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Human Motion Simulation for Vehicle and Workplace Design

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ABSTRACT

Digital Human Models (DHMs) are fast becoming an effective tool for performing proactive ergonomics analysis and design. DHM software, such as Jack, SAFEWORK, RAMSIS, SAMMIE, and the UM 3DSSP, are meant to assist a designer early in a product development process, when he or she is attempting to improve the physical design of vehicle interiors and manufacturing workplaces. To become even more effective in meeting such a goal, it is proposed that future DHMs must include valid posture and motion prediction models for various populations. It is argued in this article that existing posture and motion prediction models now used in DHMs must be based on real motion data to assure validity for complex dynamic task simulations. It is further proposed that if valid human posture and motion prediction models are developed, these can be combined with psychophysical and biomechanical models to provide a very powerful tool for predicting dynamic human performance and population specific limitations. © 2007 Wiley Periodicals, Inc.

1. INTRODUCTION

As part of the rapidly expanding global competitive environment, new products must be designed and manufactured in a short time frame and also provide a high level of convenience and safety for end users. Many different types of ergonomic software design tools are being created to meet this challenge. For improvement of the physical aspects of a product or manufacturing workcell, these tools allow a designer or engineer to create an avatar (virtual human) with specific population attributes. These avatars then can be inserted into a designer's three-dimensional (3D) graphic renderings of proposed work environments. Figure 1 is an illustration of such a design tool referred to as Jack being used to assess a potential manufacturing workplace layout problem.

In this context, most often questions of reach or sight line capability for a specific proportion of the population who might perform a task of interest are simulated. To undertake such a digital human simulation, the designer is required to first specify the population segment, or relevant group attributes of concern, such as stature, body weight, gender, age, and so forth. Then the designer must position the representative avatar in the posture that the designer believes best represents the functional postures of concern. Some Inverse Kinematics (IK) algorithms are normally provided as part of the avatar's supporting

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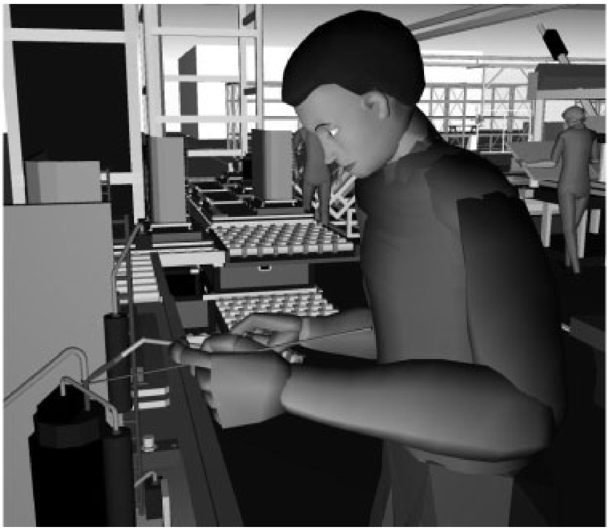

Figure 1 A typical digital human figure model for static reach, fit, and line-of-sight analysis using Jack software (courtesy of Ulrich Raschke, UGS-PLM Solutions, Ann Arbor, Michigan, USA).

software to assist the designer in choosing the appropriate postures for analysis. Unfortunately these IK methods may not be very biomechanically sophisticated, however, and can result in erroneous postures being chosen (Chaffin, Faraway, & Zhang, 1999). This becomes an overarching reason for the type of research under way in the Human Motion Simulation (HUMOSIM) Laboratory at the University of Michigan, described later.

It appears that recently many different companies have established internal organizations to utilize this new digital human modeling technology. Seven case studies reported by Chaffin (2001) describe the successful use of various digital human models to analyze and improve the physical ergonomics of different designs. This view is consistent with the concept of reducing total design and engineering costs by using computer-aided engineering (CAE) and digital mock-up (DMU) methods to achieve rapid, virtual prototype development and testing, as diagrammed in Figure 2.

One issue in supporting this trend was highlighted by Broberg (1997), who reported that over 90% of the system designers and engineers in Europe whom he surveyed recognized that they needed to consider ergonomics early in the product development process. Unfortunately, he found that they reported that they had little time and training in ergonomics to accomplish this. This latter issue was further illustrated in a recent, small survey of engineering educators by Chaffin (2005). He reported that fewer than 10% of engineering degree recipients in the United States have completed even one course in human factors and ergonomics. Given this situation, why should we expect a product or machine designer to make appropriate decisions about the postures and motions of various people in a proposed digital human model (DHM) simulation if the DHM tool does not provide a great deal of effective guidance in accomplishing this important task?

Despite this situation, the case studies reported by Chaffin (2001) seem to indicate that when an ergonomics expert is included in the design team, the most prevalent use of digital human modeling is to simulate people of extreme sizes (i.e., to perform three-dimensional anthropometric functional analyses) for the purpose of evaluating

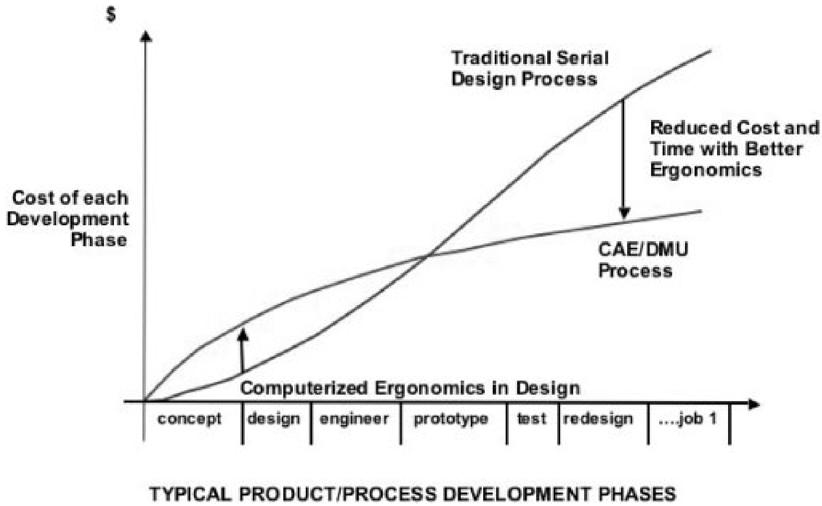

Figure 2 Typical development phases and hypothetical cost profiles believed to exist when using a DMU (with human simulation) early in the design process compared to not using DMUs, which results in increased prototype building and ergonomics evaluation costs late in the development process.

alternative designs that will accommodate a large variety of people. In a few cases, there existed a need to use a DHM for predicting a population's reach and clearance capability, including the mitigating effects of different clothing or personal protective equipment, such as heavy gloves or helmets. In some other cases, the issue was one of how much human strength and/or endurance was required to perform a manual exertion, with special concern that the final design comply with U.S. NIOSH or DOT policies. This latter use of DHM technology is illustrated in a case study reported by Feyen, Liu, Chaffin, Jimmerson, and Joseph (2000), wherein the University of Michigan's 3DSSPP software was used in an AutoCad application to suggest job design changes to accommodate a larger worker population. Finally, in a few cases, the authors in Chaffin (2001) believed one of the most important features of a DHM was that the human simulations and associated graphics allowed both product and process designers to understand better the potential problems and associated risks a particular population subgroup could have when operating or servicing a proposed design.

One general problem revealed in these case studies is that designers were often highly challenged when predicting how a person of certain anthropometric characteristics should be positioned in the virtual workplace, especially if dynamic motions were to be simulated. As discussed by Chaffin et al. (1999), posture and motions of people are not well modeled in existing digital human models, and using inverse kinematics and other related robotics methods can assist in this task, but may not be sufficient, particularly if the designer does not have a profound understanding of biomechanics as well as the time to experiment with alternative postures and motion scenarios. This is a very serious deficiency if one is to evaluate the strength and biomechanical stresses of a manual task being simulated, as it has been shown that small errors in postures can result in very large errors in the predicted population strengths. It is the inability of existing digital models to predict realistic and valid population postures and motions that has motivated the development of the HUMOSIM Laboratory at the University of Michigan.

2. SOME METHODS FOR PREDICTIVE MODELING OF HUMAN MOTIONS

Many different methods have been employed to predict how people move. It is beyond the scope of this article to review these methods in detail, but the reader is referred to several excellent reference sources by Allard, Cappozzo, Lundberg, and Vaughan (1998), Jagacinski and Flach (2003), Nigg, MacIntosh, and Mester (2000), and Zatsiorsky (1998). All of the existing methods can produce realistic-looking motions, but most have been tested with limited human motion databases, and many of these methods are applicable to small linkage systems, normally three to five links.

Many different approaches to human motion prediction are being developed and promoted by various research groups. In this regard, it is proposed that the following criteria be considered when evaluating these for use in DHMs for proactive ergonomics:

1. Simulated motions must be based on real human motion data to have internal "construct" validity and "empirical" validity.
2. Models of motions should be able to represent motions not in an existing database—have extrapolation capability while retaining the essential motion behaviors contained in the motion database.
3. Models should be computationally fast and portable for real-time simulations and use in commercial CAD-DHM software products.
4. Models should be adaptable so that they can assimilate new motion data and algorithms, so as to become more robust in predicting novel motion situations of interest to a designer.

2.1. The University of Michigan's HUMOSIM Laboratory for Posture and Motion Prediction

The following is a brief description of the current state of the UM Human Motion Simulation Laboratory. Fixtures were first built in 1998 to allow the study of both seated and standing reaches, materials handling, and vehicle driving tasks. Older biomechanical models were expanded to include the ability to model the kinematics of a multiple link human form representing the whole body, with over 45 degrees of freedom. To date over 245 subjects of both genders, ranging in age from 18 to 81 years, have served as subjects in a series of motion studies. These studies have resulted in almost 100,000 motion data sets. These data sets have been shared with researchers all over the world. For more information on accessing the data as well as a description of the laboratory studies, see www.HUMOSIM.org.

2.2. Modeling of Motions in the HUMOSIM Laboratory

2.2.1. Function regression method for reach modeling. The predominant method used in the HUMOSIM laboratory is referred to as the functional regression method for predicting joint angles and segment trajectories during the motion of a hand or foot while the subject is performing a specific manual task. This methodology is particularly useful in dynamic motion modeling, wherein 3D motion capture technologies can rapidly produce very large and dense data sets that are not very noisy throughout a motion (i.e., the joint angles $\theta(t)$ and segment trajectories are rather smooth, regular, and known), and yet there is a great deal of variance from person to person and from task to task.

Faraway (1997) has developed a functional regression model for this purpose. It uses the form

$$\theta(t) = \beta_0(t) + C_\chi \beta_\chi(t) + C_y \beta_y(t) + C_z \beta_z(t)$$

$$+ C_\chi C_y \beta_{\chi y}(t) + C_y C_z \beta_{yz}(t) + C_z C_\chi \beta_{z\chi}(t)$$

$$+ C_\chi^2 \beta_\chi^2(t) + C_y^2 \beta_y^2(t) + C_z^2 \beta_z^2(t) + D,$$

where $\theta(t)$ are the predicted joint angles over time, C_χ, C_y, and C_z are target coordinates, $\beta(t)$ are parametric functions to be estimated, and D are demographic variables (e.g., age, stature, gender, etc.) that could modify the predictions.

This quadratic regression model was found by Faraway (1997) to account for approximately 80% of the joint angle deviations measured in one set of reach data. Because this method provides statistical estimates of both the average and standard errors related to environment, task, and population attributes, it was the method used by Chaffin, Faraway, Zhang, and Woolley (2000) to statistically describe the dominant role that stature has in predicting seated reaching motions, compared to gender and age affects.

The realization of an end-point prediction error when using the functional regression method for design of a reaching task led Faraway (1999) to develop a new formulation for motion prediction, now referred to as the "Stretch Pivot" method. The Stretch Pivot motion prediction method combines the former statistical functional regression model of joint angle and location predictions with an estimate of the hand coordinates predicted by a regression of the trajectory and orientation of the hand as it is moved from the origin to a destination in a task. This is done in such a manner that the hand is guaranteed to land where it is supposed to land in any given reach task simulation. To accomplish this, the multisegmented body is decomposed into two or three link groupings that can stretch and pivot as they are moved as groups within an IK structure using the functional regressions of critical angles and joint locations for each group, but with the ends of each group connected as a kinematics linkage. The latter constraint assures that the motions of adjoining links remain connected to the whole linkage throughout the motion. The new formulation produces joint coordinate trajectories during a motion that are smooth in time and robust to varied input conditions.

2.2.2. Motion engineering algorithm development. Park, Chaffin, and Martin (2004) proposed a motion engineering system consisting of three components: a motion database (memory of general motions), a motion search and comparison method (retrieval), and a motion modification algorithm (generalization). An organized motion database can be thought of as a model of a human memory of motor skills. Either the Stretch Pivot method can now be invoked to render the motion of interest or "nearest neighbor" root motions can be chosen and analyzed by a motion structural analysis algorithm to further identify their fundamental angle–time patterns. In this latter regard, Park has developed a motion modification method to identify the underlying structure of competing root motions and then modify these slightly while retaining their inherent joint angle patterns to satisfy a newly designated reach scenario (Park, Chaffin, Martin, & Faraway, 2005).

2.2.3. Spinal-pelvic motion modeling. One limitation in many of the existing DHM models for reach modeling is due to the use of an overly simplistic torso kinematics algorithm. The torso often is geometrically modeled with a large number of links, sometimes mimicking the vertebral column, but the underlying kinematics model that predicts the relative motions of these segments is a highly reduced model, often using simple proportionality rules for each segment's movements relative to the motion of the entire column. Reed, Parkinson, and Chaffin (2003) discuss this issue and propose a much more sophisticated model, one that is based on careful observations of the curvature changes in the spinal column and rotations of the pelvis of people reaching around a seated workplace. Some results of this study are illustrated in Figure 3.

2.2.4. Seated balance during reaching motions. Another issue that must be considered in predicting reaching capabilities to the side when seated is the ability to maintain balance as one leans the torso in a lateral direction. Parkinson, Chaffin, and Reed (2006) have studied this phenomenon in 38 anthropometrically different individuals from age 21 to 74 years. What they found was that the soft tissue around the greater trochanterion of the hip appears to provide the maximum excursion limit for the center of pressure during lateral reaches. This is a much larger excursion than normally assumed in

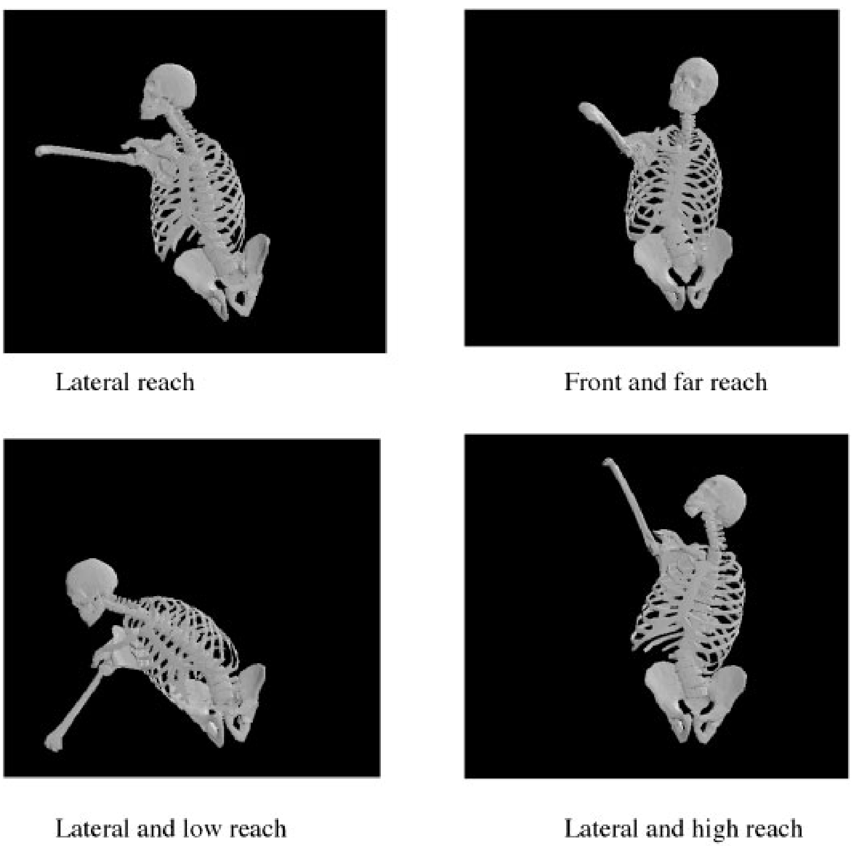

Figure 3 Illustrations of the complex pelvic orientations and spinal column curvatures associated with four different arm-reaching tasks in a seated posture (from Reed et al., 2003).

most DHM models. They also reported that their older subjects were less inclined to lean their torsos as much as younger subjects, and thus did not take advantage of the extra stability provided by the soft tissue and associated greater trochanterion structures.

2.2.5. Head–hand coordination modeling. Though most models of human motion have concentrated on understanding the kinematics involved in hand or foot gait motions, the need to understand the kinematics of head positioning and movement also is being studied. One issue has been whether the head move in certain ways to assist in visually guiding the hand throughout the motion of the hand or does it simply assist in the final phase of precise hand motions. And what visual requirements may alter head motions during reaching tasks? Some of this work is described by Kim and Martin (2001).

2.2.6. Shoulder muscle stress modeling during reaching and object moving tasks. Perception of shoulder stresses is very dependent on upper extremity postures, as shown by Kim et al. (2004). Additional modeling of the shoulder musculoskeletal complex by Dickerson (2005) has shown that when lifting and moving even moderate mass objects the shoulder muscles can become highly stressed. Such tissue stress is sensed and used to limit the excursion of the shoulder–arm complex in some tasks, thus causing more torso motion compensation. This was shown empirically by Chaffin et al. (2000) with older individuals in particular.

2.2.7. Foot placement during load transfer tasks. Another study underway at this time is meant to predict the complex foot placements chosen by people when lifting and carrying objects of varying weight. Though several excellent models exist of foot stepping trajectories for situations when a person is not performing a manual task, when a simulation requires the DHM to execute a lifting or object manipulation task, the predicted foot trajectories are highly dependent on environmental, task, and personal attributes. Work by Wagner, Reed, and Chaffin (2005) is attempting to develop a model to predict the affect of these for a variety of manual handling tasks.

2.2.8. The UM Motion Framework. As can be imagined from the above descriptions, modeling human reach and object manipulation tasks for a variety of people requires many different considerations and models to be integrated into a robust and valid motion prediction system. This is the goal of the "Motion Framework" proposed by Reed et al. (2005). This motion model integration approach is illustrated in Figure 4. This structure displays how various geometric properties of objects displayed in a typical CAD program are combined with task and population input statements at the top to select and utilize various motion prediction models at the bottom. The result is a set of algorithms based on the past 8 years of human motion studies, which work together in a seamless and transparent fashion to render a very large variety of whole body motions for ergonomics assessments. Though this development is still continuing, its worth has been demonstrated in several design case studies.

3. TOWARD AN INTEGRATED DYNAMIC HUMAN SIMULATION MODEL

The procedures described above provide a means to efficiently estimate values for the joint and segment kinematics involved in normal reaching and object movement behaviors. The resulting kinematics, when combined with a good digital human figure model,

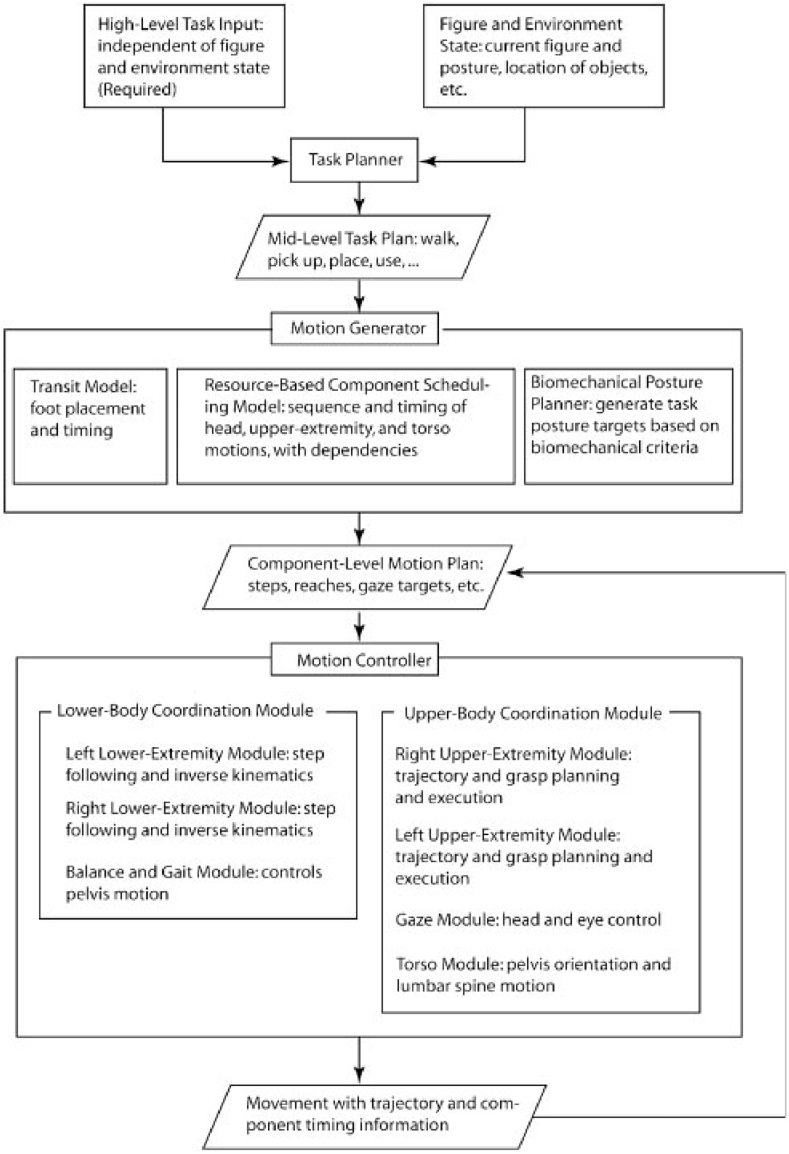

Figure 4 An integrative Motion Framework developed by Reed to provide a robust method of predicting motions associated with different environments, tasks, and population attributes.

as shown earlier in Figure 1, provide an improved means of assessing dynamic population fit/clearance, reach, and visibility requirements.

More importantly for many ergonomics analyses, we can link an existing biomechanical model to our new motion kinematics model. Such linking, as done in the 3DSSPP and Jack programs, provides a prediction of population muscle static strength requirements at each joint throughout the movement, develops estimates of lumbar motion segment static

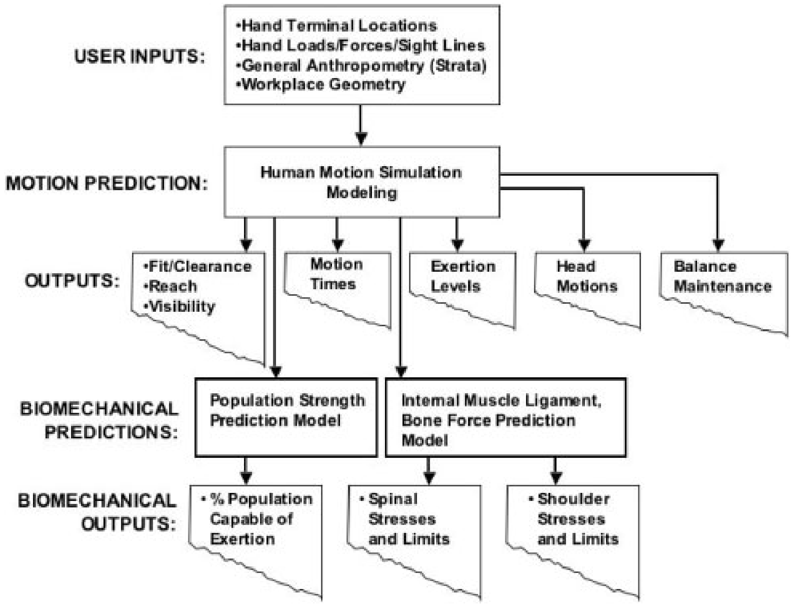

Figure 5 University of Michigan's HUMOSIM integrated ergonomics modeling project.

compression and shear forces, estimates balance and foot slip potential, and references a variety of psychophysically determined human strain indices, reach envelopes, and NIOSH limits. The general logic for these combined programs is illustrated in Figure 5.

4. SUMMARY

This article has attempted to outline some of the major issues that must be addressed to improve the functionality of existing DHM tools. The underlying thesis is that only when valid postures and motions are readily available to a designer using a DHM will the biomechanical and other ergonomics analysis model predictions be correct. As described, the HUMOSIM laboratory is attempting to meet this fundamental need, as well as link the resulting motion predictions to other new ergonomics assessment models. The motion database and human motion models provided by the HUMOSIM Laboratory hopefully will be of great assistance to many other groups concerned with this emerging proactive ergonomics technology. For additional information and references about the work reported here, please consult www.HUMOSIM.org.

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