SAE TECHNICAL PAPER SERIES

2006-01-2365

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Digital Human Modeling for Design and Engineering Conference
Lyon, France
July 4-6, 2006

SAE International™

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-0790 Web: www.sae.org

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

Printed in USA

2006-01-2365

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ABSTRACT

The potential of digital human modeling to improve the design of products and workspaces has been limited by the time-consuming manual manipulation of figures that is required to perform simulations. Moreover, the inaccuracies in posture and motion that result from manual procedures compromise the fidelity of the resulting analyses. This paper presents a new approach to the control of human figure models and the analysis of simulated tasks. The new methods are embodied in an algorithmic framework developed in the Human Motion Simulation (HUMOSIM) laboratory at the University of Michigan. The framework consists of an interconnected, hierarchical set of posture and motion modules that control aspects of human behavior, such as gaze or upper-extremity motion. Analysis modules, addressing issues such as shoulder stress and balance, are integrated into the framework. The framework encompasses many individual innovations in motion simulation algorithms, but the primary innovation is in the development of a comprehensive system for motion simulation and ergonomic analysis that is specifically designed to be independent of any particular human modeling system. The modules are developed as lightweight algorithms based on closed-form equations and simple numerical methods that can be communicated in written form and implemented in any computer language. The modules are independent of any particular figure model structure, requiring only basic forward-kinematics control and public-domain numerical algorithms. Key aspects of the module algorithms are "behavior-based," meaning that the large amount of redundancy in the human kinematic linkage is resolved using empirical models based on laboratory data. The implementation of the HUMOSIM framework in human figure models will allow much faster and more accurate simulation of human interactions with products and workspaces using high-level, task-based control.

INTRODUCTION

Digital human figure models (DHM) are now widely used for ergonomic analysis of products and workplaces. In many organizations, DHM software is a tool of first resort for answering questions relating to physical interaction between people and objects. Yet any objective appraisal of the technology would conclude that the current reality of DHM software capability is far from the promise of a "digital human" that can interact realistically with products and environments. This paper is focused on efforts to improve the ability of DHM software to simulate physical posture and motion. Nearly every other aspect of DHM functionality also warrants improvement, including body shape representation, strength simulation, and cognitive function, but posture and motion are critical to the primary applications of DHM to the assessment of physical tasks.

Posture simulation is as old as computerized manikins, because the manikin must be postured before an analysis can be conducted. Important early work was performed by Ryan for the U.S. Navy (Ryan 1970). Porter et al. (1993) summarized applications of digital human models in vehicle ergonomics during the early years of personal computers, at which time few of the current commercial DHM software tools were in use. Chaffin (2001) presented case studies of the expanding use of DHM for both product and workplace design and assessment. As evidence of the importance of posture and motion simulation, dozens of papers in the SAE literature and in other forums have presented a wide variety of methods for human simulating postures and motions, including multiple-regression (Snyder et al. 1972); analytic and numerical inverse kinematics (Jung et al. 1995; Tolani et al. 2000); optimization-based inverse kinematics (Wang and Verriest 1998); differential inverse kinematics (Zhang and Chaffin, 2000); functional regression on stretch-pivot parameters (Faraway 2000); scaling, warping, and blending of motion-capture data (Park et al. 2002; Faraway 2003; Monnier et al. 2003; Park et al. 2004; Dufour and Wang 2005); and many forms of optimization (e.g., Flash and Hogan, 1985; Englebrecht 2001; Marler et al. 2005; Wang et al., 2005).

Every software manikin used for ergonomics includes some inverse kinematics (IK) capability for posturing. Given a particular target in space for a hand or foot, the software will calculate the angles of the joints of adjacent segments to attain the goal. The methods for performing these calculations vary widely. An extensive literature on inverse kinematics has emerged from the field of robotics, because placing an end effector at a particular location in space, or tracing a path, is an essential function of industrial robots. However, inverse kinematics alone produces a feasible posture, not necessarily a likely or accurate posture. In some cases, as in the RAMSIS software, the joint angles are calculated to maximize the probability of the joint angles relative to a stored set of joint-angle probability distributions. When applied in task situations similar to those used for collecting the underlying data, this approach yields postures that have the most likely joint angles for similar size people while meeting the kinematic constraints. Researchers have used a wide variety of weighting and optimization techniques to solve the redundancy problem, including minimizing joint torques (Uno et al. 1989), minimizing the rate of change of segment acceleration (Flash and Hogan, 1985) minimizing joint deviations from neutral (Marler et al. 2005), and maximizing strength as a function of joint angles (Zacher and Bubb, 2005).

A researcher in this field might have concluded 10 years ago that the problem of human motion simulation was likely to be solved very quickly because of the rapid increase in computer animation in entertainment. The extremely time-consuming nature of traditional keyframe animation creates a large financial incentive to develop predictive tools. Yet, what has evolved to meet the ever-growing need for commercial animation is not motion prediction but the capture and editing of specific human motions. In feature films, commercials, and video games, nearly every movement of a computer-generated character is produced by playing back motion data obtained from a human actor, possibly after modifying or "warping" the motion. The seemingly insurmountable advantage of motion-capture data over motion prediction for commercial animation is the obvious naturalness of the motion. When the movie director knows that a particular character will perform a particular motion with a particular prop, or when the physical repertoire of a game character is limited to a handful of actions, motion capture (with sophisticated editing and modification software) meets the need. Hence, relatively little effort has been directed toward the realistic prediction of novel human motions.

The use of motion capture for ergonomics analysis has also increased in recent years as the tracking systems have become less costly and more capable. The utility of motion-capture data for performing ergonomic analyses is bolstered by the use of motion-modification algorithms to retarget motions to different human figures and to alter end-effector targets (e.g., Park et al. 2004). But motion-capture has substantial disadvantages as a general-purpose tool for ergonomics analysis, particularly for simulation of industrial and maintenance tasks. The scope of potential motions is so varied, and the worker population so diverse, that new motion-capture data are often needed to simulate tasks of interest. Motion capture for ergonomics requires expensive equipment and fabrication of appropriate props to represent the environment of interest. The time required to analyze tasks via motion capture limits its application for proactive ergonomics early in the design of a product or work task. Yet improving on the utility of motion capture by motion simulation requires a deeper understanding of the organization and control of human motion.

In the large literature devoted to posture and motion simulation, few papers have presented comprehensive systems that could provide robust capability for large range of tasks. Considerable progress in this area has been due to the leadership of Badler at the University of Pennsylvania (Badler, 1993) including the original development of the Jack human model. More recently, Badler et al. (2005) presented a vision for a comprehensive system of control of avatars implemented as the Human Model Testbed. The approach builds on other developments including Parameterized Action Representation (Balder et al. 1999) and recent progress in obstacle avoidance (Zhao et al. 2005). This work has found both direct and indirect application in the developments reported in the current paper. Commercial software developers are also addressing the need for integrated, high-level control of human simulations. Raschke et al. (2005) described the Task Simulation Builder, an approach to task programming in the Jack™ human modeling system that incorporates aspects of the Parameterized Action Representation.

A primary motivation for the development of the research reported in this paper is the large disparity between the human model functionality reported in the literature and the capability of commercial human models used for ergonomic analysis. The promise shown in the research laboratories has been slow to find its way onto the user's desktop. This disappointing lack of progress is not due to a lack of initiative or commitment on the part of commercial vendors, but rather is due primarily to the way that the research is structured and communicated. It is not enough to develop a good method for accomplishing the goals of rapid, accurate posture and motion simulation. Rather, it is necessary to accomplish those goals in a manner that conforms to the realities of the development and usage of ergonomics software. This means that the algorithms and the organization of the entire approach to motion simulation and analysis must be developed with the requirements of commercial software implementation in mind.

Application Context for Ergonomics Analysis and Consequences for DHM Functionality

The application of human figure model software to ergonomics analysis differs in important ways from other applications of DHM technology. The goals of ergonomic analysis, its methodologies, and the software environments in which it is performed create demands for functionality that differ substantially from those of other DHM applications, such as entertainment, medicine, and training. Ergonomic analysis is intended to produce quantitative answers to questions posed early in the design of human-hardware systems, such as:

- What percentage of operators can reach a proposed control and exert the required hand force?
- Can a box of parts be lifted by most workers without exceeding established limits for low-back loading?
- Will most workers be able to reach into a confined space to install a part?
- Can an acceptably high percentage of operators see an important target in front of a vehicle while operating the primary controls?

The commonalities among these typical questions highlight some of the important characteristics of ergonomic analysis that different from other DHM applications.

1. Ergonomics is usually concerned with populations of people, not particular individuals. DHM software for ergonomics must be capable of performing any particular analysis with any of an infinite number of different human representations. Often gender and body dimensions are the only variables used to specify different figure models, but strength, range of motion, and other factors should also be manipulated. In contrast, motion simulations for entertainment and training usually need only be applied to a single figure, the dimensions of which are known in advance.

2. The tasks to be simulated for ergonomic analysis are known in advance and usually take place over relatively short periods of time (usually a few seconds). Longer task sequences (such as industrial workcell activities) can be decomposed into task elements for simulation purposes, and can be scripted in advance. For entertainment and training, realism requires that the characters react to situations, so it is not possible to script all actions in advance and artificial intelligence to select character behaviors is important.

3. Ergonomics is used as part of an engineering process to develop and to improve the design of products and work environments. To function as an engineering tool, the ergonomics software must produce repeatable and reproducible results. A single analyst performing an analysis on two separate days must achieve approximately the same results, and two analysts using the same software must achieve the same results. Moreover, the results must be quantitatively accurate, so that the engineering decisions made using the results of the analysis will be correct. In entertainment and training, visual realism is much more important than repeatability or quantitative accuracy.

The information-technology environment in which ergonomic analysis is performed using DHM also imposes some requirements on the technology. The ergonomic analysis questions above demonstrate that DHM tools are used to analyze the *interactions* between people and products and environments. Hence, the simulated human and the system to be evaluated must reside in the same virtual space, i.e., a computer graphics system. In the early years of human modeling, virtual humans were constructed within computer-aided design systems, in part because those systems provided the best access to computer graphics. During the 1990s, several new standalone DHM software systems were developed. The product or workstation geometry with which the virtual humans would interact was imported after being exported from the systems used to create it. This process, although technically feasible, has proven to be a major impediment to more widespread use of human modeling. The acceptance of human modeling as a legitimate engineering tool, on par with finite-element stress analysis or multi-body dynamics, requires that the virtual humans go to the geometry, rather than the geometry coming to the virtual humans. DHM ergonomics functionality must be integrated into the large data creation, management, and analysis systems used by major corporations.

A consequence of the need to embed DHM technology in large-scale product and workplace design and analysis systems is that the DHM technology must be relatively lightweight. The code required to create and use the virtual humans should be small, including any needed databases. The system should execute quickly, on typical computer hardware, and the system should function without special-purpose processing code that must be licensed or maintained separately.

The context of ergonomic analysis also indicates that the ideal user for DHM is the creator of the product or workplace, who is by definition not an expert in ergonomics. Well-trained experts will be needed to set design criteria and to perform detailed analyses, but the potential of DHM to improve the design of systems for human interaction requires that the virtual humans interact with the product very early in the design cycle. In the case of manufacturing ergonomics, the people who are designing the parts, assemblies, and fabrication fixtures should be able to use DHM to determine whether there is sufficient clearance for assembly workers and that the postures and forces they will need to use are acceptable. DHM use by non-experts requires a high level of functionality in the software. The user should have to perform little or no low-level posturing of the figure, both to reduce complexity and to minimize the chances of obtaining erroneous results.

THE HUMOSIM ERGONOMICS FRAMEWORK

Overview

The Human Motion Simulation laboratory at the University of Michigan was founded in 1998 with the goal of improving motion simulation in digital human models. The laboratory's activities have differed in one crucial way from most other motion simulation research efforts in that the research is explicitly designed to be independent of any particular human model software system. This objective has proven to be a substantial intellectual challenge, but the merit of the approach has also been supported by our experience working with our industry partners and software vendors.

The HUMOSIM ergonomics framework is a modular system of algorithms that function together to produce realistic human motion in a wide variety of task scenarios. This section of the paper gives an overview of the framework and provides some examples of how it is applied to simulate seated and standing tasks.

Guiding Principles

Based on the observations described above concerning the context for figure-model-based ergonomics, and the functionality required by that context, the development of the HUMOSIM framework has been guided by a set of principles.

Modularity — Functionality for motion simulation and analysis is developed in small, rationally scoped modules. For example, one module handles task-oriented head and eye movement. The modular approach allows implementers to add HUMOSIM functionality to their existing systems without having to replace other components. In our experience, all-in-one solutions are unlikely to be implemented in commercial software.

Algorithmic — HUMOSIM modules are based on algorithms that can be documented completely in written form. DHM software vendors will implement these modules by writing software in the appropriate language for their systems. Hence the modules are created not as source code that must be ported to another language, but rather as written algorithms presented at a level of complexity accessible to experienced programmers. Numerical methods are limited to public-domain algorithms.

Behavior-Based — The modules are based on human-subject research performed in the HUMOSIM laboratory. The critical features of the modules are based on statistical analysis of motion data and on findings concerning human movement patterns and coordination. In many cases, the problem of the kinematic redundancy of the human skeletal linkage is solved using statistical models generated from motion data. However, by design, the modules are not purely empirical, but rather are based on principles of human motor control and robotics overlaid with the findings of HUMOSIM laboratory studies. This allows the modules to be more robust than statistical models that lack the underlying kinematic structure.

Coordination — The central problem posed by the modular approach is the coordination of body segments and subsystems of segments during complex whole-body motions. The HUMOSIM framework addresses coordination at three levels: (1) Individual modules, such as the upper-extremity module, produce coordinated patterns of behavior within a subsystem of segments. (2) Communication among the modules produces inter-region coordination. For example, the seated torso module monitors the upper-extremity modules to ensure that their requirements for shoulder placement are met. (3) The coordination of complex tasks results from the cooperation of several subsystems to control common body segments. Success with this approach suggests that the benefits of modularity can be achieved without sacrificing whole-body coordination, and in fact may be integral to achieving coordination for a large range of tasks.

Robustness — All approaches to whole-body motion simulation confront issues of robustness, in that they necessarily perform better for some tasks than others. The HUMOSIM framework approach is to create models that are robust by design. The modules are designed to function plausibly far beyond the data on which they were originally developed. Given the context in which DHM analyses are performed, it is unreasonable to expect people to implement and to use modules that function well only within a narrow domain and that must be bypassed frequently to perform needed analyses. Hence, the HUMOSIM modules are intended to function throughout the DHM performance space and to fail gracefully when pushed to the limits. The current version of the framework produces good results for a broad range of tasks, but improving the scope of tasks that can be accurately simulated remains an important objective. One consideration in supplying users with robust algorithms is that it will not be apparent to the users in which situation the results have been validated and which are extrapolations. The issue of reporting the level of validity to the user in a fined-grained manner, analogous to confidence bounds on statistical findings, is an important ongoing topic of research.

Integrated Analysis — Simulations with digital human models are usually performed with the intent of assessing the suitability of the product or workplace with respect to operator safety and performance. Motion simulation for ergonomics is therefore not an end in itself, but rather a means to obtaining accurate assessments of accessibility, clearance, muscle and joint loading, fatigue, and other aspects of human/system interaction. Historically, few ergonomic assessment tools have been developed with human models in mind, and consequently many tools are difficult to deploy in a human model environment.

The HUMOSIM framework is designed to integrate modular assessment tools that have the same characteristics as the motion simulation modules. That is, they are algorithmic and can be described with concise mathematical expressions; they use as inputs information that is available in the human modeling environment; they are capable of prediction using human attributes (body dimensions, strength, range of motion, gender, age, etc.) as predictors.

Structure

Figure 1 outlines the structure of the framework by highlighting the information flow through the system during a simulation. Environment-independent task information provided by the user is processed by a task planner that integrates information from the current environment, such as the locations of figures, parts, and obstacles, to develop a mid-level task plan. For example, a high-level task directing the figure to pick up an object and place it at a particular location might generate a mid-level plan consisting of walk, pick up, carry, and place tasks. The high-level task plan corresponds closely to the Parameterized Action Representation of Badler et al. (1999), but is expected to be customized for the user interfaces of the DHM systems in which the HUMOSIM framework is used.

The midlevel plan is analyzed by a set of modules that decompose each task element (e.g., pick up) into a component-level motion plan. For example, "pick up" might be constructed from a set of foot motions, a torso motion, a head motion, and two upper-extremity motions. The component-level motion plan is passed to a motion controller that dispatches the elements in a coordinated sequence to modules that control the upper and lower body. The application of the framework to two example tasks is described below.

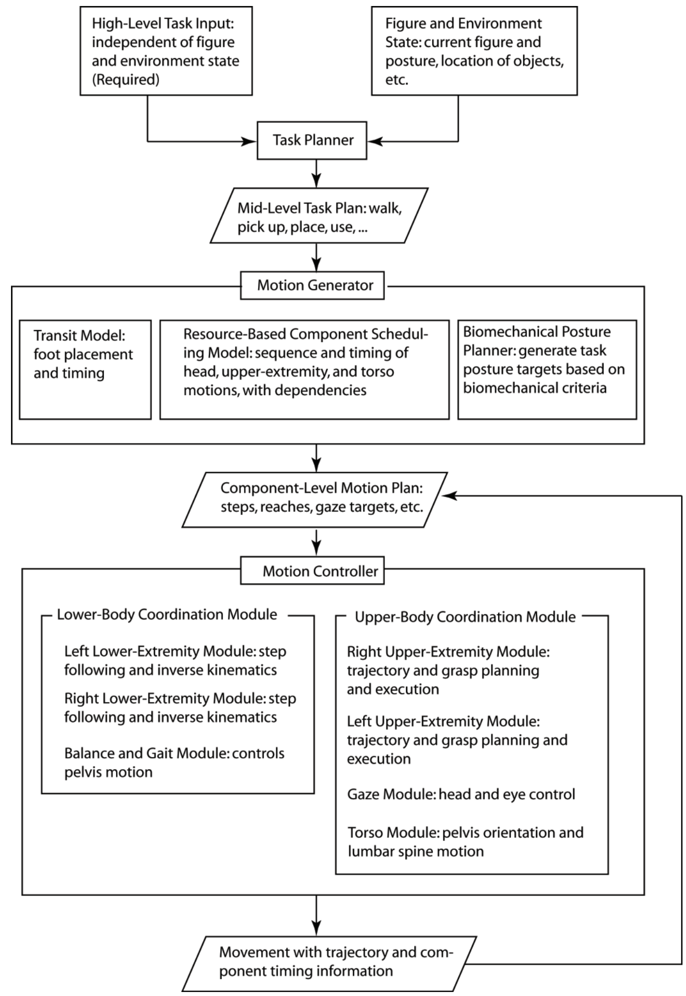


Figure 1. Schematic of the HUMOSIM ergonomics framework, showing information flow.

Reference Implementation

The framework modules are designed to be implementable in any human modeling system. The only requirements are forward kinematics (the ability to set joint angles programmatically) and the ability to extract current joint and body segment locations. To aid in the development and demonstration of the algorithms, a reference implementation has been developed for use in the Jack™ human modeling software system from UGS. The Jack software includes a Python-language interpreter with access to the scene graph and control of the figure. The reference implementation does not rely on any Jack-specific functions (e.g., the constraint solver, animation system, or inverse kinematics). Only the basic forward kinematics and figure introspection functions (e.g., human.right_foot.GetLocation()) are used, ensuring that the algorithms can be implemented in any other DHM environment that allows programmatic figure control.

Background on Selected Modules

Head Motion — The head motion (gaze) module is based on HUMOSIM research on the coordinated patterns of eye, head, torso, and upper-extremity movement (Kim and Martin, 2002). The vision target location in a human -centered coordinate system is used to calculate the most likely posture of the neck, eyes, and head for gazing at the target, based on laboratory data. The motion algorithm produces a gaze transition to a new target using movement timing and velocity profiles developed from laboratory data.

Hand Trajectory — Hand trajectory prediction is an important part of the upper-extremity motion module. Faraway (2000) developed a method for upper-extremity motion prediction that begins with a Cartesian hand trajectory predicted statistically from data on similar motions. Wang (2006) used laboratory data from reaches to a wide range of target locations to develop new approaches to modeling and predicting hand trajectories. Predicting the hand trajectory directly, rather than allowing the trajectory to emerge from prediction of joint angle trajectories, provides a better fit to observed movement patterns. Recently, the methods have been extended to six degrees of freedom, predicting hand position and orientation for laden and unladen reaches (Wang, 2006; Choe and Faraway 2004).

Upper-Extremity Inverse Kinematics — Upper-extremity motions are produced by using an analytical inverse-kinematics approach to track pre-computed hand trajectories. The approach uses the stretch-pivot methodology developed by Faraway (2000). The approach is also influenced the methods presented by Tolani et al. (2000) and Jung et al. (1995), but it improves on the earlier methods by using a behavior-based approach to address kinematic redundancy. The approach is similar in some respects to work by Kallman (2005) and Zhao et al. (2005), who have used analytical inverse kinematics to produce upper-extremity motions. Specifically, regression functions fit to motion capture data are used to ensure that the movement patterns are accurate and not merely feasible (Danker and Reed, 2006).

Torso Motions — Torso motions are also governed by a behavior-based inverse-kinematics approach. In the HUMOSIM framework, the torso acts as a resource that enables the head and hands to function as necessary for the task. Torso motion trajectories that will bring the shoulders and the base of the neck into the locations required for the task are computed using degree-of-freedom-reduction and coupling strategies developed from analysis of motion-capture data (Reed et al. 2003; Reed et al. 2004). The methods are designed to produce the range of behavioral complexity reported in Reed et al. (2004).

Lower-Extremity Motions — The lower extremities are controlled using an innovative combination of behavior-based prediction and inverse kinematics. One of the more obvious motion anomalies observed with current DHM simulations of walking and stepping workers is “foot skate,” or more generally violations of the kinematic constraints at the foot-ground interface. Respecting kinematic constraints imposed by the environment, as well as those internal to the figure, such as joint angle limits, is critical for accurate motion simulation (Reed et al. 2005). The lower-extremity module follows the upper-extremity approach of combining prediction of the motions of the end effectors (hands, feet) with behavior-based inverse kinematics to achieve realistic lower-extremity motions. This method allows foot placements to be predicted using task and operator information (Wagner et al. 2005), which is necessary for accurate posture prediction for load pickups and other hand force applications.

Reach and Object Transfer Effort and Difficulty — Concurrent with the development of the motion simulation algorithms, statistical and biomechanical models addressing the perception of effort and difficulty have been developed (Kim et al. 2002b; Dickerson and Chaffin 2003; Reed et al. 2003; Martin and Kim 2003; Dickerson et al. 2004a). Together with design criteria, these models can be used to determine which tasks will be acceptable to workers or vehicle operators.

Biomechanical Analysis — Many of the criteria that are used to identify industrial tasks as stressful are based on biomechanical analysis, particularly of back and shoulder loading. A detailed model of shoulder stress for one-handed materials handling tasks has been developed (Dickerson et al. 2004b). Motions predicted by the framework can be used as input to the model.

Dynamic Environments — Most of the development of modules for motion simulation and analysis have addressed static environments, but a complementary program is underway to study and model the behavior of human operators in land-vehicle ride-motion environments. The analysis of motion-capture data from seated reaching tasks performed in a ride motion simulator has been used to develop models to predict task speed and accuracy and hand trajectories (Rider et al. 2003; Rider et al. 2004a; Rider and Martin 2005). Future work will integrate these findings with the other modules used for static seated reach simulation.

Example: Seated Reach

As an example of the application of the framework to a task simulation, consider seated reach by an automobile driver. The framework implementation is shown schematically in Figure 2. The task for the driver is to reach to a control on the instrument panel. The instruction to the software is in the form “human reach right hand control A.” The software user has associated information with the control, including appropriate grasps, level of precision required, force levels, etc.

The task compositor determines, from the type of control and grasp information, that an initial glance at the target location is required. A component-level task sequence comprised of a gaze transition to the control and a right hand reach to the control is generated. These task components are dispatched to the gaze and upper-extremity modules, respectively, for execution.

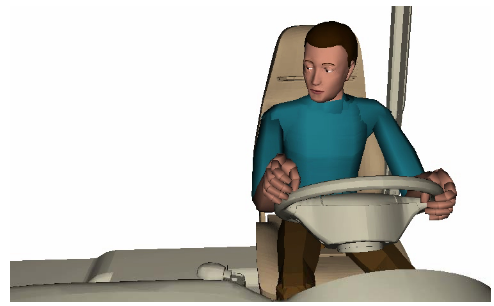
The gaze module computes a preliminary terminal head/neck attitude for gaze to the target, and, using quaternion interpolation, establishes initial trajectories for the eyes, head, and neck. The upper-extremity module computes a six-degree-of-freedom hand trajectory. The torso module, which is continually monitoring the requirements of the head and upper extremities, determines that torso motion will be necessary to accommodate the terminal posture. The module computes a torso posture trajectory that is consistent with the kinematic constraints (left hand location and seat contact) and that will achieve the terminal posture.

Execution of the motion begins at the established frame rate. Each module that has a task-oriented trajectory to execute, in this case the gaze and right upper-extremity modules, iterates through the planned trajectory. At each frame, the torso is moved first. The gaze module acts next, compensating for any motion of the torso that has occurred. The upper-extremity module uses behavior-based inverse kinematics to set the postures of the clavicle, arm, forearm, and hand segments to achieve the desired location on the trajectory. As the pelvis moves with the torso, the lower-extremity modules use behavior-based inverse kinematics to maintain the foot positions, and the left upper-extremity module maintains the left-hand position on the steering wheel.

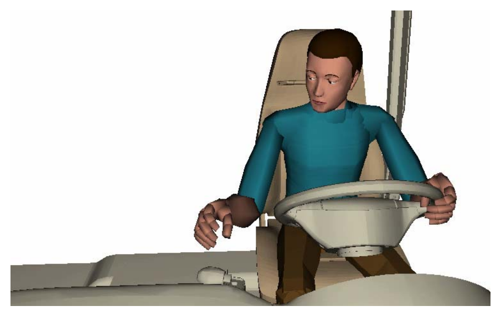
This example illustrates a number of important concepts that underlie the framework. First, individual modules represent motor subsystems that are believed to be capable of semi-autonomous operation. For example, the head/eye trajectory is planned without any knowledge of whether concurrent torso motion will occur. This greatly simplifies the motion planning process, but also necessitates that the gaze module be able to compensate for such motion.

Starting posture. Hand and gaze trajectories planned.

Gaze movement initiated.



Gaze movement near completion as hand movement is initiated.



Torso movement underway, left-arm IK maintaining steering wheel constraint, gaze system compensating for torso movement, right hand in mid-trajectory.

Movement completed.

Figure 2. Steps in simulating a seated reach task with the HUMOSIM ergonomics framework using the Jack human figure model.

Similarly, extremity modules that are maintaining end-effector position (the lower extremities and the left upper extremity in this example) are able to compensate for torso motions without any need for coordinated planning with the other extremities.

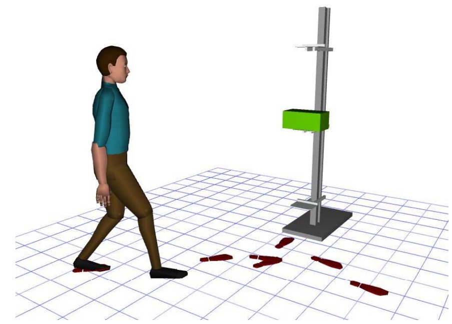
The combination of hand trajectory planning and upper-extremity inverse kinematics has proven to be a very effective way of producing realistic motion with a large number of degrees of freedom with relatively simple algorithms.

One key to the overall system performance is that the six-degree-of-freedom trajectory for the hand is accompanied by a weight vector that indicates the priority for meeting the location and orientation specified. As the motion progresses, exactly matching both the preplanned torso and hand trajectories can produce unrealistic motion, since these are planned independent of each other. Consistent with observations of human motions, the progression along the preplanned hand trajectory can be limited by smoothness considerations in keeping with the weighting function applied to the hand degrees of freedom. For example, the hand position weight is low during a reach that is unconstrained by an externally imposed trajectory (as in the current case). The hand position and orientation weights always return to unity at the termination of the reach, so that the reach targets are achieved. As a result of this procedure, both the upper-extremity joint angle trajectories and the hand trajectory show the smoothness characteristic of human motions.

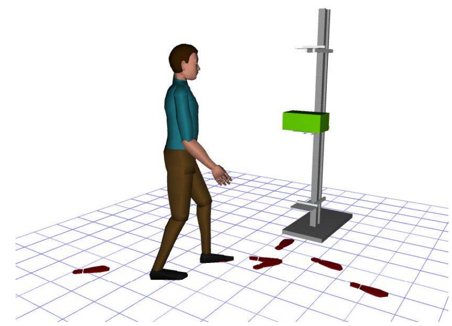
Example: Standing Movements

A second example considers an industrial worker moving a box from one location to another (Figure 3). The high-level task input given to the software is “Worker1 carry Object1 to LocationA.” Focusing on the pickup action, the task analyzer determines that the worker must take several cyclical gait steps to reach the area of the current location of the box. The TRANSIT model calculates the timing and location of footsteps associated with the approach and turning motion at the pickup location, using information about the worker and the task (box location, shelf height, and other factors). The gait steps from the current location to the transition steps are computed in a similar fashion, and the time of contact with the object relative to the start of the motion is calculated.

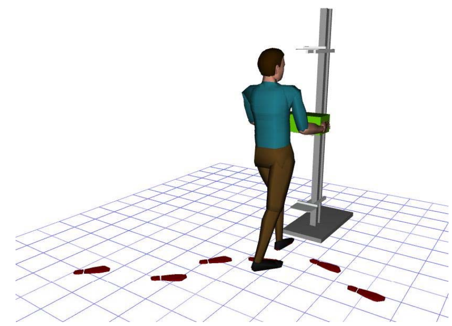
The standing pelvis module is primarily responsible for balance in standing tasks and performs in both active and reactive modes. For the current example, the pelvis module functions in active mode by pre-computing a 6-DOF trajectory relative to the planned sequence of footsteps.



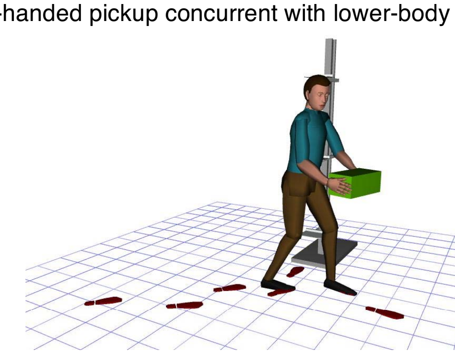
Transition stepping behavior (illustrated by footprints) initiated.



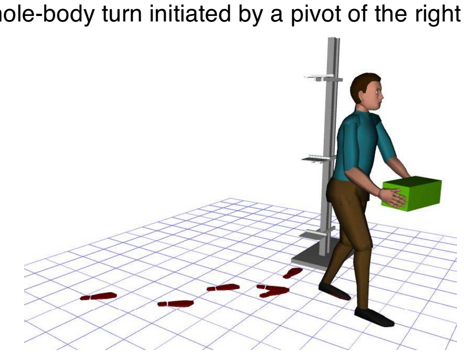
Reach motion initiated as the figure approaches the pickup.



Two-handed pickup concurrent with lower-body motion.



Whole-body turn initiated by a pivot of the right foot.



Transition to delivery of the load.

Figure 3. Steps in simulating a materials handling task with the HUMOSIM ergonomics framework using the Jack human figure model.

The mid-level motion plan for this task includes a two-handed reach and grasp to pick up the object. The planning of the upper-extremity and torso actions for these motion components is complicated by the fact that the entire body will be in motion relative to the target as these components are executed.

Hence, the trajectories for these motions are computed in a human-centered coordinate system based on the planned location of the human at the time of object contact. The duration of these motions, estimated using statistical models based on the spatial magnitude of the motions (reach distances relative to neutral standing posture), is used in the sequencing of the motion components.

As the motion simulation begins, the motion elements are dispatched in sequence, at the appropriate times, to the associated modules. The pelvis module executes its preplanned trajectory and each lower extremity executes the specified footsteps. The stance-phase behavior of each lower-extremity is designed to produce typical foot motions for cyclical strides (the rapid toe-off push, for example) while also maintaining realistic knee and hip angle trajectories. As with the other inverse kinematics algorithms used in the framework, the lower-extremity module uses knowledge of typical human motions to maintain smoothness without being constrained to play back particular motion patterns. One consequence of this approach is that non-cyclical stepping motions use the same prediction algorithms as cyclical gait, with the important differences between these types of lower-extremity motion generated by the foot and pelvis behavior algorithms.

As the human nears the pickup point, the upper-extremity and torso motions are initiated at a time determined by offsetting their estimated duration from the pre-computed pickup time. Changes in torso orientation may lead to alterations in the pelvis trajectory as the pelvis module seeks to maintain balance. The balance algorithm uses a static center-of-gravity projection rather than a dynamics calculation to reduce processing requirements, but includes consideration of future foot placements during lower-extremity motions when calculating the base of support. As the load is picked up, the mass of the object is included in the balance calculation.

DISCUSSION AND FUTURE WORK

The relatively simple structure of the modeling approach presented in this paper is motivated by the needs of the application domain. A complicated modeling structure that requires extensive custom software is unlikely to be implemented in the commercial modeling tools that large corporations use for ergonomics analysis. The modular approach to algorithm development allows for frequent updates as more data become available and provides a good structure for collaboration among the research team.

The motion-simulation and analysis framework presented in this paper represents a significant step forward in the development of robust, readily-implemented human modeling technology, but many tasks of interest for DHM analysis will still require alternative means of obtaining realistic postures and motions. For some movements, particularly those in constraining environments (such as some auto assembly situations), the complexity of the human adaptation to the environment will necessitate the software user to intervene to improve the prediction. For example, the framework cannot currently determine that a worker would brace against part of the vehicle structure to facilitate a reach. However, the framework can indicate that a particular motion is out of balance, prompting the user to specify a bracing task for the contralateral hand. The details of how such user interaction will be facilitated will need to be worked out during implementation.

Currently, only a few human interactions with products and workspaces are simulated, in part because the current DHM tools are too cumbersome to be applied rapidly to many scenarios with a wide range of simulated humans. Automated methods for posturing and motion simulation have the potential for greatly improving analysis throughput, so that many more analyses can be performed with multiple human figures. Even when user interaction is required, a well-constructed software interface, combined with the framework algorithms, can improve analysis speed, accuracy, and repeatability.

The most important challenge for human motion simulation is validation. Individual components of the framework have been shown to be valid for the range of available data, but the laboratory experiments necessarily cover only a small part of the range of potential application. Quantitative validation of the multi-module coordination approach has only begun. Nonetheless, the initial results are encouraging.

A number of important topics are under consideration but have not yet been implemented in the framework. Grasp can be simulated in many human modeling packages by combining hand posture interpolation with collision detection. The grasp postures obtained by this method can be poor if the starting wrist location or forearm orientation is unrealistic. Moreover, the hand motions obtained by this method are seldom realistic, because many grasps are accompanied by forearm motion. More study is also needed of the grasp changes that occur after an object is picked up.

Obstacle avoidance is a multi-facetted problem that has been the subject of considerable research in robotics, human motor control, and digital human modeling (e.g., Vaughan et al. 2001; Park et al. 2001, Zhao and Badler 2005). Its importance for ergonomics analysis, however, is considerably less than in other domains, such as entertainment and training, in which the virtual humans must act without the intervention of the software user. As noted above, one of the characteristics of most simulations for ergonomics purposes is that the tasks are known in advance and the task times are relatively short. This means that user interaction aided by a good user interface may be the most efficient way to achieve some types of obstacle avoidance. The framework and its modules are designed to have a small number of parameters that can alter the way a movement is performed. For example, controlling the hand trajectory and altering the preferred arm splay angle can provide a large amount of maneuverability for avoiding obstacles with the upper extremity without resorting to low-level joint control or key-frame animation. Nonetheless, a more automated procedure for obstacle avoidance may become a higher priority as the overall system performance improves.

The HUMOSIM ergonomics framework encompasses many individual innovations in motion simulation algorithms, but the primary innovation is in the development of a comprehensive system for motion simulation and ergonomic analysis that is specifically designed to be independent of any particular human modeling system. Nonetheless, the current diversity of research in human motion simulation will benefit the framework, because the modular structure allows the components to be continuously improved as better algorithms or more validation data become available.

ACKNOWLEDGMENTS

This research was sponsored by the partners of the Human Motion Simulation program at the University of Michigan. The current HUMOSIM partners are DaimlerChrysler, Ford, General Motors, International Truck and Engine, the United States Postal Service, and the U.S. Army Research and Development Engineering Command (RDECOM). TRW, Johnson Controls, and Lockheed Martin have also supported the program. Technical partners of the HUMOSIM program are UGS and Delmia. Additional support for the research was provided by the Automotive Research Center at the University of Michigan. The authors gratefully acknowledge the contributions of Ulrich Raschke of UGS, who has provided valuable insight from the perspective of DHM software vendor. The authors are also grateful to the industry representatives on the HUMOSIM Industry Advisory Panel who have provided a detailed view into the current and potential applications of digital human modeling for ergonomics.

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