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ABSTRACT

Industrial tasks performed by standing workers are among those most commonly simulated using digital human models. Workers often walk, turn, and take acyclic steps as they perform these tasks. Current human modeling tools lack the capability to simulate these whole body motions accurately. Most models simulate walking by replaying joint angle trajectories corresponding to a general gait pattern. Turning is simulated poorly if at all, and violations of kinematic constraints between the feet and ground are common. Moreover, current models do not accurately predict foot placement with respect to loads and other hand targets, diminishing the utility of the associated ergonomic analyses. A new approach to simulating stepping and walking in task-oriented activities is proposed. Foot placements and motions are predicted from operator and task characteristics using empirical models derived from laboratory data and validated using field data from an auto assembly plant. The motions of the pelvis and torso are predicted from the foot placements, operator characteristics, and task requirements. The lower-extremity motions are then generated using behavior-based inverse kinematics that relies on laboratory observations to address kinematic redundancy while respecting boundary constraints. This modular approach is highly general and can simulate gait, transition stepping, and stepping for balance maintenance in a single integrated system that can be implemented in any digital human model.

INTRODUCTION

Digital human modeling (DHM) is rapidly emerging as a critical tool for proactive ergonomic analysis. In auto manufacturing, the simulation of human workers in the process of software-based "virtual builds" is essential to ensuring that the vehicle can be built safely (Stephens and Godin 2006). However, only a few static postures are analyzed for most tasks, because the simulation of realistic motions is beyond the capability of most human modeling software. New software systems for simulating realistic human motions are the subject of ongoing research (Raschke et al. 2005, Badler et al. 2005, Reed et al. 2006). One important category of movement for simulating the activities of industrial workers is locomotion, or more specifically the combination of cyclic and acyclic steps with which workers move around the industrial workcell. Even if the task analyses are primarily static, accurate prediction of foot placement is critical for accurate analyses of lower-back or shoulder loading for manual materials handling tasks (Wagner et al. 2005). Increasingly, DHM software is used to perform large-scale simulations of multiple workers as part of the design of manufacturing facilities. In this context, realistic stepping is required for visual realism and to perform accurate assessments of task timing and workcell congestion.

Most digital human modeling software used for industrial ergonomics includes simulation of walking among its stated capabilities. The walking simulations in most DHM software are generated by "playing back" the patterns of joint motion associated with cyclic gait while the pelvis (usually the kinematic root of the figure) is moved along a path. Because these patterns are developed from motion capture data, the visual appearance can be realistic for straight-line or curved-path walking with a figure whose proportions are similar to those of the performer who generated the original data. But these techniques are inadequate for most workcell simulations. The limitations include:

- routine violation of the boundary conditions at the feet ("footskate") due to the practice of driving the figure via a pelvis trajectory while moving the feet,
- no provision for accurate prediction of foot placements during hand tasks, including materials handling and force exertions,
- no prediction of the acyclic stepping that represents the majority of foot movements in workcell tasks, and

- difficulty with performing upper- and lower-extremity motions concurrently.

Objectives

Improving the simulation of locomotion has the potential to improve the utility of DHM for ergonomics analysis in at least three ways. First, the accurate placement of the feet with respect to hand tasks is critical to accurate ergonomic analyses of these tasks (Wagner et al. 2005). Second, high-level control of the motions associated with ambulatory tasks will allow more accurate, repeatable, and reproducible analyses than is possible with the current tools, which often require the user to manually create the postures of interest and to simulate motion through key-frame interpolation. Third, visually realistic locomotion will improve the face validity of DHM simulations, which currently is compromised by the clearly unrealistic patterns of motion.

Cyclical, straight-line human gait has been studied extensively (see Inman, 1981, and Perry, 1992, for reviews), but other aspects of locomotion have received limited focus. "Locomotion" in this paper is used to refer to non-seated activities in which the primary body support is provided by foot interaction with the floor, ground, or other surface, and that in involve one or more cyclic or acyclic steps. The current paper focuses on the prediction of gait, turns, and transition steps that occur during load pickup and delivery, but the formulation of the model is designed to apply to all types of work-related locomotion, including traversing stairs and stepping over obstacles. Due to the clinical importance of falls by the elderly, investigators have examined gait initiation (Breniere et al. 1991, Burleigh et al. 1994), turning (Meinhart-Shibata et al. 2005, Orendurff et al. 2006, Taylor et al. 2005), and gait termination (Sparrow et al. 2005, Winter 1995), but the focus of these papers has not been on the development of a general model to predict the kinematics of locomotion.

This paper presents a new approach to the simulation of locomotion in DHM software used for ergonomics that overcomes these limitations. The new methods differ in substantial ways from the alternatives that have been proposed so some comparison of the current method to these other approaches as candidates for use in ergonomics software is warranted.

Alternative Simulation Approaches

The simulation of human walking for various purposes has received considerable attention in a number of fields. The previous approaches can be usefully divided into three categories:

Motion Capture — The motion-pattern simulation method commonly used in commercial DHM software is a minimal application of the general approach of using detailed data gathered from human performers. Unsurprisingly, given the high degree of realism that is possible with this approach, the majority of the published research relating to human motion simulation for entertainment is focused on the manipulation of motion-capture data. The primary problems to be addressed are efficient storage and retrieval of data; splicing together multiple motions to achieve good movement continuity; modification of motions to conform to a different kinematic linkage; and enforcement of (typically Cartesian) constraints imposed by the environment. Kulpa et al. (2005) provides a good review of recent work in these areas.

Gait is perhaps the category of human motion that is most difficult to simulate sufficiently well as to be indistinguishable by a typical observer from motion-capture data (Reed et al. 2005). Humans can readily detect idiosyncrasies in gait sufficient to identify an individual (Stevenage et al. 1999), are able to infer emotional state from gait patterns (Cluss et al. 2006), and can identify gait using minimal visual cues, e.g., “point light displays” similar to motion-capture marker traces (Johannson 1973). This finely tuned visual perception raises a very high bar for gait and stepping simulations.

In view of this human perceptual capability, it is not surprising that motion-capture data produce particularly realistic simulations, because they readily reproduce the nuance of upper-body motions that create much of the affect of gait. (See, for example, the Walk Designer in the animation software Poser: http://www.e-frontier.com/.) A central problem in applying motion capture data to produce realistic locomotion is the violation of boundary conditions, one type of which is commonly called footskate (Kovar et al. 2002). A variety of methods have been developed to modify or “retarget” motions to kinematic linkages different from the original performer while respecting boundary constraints, particularly at the feet (e.g., Choi and Ko 2000). Motion-modification techniques have been applied in the ergonomics domain as well (Park et al. 2004), including extensive work on vehicle ingress-egress (Dufour and Wang 2005, Wang et al. 2006). Motion capture with modification can produce very realistic results, provided the data were obtained from similar-size individuals performing similar tasks with similar constraints. The shortcomings of the approach include the considerable time and expense required to obtain and process the needed data; the need to store, maintain, and edit the motion library; and the computational requirements for online selection and modification of root motions (Wang et al. 2006).

Nonetheless, one might anticipate that motion capture would be a viable alternative to the model presented in this paper. The steps that would be involved in such an effort provide an illuminating contrast to the current method. First, a large motion-capture library would be assembled. (A considerable volume of human locomotion data with the required level of detail have been gathered in the HUMOSIM lab — see Wagner et al. 2006 and www.humosim.org.) Second, an efficient storage and searching procedure would be created. Commonly, such a database is stored as joint angle trajectories, but this limits the database to one particular kinematic linkage definition. Kulpa et al. (2005) discuss an alternative motion storage approach that overcomes this limitation. Third, the motions would be retargeted (modified) to conform to the requirements of a particular simulation. This would involve ensuring that the feet are placed accurately with respect to the environment, that the figure remains in balance, and that the upper-body tasks (which can vary so widely relative to lower-body activities that they probably must be captured, stored, and applied separately) are completed as required. As discussed below, the implementation of this final step would create a result essentially indistinguishable from the output of the current model, making the use of a motion-capture library unnecessary. In essence, the current approach distills from motion capture data the key aspects of locomotion and applies them in a flexible framework designed for concurrent simulation of a wide variety of upper-body tasks.

Bipedal Robotics — Some of the current work relating to human walking is directed at the creation of physical robots that can walk bipedally (e.g., Hirose and Ogawa 2007). The constraints of this research area include the need for real-time, online control and fast, powerful, lightweight actuators. The control algorithms monitor the system dynamics and specify time-varying torques and forces in actuators to accomplish locomotion. The resulting algorithms are of substantially greater complexity than are currently needed for ergonomics simulation. While in principle a physics-based approach could provide greater generality and realism, in practice the complexity of the forward dynamics and control problem results in computationally intensive systems that are capable of a relatively narrow range of behaviors compared with kinematic systems.

Musculoskeletal Simulation — Considerable progress has been made in recent years in the simulation of the musculoskeletal system with increasingly fine detail. Several commercial and research models of the lower extremities are available that include geometric representations of all of the major bones and muscles (e.g., Damsgaard et al. 2006). These tools have typically been used for inverse-dynamics analysis, in which internal body forces and moments are calculated based on the input of kinematics (motion) and external forces. Much of the research is focused on the simulation of muscle activation patterns, which are major determinants of tissue stress that may lead to injury. Efforts have also been made to use these detailed musculoskeletal models for forward-dynamics predictions of motion, using force-control at the muscle level (Holzbaur et al. 2005). These efforts encounter the same basic problems as the bipedal robotics research, except that the problem is made more complex by the redundant and geometrically complex musculature. The approach has a strong appeal for ergonomics, in that the analysis of work tasks could potentially benefit from accurate simulation of internal muscle forces and tissue stresses.

However, it seems more reasonable, given the current state of the art, to apply these complex musculoskeletal models first in inverse mode, with kinematics supplied by either a motion-capture or kinematics-based model. For example, the locomotion model described in this paper can be used to drive an inverse musculoskeletal simulation to obtain estimates of muscle forces. This approach to simulation of muscle stresses is considerably more computational tractable than computing kinematics based on musculoskeletal dynamics. The inverse dynamics analysis (in particular, computation of joint torques from kinematics) is a potentially valuable tool for validation of kinematics-domain predictions, because realistic motions must result from reasonable joint torque histories. Unnatural accelerations of body segments, for example, will result in the calculation of unrealistically high joint torques.

Context

The application context is important when considering the characteristics of a good model of standing mobility. To take but two examples, the best models for simulating gait in an avatar used for real-time infantry simulation and in a computational model used to predict the outcomes of surgery to correct lower-extremity pathologies might differ substantially. The context for industrial ergonomics imposes some requirements on the simulation tools (Reed et al. 2006). Models intended for general-purpose ergonomics analysis must be:

- lightweight and able to be implemented from algorithms rather than requiring special-purpose software;
- capable of functioning using any plausible figure model linkage and therefore independent of any particular set of joint angle definitions; and
- capable of predicting realistic body movements, including accurate foot placements and timing, for figures with a wide variety of body dimensions performing a wide range of tasks.

Additionally, tools for simulating particular aspects of human motion, such as gait and stepping, must be integrated into a larger structure for managing human model behavior using high-level commands and controls. Several similar approaches to this task- or goal-level control of human simulations have been published in recent years. Raschke et al. (205) presented the Task Simulation Builder, an addition to the Jack human modeling software that allows users to specify tasks independent of the particular figure or environment configuration. Badler et al. (2005) introduced the Human Model Testbed, a structure for producing complex simulations of human activities based on the Parameterized Action Representation (Badler et al. 1999). Recently, Reed et al. (2006) described the HUMOSIM Ergonomics Framework, a structure for simulating and analyzing task-oriented movement that was developed at the University of Michigan Human Motion Simulation Laboratory.

The models presented in the current paper are being developed as part of the HUMOSIM Framework. In keeping with the characteristics of general-purpose human simulation tools described above, the HUMOSIM Framework is a modular system that is independent of any particular figure model. A reference implementation of the Framework has been developed in Jack, but many of the Framework modules, including those described in this paper, are also being implemented independently in the DELMIA (Safework) environment.

METHODS

Overview of Approach

The HUMOSIM locomotion model is primarily kinematic. That is, the predictions are based mainly on considerations of movement without the necessity to take into account the forces producing the motion (kinetics) or the resulting inertial effects (dynamics). The model predicts the *outcome* of the musculoskeletal dynamics, rather than manipulating the muscle-activations or joint torques directly. This approach provides a lightweight and robust solution that also achieves good accuracy on important kinematic parameters, such as foot placements and pelvis motions. Simulation of a sequence of cyclical or acyclic stepping motions occurs in the context of a whole-body task simulation, which can include hand tasks (reaches, grasps, object transfers) and gaze transitions. The current paper focuses only on modules of the HUMOSIM Framework that are directly involved in lower-extremity motion, namely the pelvis, lower-extremity, and Transition Stepping and Timing (TRANSIT) modules.

Model Structure

Figure 1 outlines the structure of the locomotion model. The model inputs are specified hand target locations within a work environment. These might be the locations of parts to be picked up or the starting positions of hand tools. Based on the current figure position and posture, a sequence of steps is planned by the TRANSIT model (Wagner et al. 2006). The step information includes the position and orientation of the foot and the timing of four foot-contact events: heel-down, toe-down, heel-up, and toe-up. Note that not all four of these are needed for any particular step. The step information is passed to the pelvis module, which computes a six-degree-of-freedom pelvis trajectory relative to the footsteps. The vector of steps is also passed to the lower-extremity module, which calculates foot trajectories for both stance phase (foot in contact with the ground) and swing phase (foot not touching the ground).

As the simulation is run, motor component tasks (e.g., move foot, move pelvis) are dispatched to their respective elements at the specified times. At each time step in the simulation, the pelvis is first set to the target location (position and orientation). The lower-extremity module (one instantiation for each of the lower limbs) computes hip, knee, and ankle angles to meet the foot target previously calculated based on the step information.

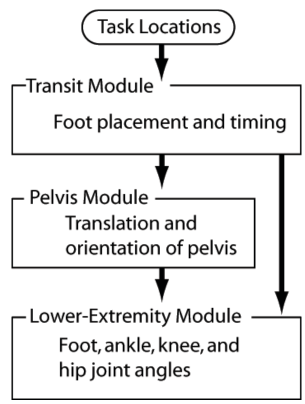

Figure 1. Schematic of the locomotion components of the HUMOSIM Ergonomics Framework, showing information flow.

Transit Module — The Transit module is based on a laboratory study of 20 men and women performing a wide range of materials handling (object transfer) tasks with one or two hands (Wagner et al. 2006). At each hand target location (e.g., an object pickup location), the Transit model predicts a foot transition behavior, characterized by a sequence of steps that result in a change in body orientation (a turn). The selected behavior is dependent on task attributes (e.g., the weight and initial height of the object) and the type and location of the next task (e.g., a delivery of an object). When presented with a new task that requires walking, the Transit model computes a series of gait steps culminating in a transition behavior. If additional tasks are scheduled, the required gait strides or transition behaviors are appended.

The output of the Transit model is a temporal sequence of foot placements, defined by location and timing, and an identification of transition events, such as gait initiation, a turn, or picking up an object. The foot placements and transition events can be used in other modules to predict the motions of other body segments, such as the pelvis.

Pelvis Module — An essential concept underlying the HUMOSIM locomotion model is that pelvis movements can be accurately predicted from knowledge of foot placements and upper-body tasks. Pelvis location in standing tasks is substantially constrained by balance requirements. Moreover, the spatial and temporal patterns of pelvis motion in walking and stepping can be described readily with respect to the placement of the feet and the associated timing (see Perry, 1992). Pelvis trajectories are computed from foot placements by identifying pelvis location targets to be interpolated during the simulation. For cyclical stepping (i.e., walking), six-degree-of-freedom targets for the pelvis are identified at midstance and the initiation of double stance (i.e., when the heel contacts the floor). Interpolation between these targets is accomplished by Bezier curves (translation) and quaternion interpolation with velocity profiles (orientation) designed to produce realistic movement patterns. The parameter values for the pelvis kinematics are obtained from analysis of HUMOSIM laboratory data and, for cyclic gait, from values in the literature (e.g., Inman 1981, Perry 1992).

Lower-Extremity Module —The lower-extremity module fits the thigh, leg (shank), and foot to a specified foot location, given a pelvis location. Considering a root at the pelvis, the system has three degrees of freedom at the hip, one at the knee, three at the ankle, and one at the fore-foot. These 8 degrees of freedom exceed the 6 degrees of freedom given by foot position and orientation, necessitating the selection of one realistic posture from among the infinite number of feasible postures. The behavior-based inverse kinematics method (Tolani et al. 2000, Wang and Verriest 1998, Danker et al. 2006, Reed et al. 2006) uses analytical methods and empirical statistical models developed from human motion-capture studies to resolve the redundancy.

The ankle and foot control portions of the lower extremity module work in two modes. During locomotion, the ankle and foot are actively engaged in propelling the lower extremity during the initiation of swing. This propulsive action of the ankle and foot is simulated using a preplanned heel-up trajectory. This behavior is well predicted based on available parameters, particularly the associated step length. During standing, the ankle and foot are reactive, maintaining the ankle within its range of motion while supporting the movements of the rest of the lower extremities. In squatting, for example, the ankle meets the dorsiflexion range-of-motion limit and the foot bends at the forefoot joint, maintaining the toes in contact with the ground as the heel is lifted. The lower-extremity module switches automatically between locomotion (active) and standing (reactive) modes, depending on the current stepping status.

Once the foot posture is specified (six degrees of freedom at the ankle), the knee angle is given directly by the distance between the ankle and hip, leaving only the rotation around the hip-ankle vector to be predicted. This angle can be predicted accurately from foot orientation and, in reactive mode, from knee angle.

RESULTS

Cyclic Gait

Figure 2 shows frames of simulated motion during one gait cycle. The simulation includes many of the visually apparent aspects of gait, including knee flexion at heel contact (load acceptance), heel elevation with forefoot (toe-joint) flexion, pelvis roll and yaw, and vertical and lateral pelvis motion. Figure 3 illustrates the pelvis and foot trajectories for this motion.

The development of the model has been aided by comparisons to normative descriptions of gait from the literature. Gait can be described in terms of the timing of events, the translational progression of body landmarks, and, most commonly, joint angles (Inman 1981). Under the current simulation approach, the joint angle trajectories are not specified as part of the simulation algorithm, but rather emerge from the behavior-based lower-extremity inverse kinematics operating on the prescribed motions of the pelvis and feet. Hence, comparison of the lower-extremity angles to human data provides a very sensitive check on the realism of the simulation.

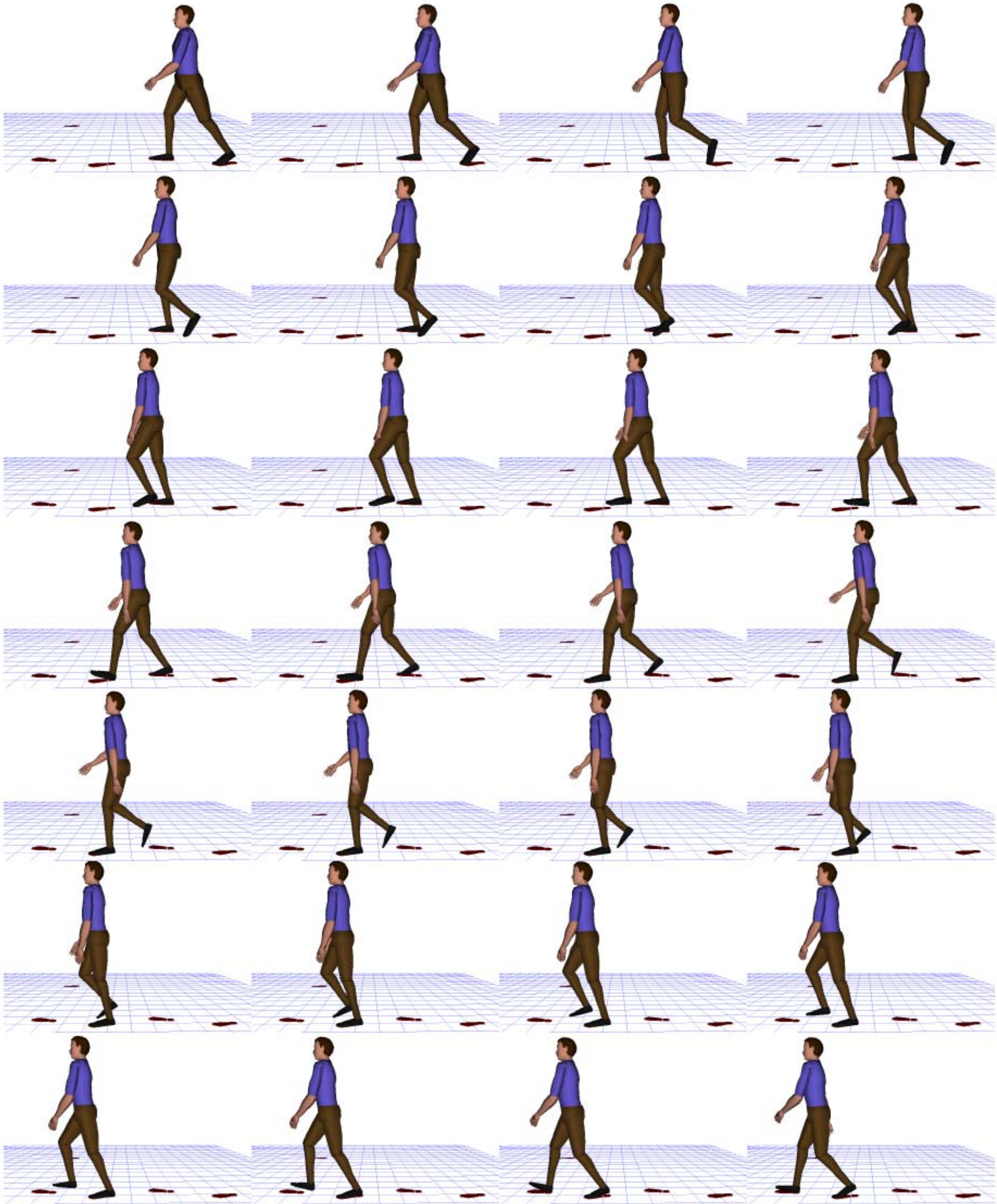

Figure 2. Kinematic sequence for one gait stride. Each frame represents 1/30 of a second.

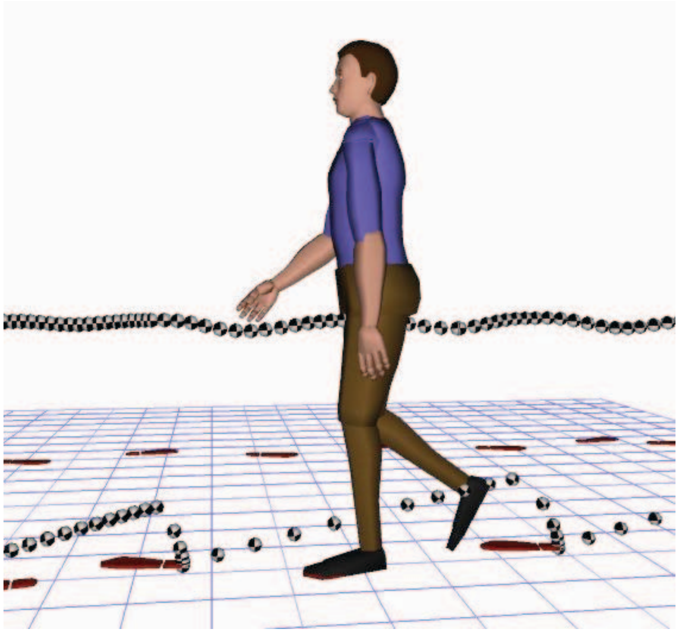

Figure 3. Frame from a gait simulation, showing the trajectories followed by the pelvis and right heel. Markers are placed every 1/30 of a second.

Figure 4 compares ankle, knee, and hip angles for the right leg to mean curves for one gait cycle presented in Perry (1992). The joint angle trajectories exhibit the general shape of the normative curves, including key features such as knee flexion at heel contact and negative hip flexion at the end of stance. The curves are generally within the ±2SD region for the midsize-male data presented by Perry. The deviations from the mean motion patterns are subjectively similar to the distribution of joint-angle patterns for multiple subjects given in Inman (1981).

The plots in Figure 4 show that although the lower-extremity joint angle trajectories follow the general pattern of normative human data, they exhibit velocity changes that are atypical of the smooth joint accelerations observed in human walking. These anomalies would pose problems for an inverse dynamics analysis based on the simulation data. The investigation to date suggests that they can be eliminated through the use of more realistic velocity profiles for both the pelvis and feet.

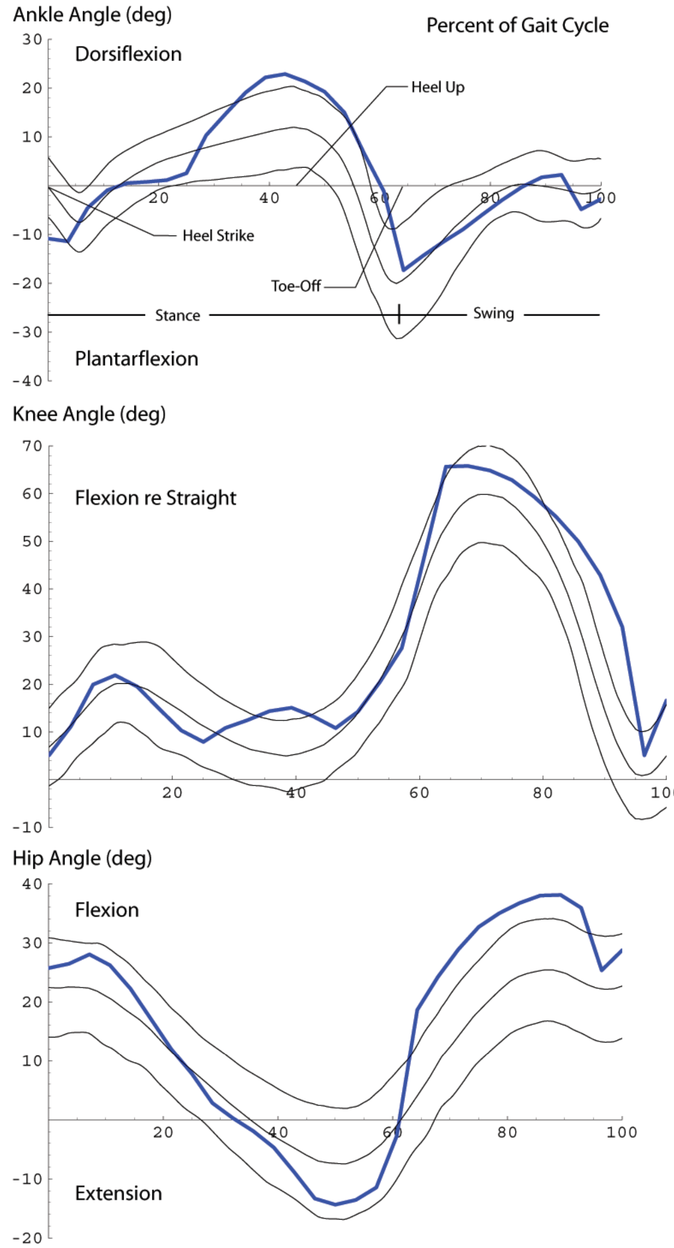

Figure 4. Comparison of right lower-extremity joint angles for one gait cycle (thick blue lines) with normative values (thin gray lines showing mean ± 2 SD) from Perry (1992).

Transition Stepping

Figure 5 shows frames of human motion and simulated motion from a trial from the laboratory study reported by Wagner et al. (2006). In this trial, the participant walked forward, picked up a box with two hands, and turned to the right to deliver it to a target about 3 m away.

Figure 5. Kinematic sequence of a transition step sequence for picking up an object while turning. Frames are taken at 10 Hz.

DISCUSSION

DHM researchers have presented several alternatives to the approach presented here. Our methods are similar in important respects to the locomotion module of the Human Model Testbed presented by Badler et al. (2005), which also drives stepping using footprints and analytical inverse-kinematics for the lower limbs. Kim et al. (2005) presented a method for predicting gait that relies on optimization and inverse dynamics. The method appears to require the foot placement and timing as inputs, the prediction of which is one of the components of the model presented in this paper.

The new model of human locomotion described in this paper represents a significant departure from the current state of the art in human modeling software used for ergonomics analysis. This approach was developed based on careful consideration of the requirements for ergonomics and has several associated strengths:

- The algorithms are lightweight and easily implemented, requiring relatively little computation, and no specialized software. For example, no optimization is required, and the algorithms work with any kinematic linkage definition (e.g., they are independent of any particular joint-angle rotation sequence definition).

- The algorithms adapt readily to different figure sizes and proportions.

- The algorithms are driven by a small number of kinematic parameters that can be readily computed from data, creating a strong validation for key aspects of the model.

- The simulation is driven by foot placements, which are in turn calculated from hand targets and other task requirements. This approach, based on statistical analysis of laboratory data (see Wagner et al. 2006), ensures that the base of support for postures associated with object transfers and hand force applications (which are typically those of greatest interest) are representative.

- The modular approach to the simulation of pelvis and lower-extremity motions in locomotion allows the lower-extremity simulations to be conducted in conjunction with complex upper-body motions, including object manipulations and interactions with both moving and fixed components of the environment. For example, Figure 5 shows upper-body motions associated with picking up a box while turning. Simulating this tasks requires coordination of upper-extremity, lower-extremity, torso, and head motions.

Challenges and Future Work

The current model is sensitive to the parameter values used for the generation of the pelvis and foot trajectories. The foot flexion behavior during stance is critical and relies on having an accurate initiation time for the heel-up motion. These parameters are strongly dependent on stride length, which is in turn dependent on figure lower-extremity dimensions. The pelvis trajectory is also critical, because an inaccurate pelvis location with respect to either foot will result in unrealistic joint angles in the lower extremity, or even an inability to reach the target foot locations. The challenge is made more difficult by the fact that the knee angles are nearly straight, which means that small errors in hip-to-ankle distance become large (and visually jarring) errors in knee angle. Fortunately, ample data are available in the literature and from experiments in the HUMOSIM lab to predict pelvis motion with respect to foot placements for both cyclic and acyclic steps with sufficient accuracy.

Work is ongoing to simulate the complex patterns of foot motion associated with transition behaviors during turns and at load pickup and delivery. The Transit model predicts the foot placements and timing with quantified accuracy, but the pelvis and foot trajectory models have not yet been validated for transition stepping. Because transition stepping has not previously been studied in detail, the literature does not provide validation values for these behaviors.

An additional challenge that is the subject of future work is to accurately simulate modifications to locomotion that occur due to external forces and constraints, such as those created by carrying an object, pushing a vehicle, or manipulating a materials handling device. These problems are a common motivation for dynamics-based models of locomotion, but it seems likely that the behavior-based approach applied here and elsewhere in the HUMOSIM Framework will prove to be an effective and much simpler way of simulating these tasks at the level of fidelity required for ergonomics analysis using DHM. Validating a dynamics-based approach to simulating laden gait will require kinematic data from people performing such tasks. Those data will be amenable to modeling in the kinematic domain using the same methods applied in this paper. Hence, the very changes in kinematics that the dynamics-based methods attempt to predict can be implemented directly under the current Framework, most likely by modifying the values of parameters already in the model.

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