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ABSTRACT

The ease of getting into and out of passenger cars and light trucks is a critical component of customer acceptance and product differentiation. In commercial vehicles, the health and safety of drivers is affected by the design of the steps and handholds they use to get into and out of the cab. Ingress/egress assessment appears to represent a substantial application opportunity for digital human models. The complexity of the design space and the range of possible biomechanical and subjective measures of interest mean that developing useful empirical models is difficult, requiring large-scale subject testing with physical mockups. Yet, ingress and egress motions are complex and strongly affected by the geometric constraints and driver attributes, posing substantial challenges in creating meaningful simulations using figure models. Previous approaches to simulating ingress and egress have focused on the modification of stored motions from laboratory studies to achieve complex motion simulations. This paper presents a new approach using the Human Motion Simulation Framework, an integrated, modular, hierarchical system designed to provide flexible control for simulating both common and novel movements in any human figure model.

INTRODUCTION

Early applications of digital human modeling to vehicle design focused on the layout of the driver's workstation (Porter et al. 1993). These static analyses were conceptually similar to the earliest DHM applications from the early 1970s (e.g., Ryan 1970) and primarily used the human figure model as a template to represent three-dimensional body dimensions. Beginning in the 1990s, driver layout design and analysis using figure models was aided by statistical models based on laboratory data that allowed software users to generate quantitatively realistic postures (Reed et al. 2002). The next vehicle design application to receive substantial attention was reaching by the driver to controls. Studies published in the SAE literature modeling of reach difficulty (Reed et al. 2003, Chevalot and Wang, 2004) and a variety of methods to simulate driver reach, including differential inverse kinematics (Zhang and Chaffin 2000), functional regression (Faraway 2000), and motion modification (Park et al. 2004, Wang et al. 2006). Motion modification methods have also been applied to simulation of seat belt donning (Monnier et al. 2003).

As motion measurement and simulation methods have improved, attention has turned to simulation of vehicle ingress and egress. Investigators have examined the kinematics of motions, usually for ingress (Andreoni et al. 2004) and have proposed modeling approaches (Lempereur et al. 2004; Rasmussen and Christensen 2005; Mochimaru et al. 2006; Pudio et al. 2006; Cherednichenko et al. 2006).

The most complete simulation of vehicle ingress and egress reported in the literature has been achieved using modification of selected motions from a motion capture library. The approach is described in detail by Dufour and Wang (2005) and Monnier et al. (2006). A database of motions is constructed using motion capture technology and a reconfigurable vehicle mockup. Subjects with a wide range of body dimensions are tested in a wide range of vehicle conditions. Subjective responses are gathered along with motion measurements. To simulate a motion with a particular human figure, a root motion performed by a similar-size individual in a similar vehicle configuration is extracted from the library. The motion, stored as joint angles, is mapped onto the figure. Modifications of the joint angle trajectories are necessary to account for differences in segment lengths between the manikin and the original subject, to maintain consistency with the required kinematic constraints, and to avoid collisions.

In addition to conducting simulations with individual reference motions, virtual experiments are conducted using either the full population of subjects for whom reference motions are available or a synthetic population generated by sampling from anthropometric distributions representing the target population. In the latter case, reference motions from subjects who are similar to the simulated individual are used.

The primary advantage of this motion-modification approach to simulation is that the resulting motions can have a very realistic appearance, particularly when the motion is modified only slightly. The method preserves the intra-joint coordination and frequency content that are among the critical criteria for subjective realism (Reed et al. 2005). Moreover, Monnier et al. (2006) describe an engineering assessment system in a variety of different motion types can be simulated using the same general approach.

Implementation of this approach requires considerable computational sophistication. Because the motion data are parameterized as joint angles, the data are inherently tied to a particular kinematic linkage. The crux of the method is the modification of the stored motions to meet kinematic constraints, including those imposed by the manikin linkage. In practice, modification of almost all degrees of freedom is necessary to accommodate the constraints of a particular vehicle and manikin.

A principal limitation of this approach is that the effects of important occupant covariates, such as stature, body weight, age, and gender, are not modeled explicitly. Rather, the effects are modeled by sampling, from the motion library, individuals who have the desired characteristics, such as advanced age and small stature. The disadvantages are clear when considering the need to simulate, for example, a tall woman of advanced age with a high body mass. A motion library that includes all reasonable combinations of subject covariates will be very large. For example, considering five levels of stature times three levels of body mass index times three levels of age times two genders gives 90 subjects. Even with this many subjects, each cell will only be represented by a single subject, and any idiosyncrasies of that subject's behavior will be interpreted as being related to the combination of occupant covariates represented by that individual.

A statistical analysis of movement data from the same 90 individuals would provide rich information about how motion is related to the subject covariates. However, using this information for kinematic simulation requires a modeling approach that allows motion to be predicted in part by statistical relationships observed in data. That is, prediction of how a young, heavy man would perform an ingress or egress would be based not on a single individual but on analysis of the entire dataset.

Faraway (2000) used functional regression techniques to quantify and to model the effects of subject covariates on whole-body motions. This methodology could be applied to ingress/egress simulations. However, additional modifications or constraints would be needed to ensure that kinematic requirements were met, including avoiding collisions.

Cherednichenko et al. (2006) present an alternative to the motion-modification approach that has several important similarities to the methods described in the current paper. Cherednichenko et al. acknowledge the importance of tactics, as have other groups (e.g., Monnier et al. 2006), but focus extensively on the importance of "leading body parts" in determining the whole body motion. Motion simulation is driven by the prescribed trajectories of these body parts (for example, the lead foot), which have useful characteristics that can be exploited to simplify prediction. In addition to smoothness in both the Cartesian and time domains, Cherednichenko et al report that the motions of leading body parts can be represented as planar, reducing the number of degrees of freedom that must be predicted. The hierarchical prediction structure these authors present, including the decomposition of the motion into component elements to be performed by anatomical subsystems (e.g., a lower extremity), mirrors closely the approach defined in the current work. Among the important differences, however, is that the HUMOSIM Framework uses empirical models rather than joint-moment-based approaches to predict kinematics.

The modeling approach presented in the current paper has many similarities to those described above, but differs in several crucial ways. Before presenting the new model, a more general consideration of the prediction problem will provide appropriate context.

Using DHM for Ingress/Egress Simulation

Simulation of ingress and egress using digital human models has three major objectives. First, visualization of ingress/egress behavior can be used to illustrate design issues identified by other means. Second, a human-model-based analysis could be used to differentiate alternative designs with respect to safety through biomechanical analysis. For example, the required coefficient of friction on the ground during egress could be compared for two designs. Third, human models could be used to predict subjective responses to the ingress and egress experience in passenger vehicles. Although a few studies have examined biomechanical issues (e.g., Rassussen and Christensen 2005), most of the recent papers have focused on the first and third objectives.

In this context, the experimental, modeling, and analysis structure for valid predictions of subjective responses is critical. That is, what are the necessary conditions for obtaining useful predictions of subjective responses based on a DHM analysis of ingress and egress? Is the DHM-based approach superior to alternative approaches?

Empirical Foundation -- Subjective Responses

We wish to predict the subjective responses for a diverse group of users by exercising models that relate the design variables and user characteristics to the subjective outcomes. One productive approach for predicting subjective responses is to create statistical models that relate the design variables and overall characteristics of the target population (e.g., gender ratio and stature distributions) to the distribution of subjective responses. Carefully designed human-subject experiments that obtain responses over a wide range of design variables can be used to develop statistical models to predict subjective responses. With appropriate analysis methods, distributions of responses (rather than mean responses) can be predicted (Reed and Flannagan, 2001).

The premise of much of the digital human modeling applications to ingress/egress is that a DHM-based analysis will be more sensitive to changes in vehicle geometry than, for example, a statistical model that related vehicle geometry and subject characteristics directly to subjective assessments. The presumption is that some measures of ingress or egress kinematics will be a better predictor of subjective response.

Lestrelin and Trasbot (2005) discussed and discarded the possibility of establishing useful relationships between design variables and subjective responses and instead concluded that a model based on intermediate variables (measures obtained from motion simulation) would be preferable. But no comparison of the relative performance of the two techniques was presented. Furthermore, validation of DHM-based methods requires data from a wide range of vehicle conditions. These data can be readily be used to create empirical statistical models using vehicle design parameters, rather than motion-derived variables, as predictors. For the DHM-based approach to be more useful than these models, kinematic or dynamic variables obtained from DHM simulations must be better predictors than vehicle dimensions. This has not yet been demonstrated.

Nonetheless, a DHM-based approach has some theoretical advantages that should be considered carefully. In particular, manikin-based simulations can potentially incorporate nonlinearities in behavior due to the geometry of the manikin and the environment that would be very difficult to represent in an empirical statistical model. For example, consider the behavior of a group of subjects with varying stature as the roofline is lowered. The taller subjects will be affected by the roofline before the shorter subjects, creating an interaction between stature and roof height. A regression model might represent this using an interaction term, but such a model would not likely capture the threshold nature of such an effect.

However, it does not follow that any or all kinematic variables are necessarily usefully related to subjective responses, or that a DHM-based approach will necessarily provide better design guidance than an empirical model. The most sophisticated methods for generating subjective assessments from kinematics (e.g., Dufour and Wang 2005) involve a priori judgments regarding the variables that are important and the structure of the discomfort functions. These judgments are speculative at best and rely extensively on intuition rather than data. Most importantly, these methods violate the principle of parsimony: they are considerably more complicated than is justified by data. For example, Dufour and Wang (2005) propose to use 32 joint angles to evaluate discomfort. Absent from the presentation of these methods has been a consideration of the least-complicated model that can accurately model the available subjective data.

In the current paper, we present an approach to the simulation of ingress and egress motions for purposes of ergonomic analysis. The focus of the method is on developing a general-purpose tool for predicting the distributions of subjective responses via kinematic simulation.

METHODS

Overview of Approach

The HUMOSIM Framework has been described in detail in Reed et al. (2006). The Framework algorithms are independent of any particular figure model, but have been demonstrated in the Jack human modeling system. This Reference Implementation serves as a testbed and makes the results of the research directly available to the industrial partners of the Human Motion Simulation Lab, who provide feedback on the performance.

The Framework provides a general structure for simulating task-oriented human motion, integrating modular components that perform both high-level and low-level functions. At the low level, the Framework has components that perform inverse kinematics calculations for the extremities to place the hands and feet in desired locations. These predominantly analytical methods use statistical models of human behavior to solve the kinematic redundancy problem.

For typical tasks, inputs to the Framework are desired hand and foot locations at a series of points in time. The Framework computes trajectories for the hands and feet to reach the desired locations. In some applications, the foot placements are computed automatically from task demands using statistical models based on field and laboratory data (Wagner et al. 2005, Reed and Wagner 2007). The body automatically responds to achieve the desired hand and foot placements while maintaining balance and respecting joint range of motion considerations. The joint degrees of freedom in the trunk are managed using behavior-based models developed from data gathered in studies of standing industrial tasks and seated reaches (e.g., Reed et al. 2004, Danker and Reed 2006).

In most other motion simulation approaches, motions are parameterized using joint angles, and the simulation algorithm operates primarily on joint angles. Yet, an important observation underlying the Framework approach is that end-effector trajectories exhibit considerably more regularity across tasks and subjects than do joint angles. For example, when reaching from the steering wheel to a variety of targets inside the vehicle, the hand trajectory can be described much more simply than the multiple joint trajectories in the shoulder and elbow (Faraway and Reed 2007). Consequently, end-effector trajectories are predicted prior to the computation of the joint angles required to achieve those trajectories. This is in contrast to approaches that work primarily with joint angles, with the end-effector trajectories arising as a result of computation or modification of joint angle trajectories.

The regularity of end-effector trajectories suggests that this approach is closer to the way human motor behavior is actually organized, but this approach also frees the primary functioning of the Framework from the particular joint angle definition used in a figure model. Motion simulation approaches based on stored joint-angle data (e.g., Monnier et al. 2006) are difficult to generalize to other figure models that use different joint angle definitions or even different linkages.

For simulation of most standing and seated tasks with the Framework, only hand, foot, and gaze trajectories are needed. For gait and acyclic stepping, pelvis trajectories are computed from foot placements (Reed and Wagner 2007). Ingress and egress motions include sit/stand transitions that require specification of pelvis trajectories.

Inputs

Figure 1 shows a schematic of the modeling approach for simulating ingress and egress. Vehicle design variables, such as seat height above the floor and seat height above the ground, are inputs, along with user characteristics such as gender, stature, and body mass.

A software representation of the vehicle environment is also needed. Typically this is available as vehicle design geometry, but because this geometry is often unnecessarily complex for ingress/egress simulations, schematic geometry like that depicted in can be adjusted to represent the vehicle to be evaluated and then used in simulations. An advantage of this approach is that much of the geometry markup normally needed (which geometric element represents the steering wheel?) can be avoided. One flexible approach is to overlay the real geometry with the schematic geometry, then hide the schematic geometry for purposes of illustration.

The vehicle design and user variables are used to predict the strategy or strategies that are likely to be observed. For any particular combination of vehicle and user, multiple strategies may be predicted. In practice, only the few strategies that together comprise most of the expected behaviors would be predicted. The strategies and the user characteristics are input to the motion simulation algorithms outlined in Figure 1. Strategies are defined by specified sequences of component motions. For example, one ingress strategy might begin with the right foot lifting from the ground before the hips enters the vehicle, while another may maintain the right foot on the ground until the hips have contacted the seat. The strategy completely defines the component elements (i.e., how many discrete motions are made with the right foot) and prescribes certain aspects of the relative timing. Generic motion patterns for the pelvis and torso are also part of the strategy description.

Prior to motion simulation, the user's seat and steering wheel adjustments are predicted, because these represent important constraints on the motion. In the current implementation, seat position prediction is performed using the SAE J4004 Seating Accommodation Model (Flannagan et al. 1998) and normal driving posture is predicted using the Cascade Prediction Model (Reed et al. 2002) implemented in Jack's Occupant Packaging Toolkit. In addition to a valid representation of the effects of driver package on posture, one advantage of these statistical approaches to posture prediction is that the effects of realistic variation in driving posture and component adjustments can be readily simulated (Parkinson and Reed 2006).

The software user must also specify two types of obstacles in the environment: those that may be contacted and those that should not be. In normal ingress and egress, it is common for drivers to contact the seat, steering wheel, and rocker panel with various body parts. Contact with the roof is uncommon as part of a normal strategy. Because the seat is conformable, avoidance of bolsters may not normally be a priority. However, avoidance of the A-pillar, B-pillar and upper door opening is normally required for realistic simulation. Similarly, avoidance of the door trim, rocker, sill, pedals, and footwell trim is normal required. Many drivers contact the steering wheel with their thighs while getting into and out of the vehicle, so contact with minimal intersection in that area is realistic.

The locations of handles and other grasp targets must also be specified. Currently, the simulation uses an interior door handle target that must be specified by the user. The user must also specify the geometric objects in the simulation environment that represent the door opening, door trim, and steering wheel. In practice, it is convenient to use simplified geometry to represent these components rather than the actual vehicle geometry. For example, a simplified, low-resolution disk representing the steering wheel can be placed invisibly at the same location as a detailed steering wheel. Using simplified geometry to "mark up" the environment speeds up the creation of simulations, allows rapid parametric experimentation, and simplifies collision avoidance calculations.

While one could in principle develop models that incorporate more detailed user characteristics as predictors (for example, hip range of motion), this detail is not useful for simulation unless the distributional information for the variable is available for the target population. For most vehicle design applications, only distributions of gender, stature, body mass, and age are available, so these predictors are most commonly used. Note that the effects of age, in particular, are difficult to quantify and to model well. Of course chronological age is only indirectly related to the functional deficits that are of interest. A typical experimental finding is that performance variance increases with age, so that the mean decrement is smaller than the change at the upper tail. One must exercise considerable care in extrapolating age effects observed in a laboratory setting to the general population, because sampling bias can be expected to differ with age. In particular, older people with substantial functional deficits are probably less likely than more-fit older people to volunteer to participate. One advantage of using statistical models rather than example motions to characterize age effects is that adjustments can be made for sampling bias.

Strategies

People often exhibit qualitatively different behaviors when performing a task. Researchers have characterized these discrete behaviors as *strategies* that represent different approaches to accomplishing the goals of the task. Examples include stooping vs. squatting when performing lifting tasks (Park et al. 2005), donning a seat belt with the left or right hand (Ebert and Reed 2002, Monnier et al. 2003), using two or three steps to turn while picking up a load (Wagner et al. 2005), and getting into a vehicle leading with the hips, foot, or head (Monnier et al. 2006). From a modeling perspective, prediction of strategy is an important first step in simulation, because the "average" between two different strategies can be an implausible or even impossible motion (Park et al. 2005).

The prediction of human movement strategies is a complex topic, but two observations are important here. First, strategy for ingress and egress is associated with both design variables and subject characteristics in an interactive way. For example, shorter-stature people may be more likely than taller people to choose a head-first strategy for a given vehicle door opening. However, decreasing the available space will cause more of the taller people to use a hip-first strategy, until for a very small door opening nearly all people will use the hip first strategy. Hence, while taller and shorter people may have preferences that are usefully associated with their body size, the preferred strategy is dependent on the environment.

Second, strategies are not deterministically related to either vehicle or subject characteristics. Rather, changes in the composition of the target population or in the vehicle design will change the distribution of strategies that are observed, but most plausible configurations and populations will produce a range of behaviors.

A consequence of the importance of strategies for ingress and egress is that a useful system for DHM-based analysis of vehicle ingress and egress must be able to predict the distribution of behaviors for a particular population and design and must also be capable of simulating a range of different behaviors independent of subject characteristics.

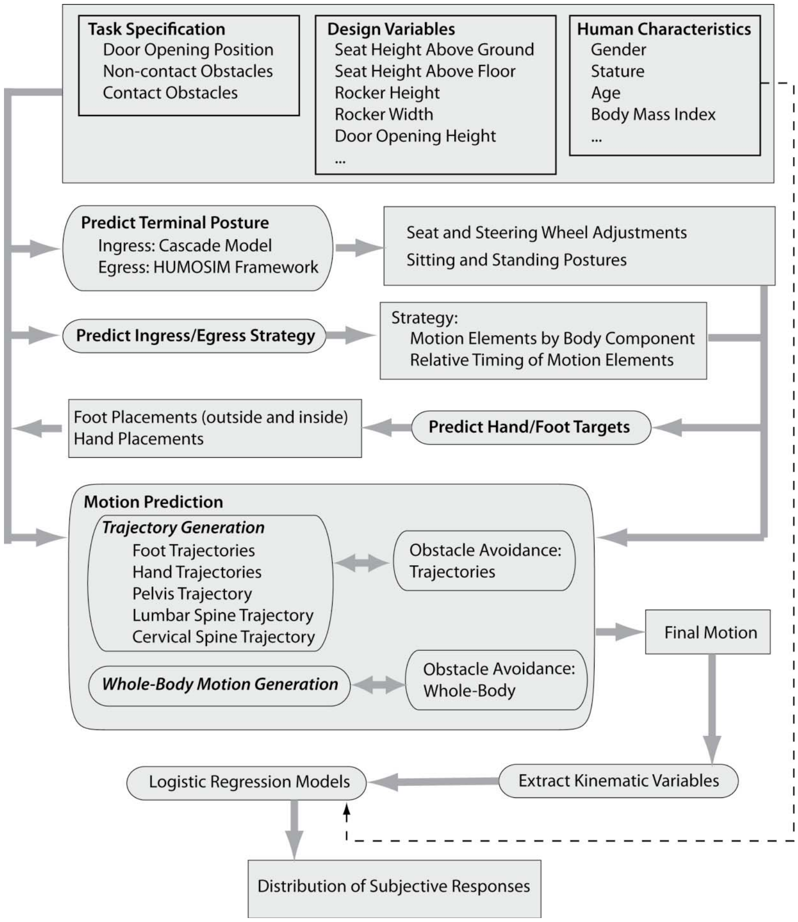

Figure 1. Schematic of prediction process.

Trajectory Generation

End-effector trajectories in the HUMOSIM Framework are represented using Bézier curves for translation and modified spherical linear interpolation (slerp) for orientation (Faraway and Reed 2007). In practice, any continuous parametric curve could be used for Cartesian trajectories, but analysis of hand, foot, and pelvis trajectories has shown that Bézier curves provide a good balance of efficiency and accuracy. Note that arbitrarily complex end-effector motions can be generated by chaining multiple motion segments represented by Bézier curves.

Preceding each trajectory prediction is the generation of 6-degree-of-freedom (position and orientation) targets for both ends of the trajectory. For ingress, the starting positions of the feet on the ground plane are predicted using statistical models generated from laboratory motion capture data. These positions are functions of the selected strategy, vehicle design variables, and user characteristics. Foot targets on the floor inside the vehicle are computed based on the same inputs. These targets are selected based on observations from laboratory studies, and thereby include consideration of the effects of collision avoidance on the lower-extremity trajectories. In the Jack human modeling system used to demonstrate the Framework, foot targets are typically represented using footprint glyphs. Figure 2 shows footprint glyphs used as targets for an ingress simulation. The Bezier trajectories, computed to provide collision-free paths for the feet over the sill, are also shown.

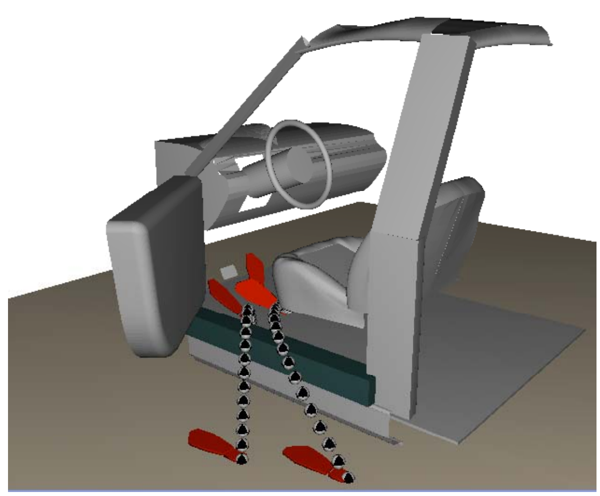

Figure 2. Foot targets for an ingress simulation, showing trajectories computed to clear obstacles.

Translation and orientation trajectories connecting each start/end pair of foot targets are generated using a default model for each strategy. The default trajectory is then checked for end-effector collision and modified as necessary. For example, the trajectory of each foot is checked for collision with the seat, door, and door opening and is modified to avoid them. The modification proceeds using a gradient-based search algorithm based on the observed postural adaptations appropriate for each strategy. People using a foot-first strategy to enter a vehicle are observed to alter the foot orientation in a toe-first manner to avoid collision with the door, whereas those using a hip-first strategy are more likely to rotate into a heel-first posture to avoid collision.

Pelvis trajectories are generated to clear the B-pillar and to provide a collision-free trajectory for the lower torso. The default pelvis trajectory for each strategy is based on observations of the patterns of motion and is subsequently modified, if necessary, to avoid collision.

Whole-Body Motion Simulation

The collision-free hand, foot, and pelvis trajectories generated in the previous step are then used as inputs to the whole-body motion simulation. The upper- and lower-extremity modules compute joint angles to follow the trajectories. Additional motion modifications are performed to avoid interpenetration of the thighs and steering wheel.

The most complex part of the motion simulation occurs in the torso. The computation of the head location includes parameterized models for the lumbar and cervical spine motions associated with each strategy. For example, with a hip first strategy, the cervical spine bends first to the right as the pelvis enters the vehicle, then to the left as the head enters. Adjusting the parameters of these strategy-specific spine motion models provides a wide range of torso behaviors. During whole-body motion simulation, the lumbar and cervical spine motions are adjusted to avoid head and torso contact with the door and door opening. Note that because the strategy determines the basic (potentially complex) motion pattern, only one or two parameters are needed to adjust the spine motion, allowing a simple and fast gradient-based optimization approach to be used.

The hierarchical structure used for motion generation (target locations followed by trajectories followed by whole-body simulation) provides efficient simulation with local control. For example, collision avoidance at the foot affects the pelvis trajectory only at the level of strategy selection; the pelvis trajectory is not modified in response to foot interference. This local control is similar to the "chains" principle described by Monnier et al. (2006), in which the joints to be modified differ according to the active constraint.

Extracting Kinematic Measures

Once the motion is predicted, variables can be extracted for use in predicting subjective responses. Many approaches have been proposed for "scoring" a posture or motion. Most are based on the assumption that deviations from some "neutral" joint angle are associated with discomfort. Dufour and Wang (2005) applied discomfort criteria to 32 joint angles, using a priori assumptions regarding the discomfort costs of deviations from the middle of the joint range of motion. As discussed earlier, complex discomfort models of this sort are very difficult to validate, in spite of their intuitive appeal.

The approach used here is to compute subjective responses only from kinematic variables that have been shown to have a statistically significant association with subjective outcomes. In this case, the horizontal and vertical displacement of the pelvis and the vertical offset of the foot trajectory from the vehicle floor are used. A measure of torso inclination with respect to vertical or cervical spine deviation from neutral would be intuitively appealing ways to evaluate the door opening restriction, but neither has been found to be statistically significantly related to subjective responses in the currently available data.

Application

The methods described here have been applied across a range of vehicle geometry. The simulations have been aided by the use of a vehicle mockup (seen in Figure 2) that is programmatically configurable across a large range of dimensions. The simulation has been tested for SAE H5 values from 400 to 700 mm, seat heights (SAE H30) from 200 to 400 mm, A pillar angles between 20 and 65 degrees, and roof heights (re H-point) from 650 to 1000 mm. Some combinations of these conditions are more extreme than those encountered in production vehicles. One advantage of this simulation approach is that it can readily be applied to any size figure, with the appropriate modifications made automatically. In application testing, simulations have been conducted with manikins ranging in stature from 1500 to 2000 mm. The simulation of obese drivers, which may be important in some vehicle segments, has not yet been conducted, due to the limitations in representing the body shapes of obese individuals in Jack.

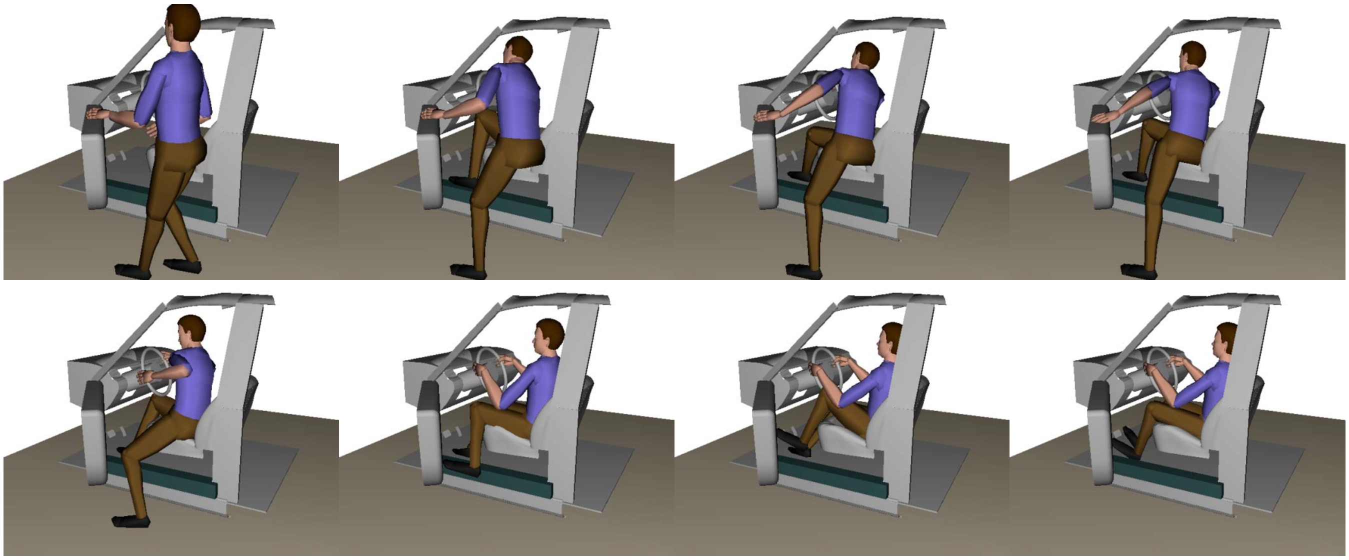

Figure 3. Head-first ingress strategy in a high-seat-height vehicle.

RESULTS

Strategies and Sample Simulation Results

The current implementation models two strategies: a head-first strategy in which the head enters the vehicle before the hips, and a hip-first strategy that is much more common in passenger vehicles. Figure 3 shows frames from a simulation of the head-first strategy into a high seat height vehicle. The simulation captures the torso and head motions needed to clear the roof line. The timing of the motions takes into account the need for continuous support, particularly the need for both a foot and hand placement inside the vehicle prior to lifting the pelvis. Note the foot trajectories have been computed to clear the sill (shown in green in the figure).

Figure 4 shows a more-common hip-first ingress strategy with a low seat height vehicle. Substantial neck and torso movement are needed to avoid head contact with the roof and the top part of the door, but the movement directions are opposite those required for the head-first strategy. The cervical spine motion shows the characteristic two-phase pattern for this type of ingress, with the neck initially bending to hold the head closer to vertical, then shifting to an outward bend to allow the head to clear the roofline. The right-leg kinematics are planned to clear the steering wheel, with an intermediate foot target to the left of the accelerator pedal.

Predicting Subjective Responses

Validating kinematic scoring systems is challenging, because it is difficult to design an experiment that will exercise each individual through a reasonable range of the potential predictors. This could require scaling the physical environment proportional to the subject's body dimensions, as has been done to address this issue for seated reach assessment (Reed et al. 2003). The latter study concluded that postural measures (joint angles) are only relatively weakly related to subjective ratings of reach difficulty.

Currently, the Framework scores ingress based on three characteristics of the pelvis trajectory and one measure of foot trajectory. The vertical and horizontal change in pelvis location between the standing and seated postures are the best predictors of ingress and ratings in the available data, as they capture the effects of seat height above ground and the lateral position of the seat with respect to the rocker. Two other variables are computed but have not yet been shown to be significantly related to subjective responses. The vertical adjustment to the default foot trajectory required to clear the sill and the adjustment to the default pelvis orientation with respect to vertical needed for the head to clear the roof are plausibly related to rocker height above the floor (SAE H130) and door opening height.

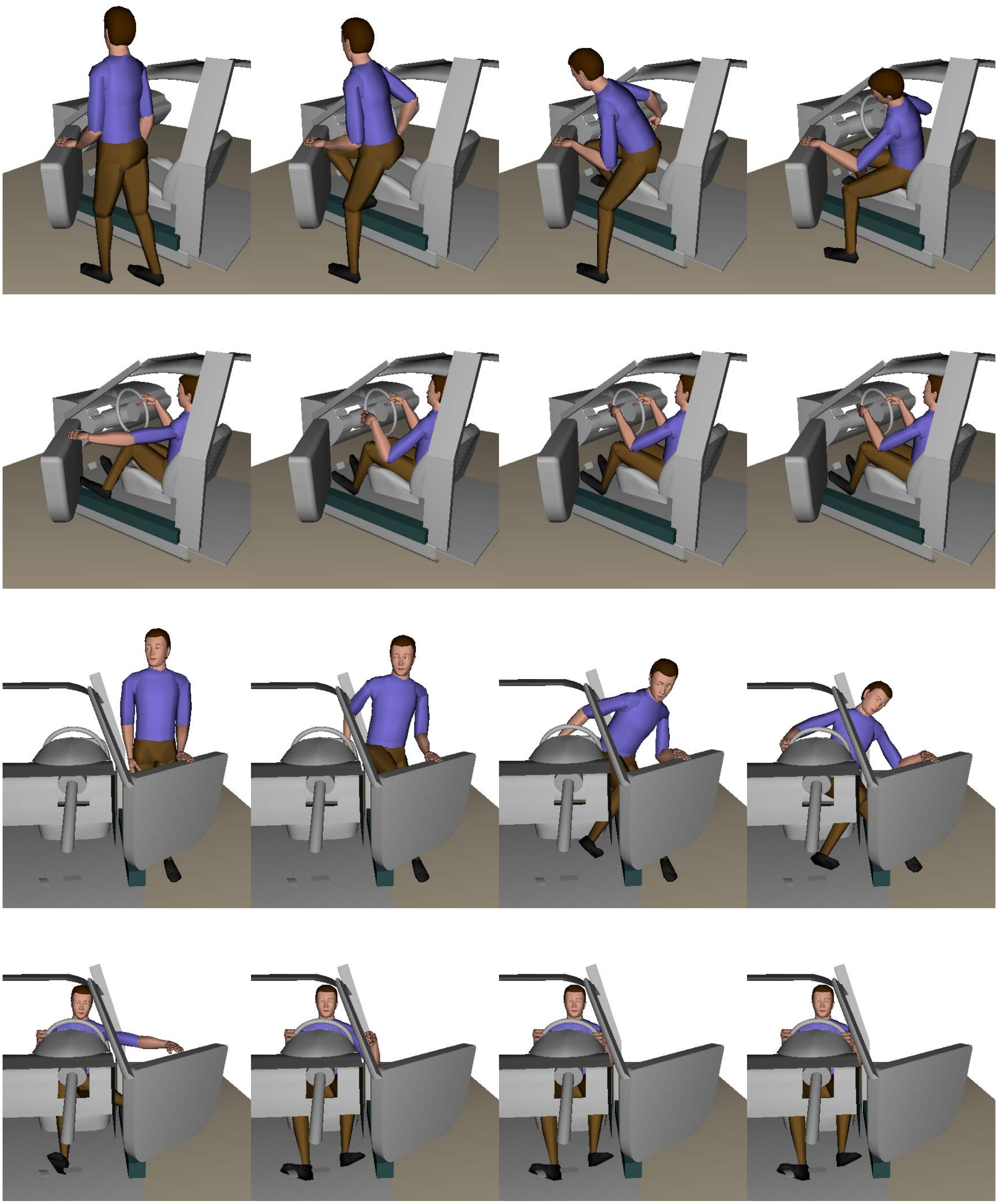

Figure 4. Frames from an ingress simulation using hip-first strategy.

DISCUSSION

Strengths of the Framework Approach

One important advantage of the Framework approach is that it is accomplished using the same underlying modeling structure that has been applied to simulating a wide range of task-oriented human activities, including walking and acyclic stepping, seated reaches, and a wide range of standing reaches, object transfers, and force exertions typical of industrial tasks (Reed et al. 2006). This advantage is shared with some other systems that have applied to ingress/egress, including the REAL MAN project (Lestrelin and Trasbot 2005) and Dhaibaman (Mochimaru et al. 2006). Of course, the value of this integration is dependent on the scope of activities one is interested in simulating with a particular tool.

The HUMOSIM Framework algorithms have been developed to function independent of any particular human model linkage. The algorithms have been demonstrated in Jack, but the near-independence of joint-angle and kinematic-linkage definition means that they can be generalized more easily than most algorithms. In contrast, systems in which joint angles are the primary control variables (rather than end-effector trajectories)

The Framework incorporates a mid-level control scheme in which goals are set at the component level, e.g., right upper extremity or gaze. Because all simulations are ultimately expressed at this level prior to execution, substantial changes in a simulation can be made with minimal effort. For example, simulations of passenger ingress can be created trivially by changing the task assignments for the hands. This flexibility is important for assessing vehicle designs that are substantially different from those for which a large amount of data is available. Of course, such simulations would need to be validated before quantitative decisions could be based on them, but often a qualitative analysis can be valuable, particularly early in a design process.

Another important aspect of the Framework approach, which it shares with the methods described by Cherednichenko et al. (2006), is that it relies on predictions of end-effector trajectories rather than joint angles. Hence, the model can be developed and validated using relatively poor-quality, sparse motion-capture data. In contrast, methods that are based on motion modification typically require unusually clean and complete motion data. This requirement leads to artificial test conditions, with the realism of the environment sacrificed to facilitate motion capture.

Weaknesses

The most important weakness of the Framework approach parallels the greatest strength of the motion-modification approach: subjective realism. Achieving subjectively realistic motions with the Framework requires careful tuning of velocity profiles for the end effectors, although in practice this needs to be done only once for each strategy. In contrast, motion modification methods tend to produce visually realistic motions that benefit from preserving “life-like” idiosyncrasies of the performance. However, visual realism, particularly the smoothness of the motions, is less important for ergonomic assessment than quantitative accuracy on critical parameters and accurate representation of the effects of subject and vehicle variables on these parameters. The performance of the Framework approach on those measures is limited only by the underlying experimental data.

The model formulation also assumes that end-effector trajectories, in particular the hands, feet, and pelvis, can be predicted independently. While in the limit this is unlikely to be true (severe restrictions on foot movements would be expected to affect the pelvis, for example), in practice this assumption appears to be reasonable, and indeed other approaches have incorporated this assumption (Monnier et al. 2006).

The current ingress/egress implementation in the Framework does not attempt to provide a complete, general-purpose collision avoidance solution. For example, self-collision is neither detected nor avoided. These collisions are visually jarring but are unlikely to have a meaningful effect on the design evaluation. Similarly, avoiding interpenetration between the steering wheel and thighs is challenging for any algorithm, but may ultimately be of little importance, provided that the overall kinematic effect of the steering wheel obstruction is represented reasonably well.

The approach to collision avoidance in the Framework ingress/egress implementation focuses on capturing the primary effects of environmental obstructions on the motion. Hence, the algorithm focuses on collision-free paths for the feet, head, and hips, with no consideration for the hands. The advantages for computational speed seem to outweigh the disadvantages of occasional visual anomalies that have no effect on the design evaluation.

Predicting Subjective Responses

Fundamentally, the validity of the DHM-based approach is dependent on the existence of documented relationships between kinematic or dynamic variables (i.e., those intermediate variables obtainable from a 3D human motion simulation) and subjective responses. While other researchers have proposed relationships between joint angles and discomfort (e.g., Kee and Karwowski 2003), these have not been validated for complex motions. Given the typically large variation in subjective evaluations of ingress or egress for people with similar body size (and hence similar postures during the motion), it seems implausible that the relationship between most joint angles and overall ratings are strong and independent (i.e., additive). Hence, a model that allows a large number of joint degrees of freedom to influence the predicted rating is nearly impossible to validate and likely to lead to spurious conclusions.

A more sensible approach would be to conduct a multivariate statistical analysis to determine which kinematic variables best predict the subjective responses. To be useful, though, such an analysis must be based on a relatively complex experiment in which vehicle geometry is scaled to participant body dimensions. Otherwise, joint angles will be correlated with body size and the (potentially) separate effects of (and interactions between) body size and posture will not be discernable. Again, this argues for a simpler model for predicting subjective responses, one that is no more complex than is justified by data.

Stochastic Simulation

The HUMOSIM Framework is designed to facilitate stochastic simulation. It is axiomatic that human movements vary both within and between individuals, but most simulation methods are deterministic. For some analyses, a stochastic simulation approach that randomly samples motions from the space of possible motions, given the vehicle geometry and a description of the population is desirable. Monnier et al. (2006) describe a virtual population approach to simulation, in which body dimensions are sampled from a multivariate anthropometric distribution to construct manikins. But simulation of the movement variability is also important. The Framework implementation of ingress/egress simulation is designed to allow random variation in critical variables, such as the foot placements inside and outside of the vehicle. The variance is drawn from statistical analysis of movement data.

Future Work

The greatest need in this area of human simulation is for improved models of subjective responses. The sophistication of the kinematic simulations far exceeds the quantity and quality of the subjective data. Ultimately, the primary output from DHM analyses of vehicle ingress and egress are predictions of the distribution of responses on a questionnaire. Additional benefit can be gained from an examination of swept volumes during relatively unconstrained motions, but costing interference with these volumes still requires a model of subjective responses. Most previous studies have examined a relatively small number of vehicle configurations, eliciting a fairly narrow range of kinematic responses. Future studies should focus on expanding the range of test conditions for which both subjective data and occupant kinematics are available.

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