and the hand at the correct elevation. The taller individual in Figure 1 is able to achieve the full 40 degrees of torso incline while maintaining balance.

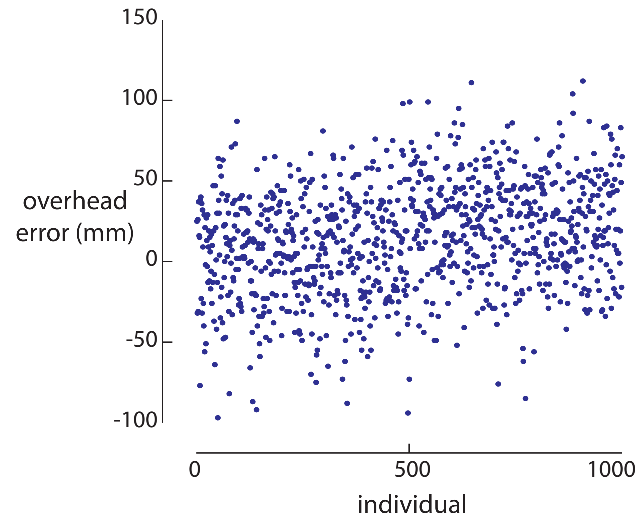

Figure 2: The error in maximum overhead reach predictions for each of the 1000 individuals. These values were obtained by subtracting the predicted value for an individual from the measured value reported in the ANSUR data.

RESULTS

The maximum excursion for 1000 individuals was predicted at 65 elevations. This was done for seven cost levels, with maximum allowable torso angles ranging from 0 to 60 degrees in 10 degree increments.

Figure 3 shows the maximum reach envelopes and hip locations for 40 people (20 males and 20 females) randomly selected from the entire sample of 1000 individuals. These envelopes were generated with a maximum allowable torso angle of 30 degrees. As expected, there is some overlapping of the envelopes across genders. Also, the shape of the envelope varies across individuals. Variations in body dimensions affect the elevations at which different constraints (torso angle, balance, shoulder range of motion) become active and inactive. The hip locations for the males are, generally, further aft than those of the females primarily because of their larger feet (recall that the origin for all the data in this paper is the toe).

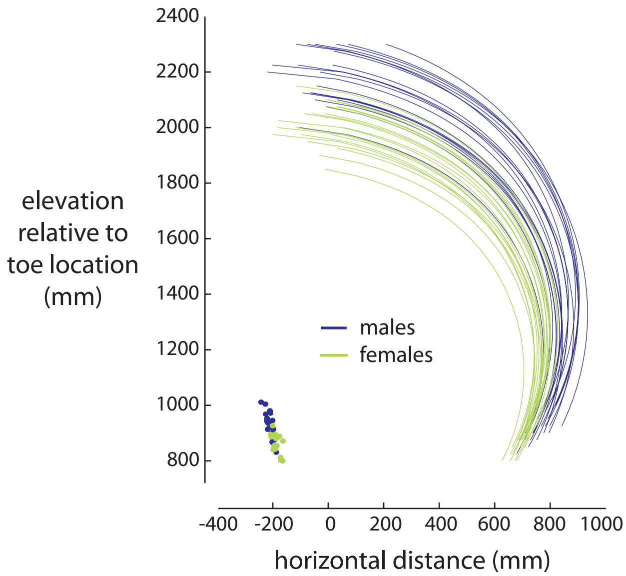

Figure 3: Maximum reach envelopes and hip locations for 40 people (20 males and 20 females) from the entire sample of 1000. Torso angle is limited to 30 degrees from vertical.

One measure of the accuracy of the predictions is the comparison of the predicted maximum overhead reach with that measured for each individual in the ANSUR data. To facilitate validation of the model, the maximum overhead reach—including the shoulder mobility—was predicted for each individual. These values were compared with the measured values of overhead fingertip reach in the ANSUR data. Figure 2 shows the error (measured - predicted) for each individual. Maximum overhead reach was predicted within 1 mm for eight of the 1000 individuals. The predicted value was greater than the measured value for 667 individuals, and the value was underpredicted for the remaining 325. The mean of the absolute value of the differences was 29.6 mm with a standard deviation of 21.4 mm. A total of 90% of the predicted reaches are within 59.5 mm of the measured values. As a percentage of the measured value, the average error is only 1.39% with a maximum of 5.62%.

A designer might wish to understand the physiological cost of requiring a reach to a particular target location as part of a task. For the purposes of this paper, torso angle is considered to be a linear predictor of this cost. Figure 4 shows the tradeoff of cost and accommodation for reaches to a particular location 800 mm forward of the toe location and an elevation of 1200 mm. As can be seen in the figure, torso inclination is required for all individuals within the sample population, but all of the individuals are able to reach the target when reaches Sengupta and Das (2004) rated as "extreme" (i.e., with the torso near maximal inclination) are allowed. There is a dramatic increase in accommodation, from 15% to 90%, as the maximum allowed torso angle is increased from 20 degrees to 40.

For a specified level of cost, the model can be evaluated for the sample of 1000 individuals. From these data, iso-

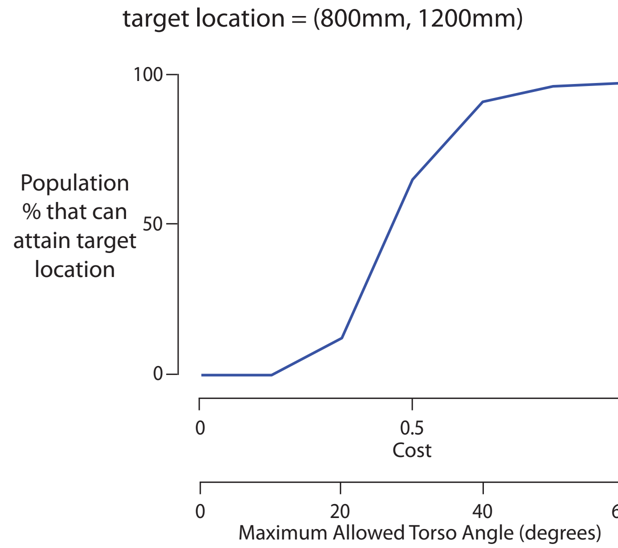

Figure 4: Cost / accommodation tradeoff curve for a reach target location 800 mm forward of toe location and an elevation of 1200 mm.

accommodation curves, such as those shown in Figure 5, can be created. These identify population accommodation levels for the entire space, subject to cost, balance, and range-of-motion constraints. These show what accommodation levels can be expected across the specified population when a reach target is placed at a particular point in space. Figure 5 identifies six accommodation levels and three levels of cost or torso angle.

Figure 6 shows how the iso-accommodation curves relate to each other as the allowable torso angle is increased across the same levels in Figure 5. Allowing forward torso mobility dramatically increases the forward distance of the maximum reach envelope, shown in the figure by the large increase in attainable distance when a 30 degree incline is allowed. The next step, to 60 degrees, does not produce as large of an increase. This is because balance is not an active constraint for any of the individuals with a 30 degree torso angle, while it *is* active for nearly all the individuals when an inclination up to 60 degrees is allowed. As the allowed torso inclination increases from 30 to 60 derees, balance becomes a concern and the posture is adjusted to maintain balance, thereby limiting their maximum reach. The benefits from the increased torso inclination limits are reduced as the reach transitions to an overhead reach, where all individuals eventually have a torso inclination angle of 0 degrees. First, as the elevation is increased, the 60 degree angle loses any advantage over the 30 degree limit and the two curves merge. Eventually, all the curves come together.

DISCUSSION

The results in this paper are not meant to supplant existing reach envelopes. Instead, they demonstrate the viability of a new approach to standing envelope prediction and assessment. Current envelopes focus on maximum

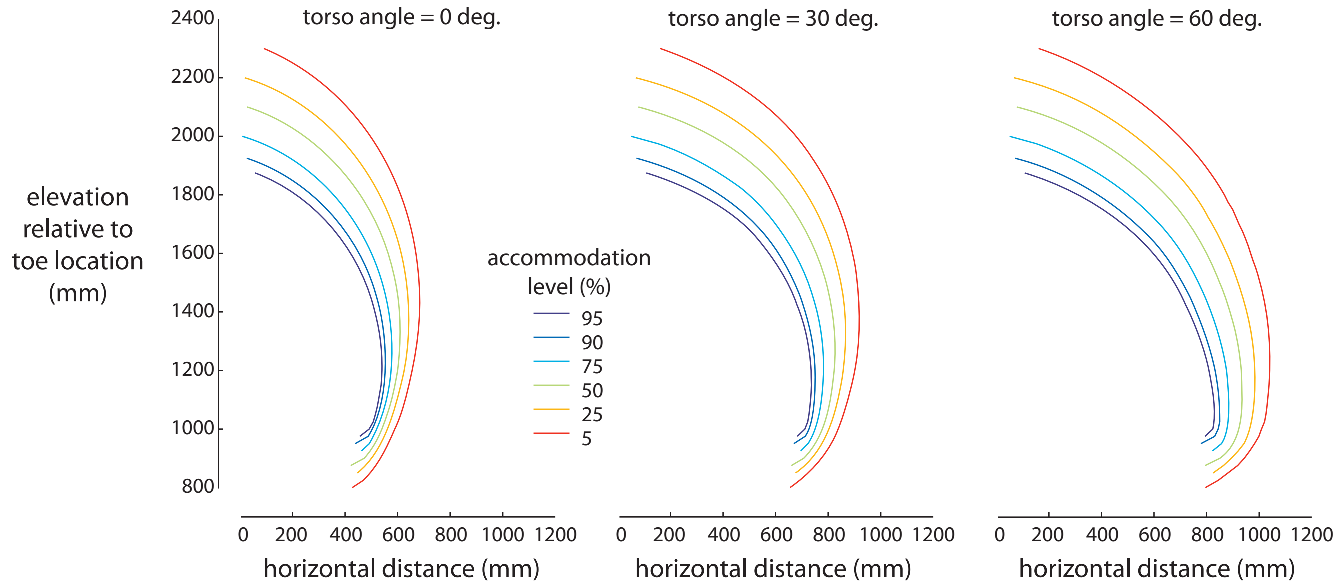

Figure 5: Iso-accommodation curves for three levels of maximum allowable torso angle: 0, 30, and 60 degrees.

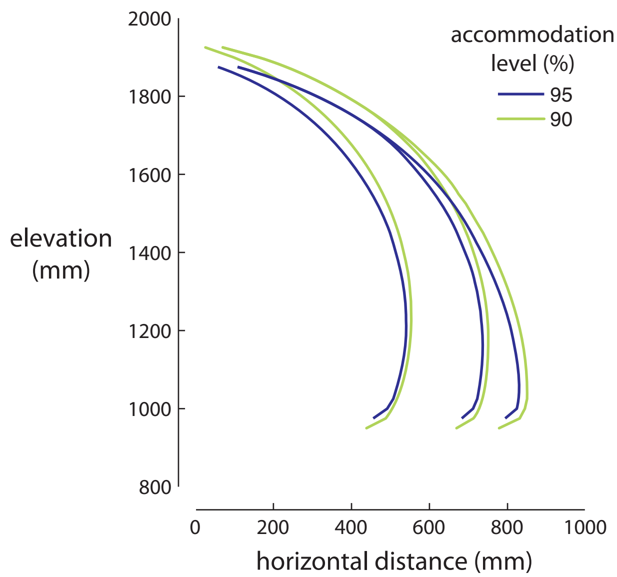

Figure 6: Iso-accommodation curves for maximum allowable torso angles of 0, 30, and 60 degrees. The curves come together as the elevation increases and the torso angle that maximize reach becomes more upright.

reach and do not incorporate a quantification of submaximal reaches or the cost associated with them. This model also roots the linkage at a global datum (the tip of the foot is in the same location for all assessments and the predictions use this same origin). The resulting accommodation and cost predictions are consequently easily applied by designers. Other envelopes are expressed relative to local reference points that vary in location for each simulated individual. An additional benefit of this methodology is the ability to readily adjust the simulation for factors such as body shape and the increased prevalence of obesity.

Although this work considers anthropometry, range of motion, and balance, other important factors should also be considered. In particular, shoulder and low back strength often limit physical capability and should be included in both the posturing and cost calculations. Additionally, the envelopes in this paper are for fingertip reaches with no force exertion. Using the methodology outlined here, accommodation predictions could readily be made for a variety of pushing and pulling tasks. In the absence of task-specific data, the recommendation from J287 of reducing fingertip reach by 50 mm to predict three-finger grasp could be used.

For simplicity, the cost model used for the current analysis was torso angle, a more complete cost function would likely be nonlinear in torso angle (due to the nonlinear effect of torso inclination on low-back moment) and would likely include a measure of shoulder moment. These values could be weighted (again, nonlinearly) depending on the duration of the reach.

Some aspects of this work were validated by comparing the predicted maximal reach with that measured in the ANSUR data. While the error was found to be small in percentage terms, the reach condition (directly overhead) reflects a condition in which only anthropometric and range-of-motion constraints are active—there are no balance concerns. As such, the favorably small errors observed indicate the linkage used and the modeling of shoulder mobility were effective, but no claims can be made about other regions of the predicted envelopes. Ongoing experiments will be used to validate other regions of the envelope.

The success of the current planar demonstration will motivates a three-dimensional implementation that takes into account the additional factors mentioned above. Critically, human behavior data are needed to validate the posture model and to provide the means for including postural variability that is unrelated to body dimensions and task variables.

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