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Validation of the Human Motion Simulation Framework: Posture Prediction for Standing Object Transfer Tasks

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ABSTRACT

The Human Motion Simulation Framework is a hierarchical set of algorithms for physical task simulation and analysis. The Framework is capable of simulating a wide range of tasks, including standing and seated reaches, walking and carrying objects, and vehicle ingress and egress. In this paper, model predictions for the terminal postures of standing object transfer tasks are compared to data from 20 subjects with a wide range of body dimensions. Whole body postures were recorded using optical motion capture for one-handed and two-handed object transfers to target destinations at three angles from straight ahead and three heights. The hand and foot locations from the data were input to the HUMOSIM Framework Reference Implementation (HFRI) in the Jack human modeling software. The whole-body postures predicted by the HFRI were compared to the measured postures using a set of measures selected for their importance to ergonomic analysis. The results demonstrate that the HUMOSIM Framework standing posture predictions agree well with motion capture data, with particularly high correlations observed for the important predictions of torso inclination and hand-to-shoulder distance.

INTRODUCTION

The accuracy of ergonomic analyses using human figure models is strongly dependent on the accuracy of the simulated postures and motions. Manual manipulation of postures by the software user can introduce large errors and lead to poor repeatability and reproducibility. Accurate postures can be obtained through the use of motion capture (e.g., Godin et al. 2006), but motion-capture studies require expensive equipment and facilities, as well as time to mock up the task and gather the data.

Posture and motion simulation methods that do not rely on captured motions offer the potential to provide accurate and repeatable ergonomic analysis without the expense of motion capture. A large number of posture and motion prediction methods have been developed, most focused on relatively narrow range of tasks. Reed et al. (2006) reviewed a variety of approaches to the human simulation problem in the context of introducing a new methodology, the Human Motion Simulation (HUMOSIM) Framework that is intended to be extensible to most human movements of interest for ergonomics. The Framework is a hierarchical set of algorithms that produce whole-body posture and motion based on the time-dependent specification of goals for the hands, feet, and gaze, along with other postural targets. The Framework has been demonstrated for a variety of task scenarios, such as standing and seated reaches, force-exertion postures (Hoffman et al., 2007), stepping while carrying objects (Reed and Wagner, 2007), and vehicle ingress and egress (Reed and Huang, 2008). [For more details on the Framework, see Reed et al. 2006.]

This paper presents an evaluation of the performance of the Framework for predicting standing object transfer tasks. Motion-capture data from 20 subjects placing objects with one and two hands on shelves were compared with Framework predictions using the measured hand and foot locations as input. The predicted and observed postures are compared using a set of dependent measures chosen for their relevance to ergonomic analysis. Most posture validation efforts have compared joint center locations and joint angles (e.g., Wang et al., 2005; Yang et al., 2007), but some

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aspects of posture are much more critical than the others for ergonomic analysis. Much of the focus on industrial ergonomics analysis is on the low-back and shoulder loading, because injuries to these areas are commonly and costly. The comparative measures used in this paper recognize these principles and reflect the intended use of the HUMOSIM Framework in ergonomic applications.

METHODS

DATA SOURCE – The data used to validate the whole-body standing posture predictions of HUMOSIM Framework were obtained in a set of experiments at the Human Motion Simulation (HUMOSIM) Laboratory at the University of Michigan. The procedure of the experiment has also been described in Faraway et al. (2007). Ten men and ten women with widely varying body dimensions, age, and strength participated in the study. The subjects ranged from 20 to 70 years of age.

The subjects were asked to perform reach and object-transfer tasks while standing. The task was to lift an object from a home location directly in front of the subject and move it to one of 30 target shelves (26 shelf locations were used for the current analysis). The shelves were located on 3 towers (in front of the subject and 45 and 90 degrees to the right side) and at 5 heights ranging from ankle to overhead level and 2 depths (near and far). The home location also included hand rests to define a neutral starting position. Subjects moved a tote box with both hands, a vertical cylinder with the right hand, and a horizontal cylinder with the right hand. The weights of objects were set as a portion of individual strength to maintain similar behaviors across subjects. The data discussed here are a subset of a larger sequence of experiments. For each of the 26 target locations, subjects performed three trials (tote box, horizontal cylinder, vertical cylinder). For the 20 subjects, a total of 269 task conditions were replicated. A total of 1685 trials (an average of 84 per subject) are included in the current analysis.

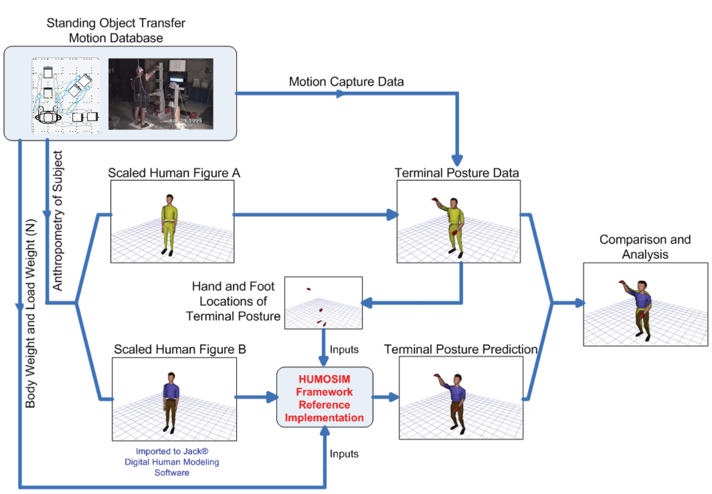


Figure 1. Schematic of standing posture validation.

An optical based motion tracking system (Qualysis MacReflex) was used to quantify whole-body motions and postures. Twenty-one markers were attached to the subjects at predefined body landmarks. The landmarks were used to estimate joint center locations using custom software.

SCHEMATIC OF POSTURE VALIDATION – The schematic of the validation procedure is illustrated in Figure 1. In the Siemens Jack 6.0 human modeling environment, two manikins were scaled to match the joint locations recorded in the trial of interest, and the body weight of each figure was set to the subject's measured body weight. The posture of one manikin was set to the measured terminal posture (joint locations) at the instant the subject delivered the object to the target shelf. The hand and foot locations from this posture were used as input to the standing posture prediction module of the HUMOSIM Framework Reference Implementation running in the Jack environment. The Framework computed a posture given the hand and foot locations and object weight, which was assumed to be evenly divided between the two hands for the tote-box tasks. The location of the center of mass of the box midway between the handles and the horizontal orientation of the box at the starting and ending locations makes this a reasonable assumption.

QUANTITATIVE COMPARATIVE MEASURES – The differences between predicted and observed postures were quantified by a set of measures selected for their relevance to ergonomic analysis. Many other variables could be computed, but accurate prediction of these variables is essential for accurate biomechanical analysis.

Torso inclination angle θ_{ti}: The torso inclination angle was defined as the angle of the vector from the midpoint between the hip joints to the midpoint between the shoulder joints with respect to vertical. The torso angle with respect to vertical is the main determinant of low-back moment across a wide range of tasks. Low-back moment is the most commonly evaluated biomechanical variable in industrial ergonomics.

Pelvis location in mid-heel coordinate system $\mathbf{x}_{pelvis\_mh} = (x, y, z)_{pelvis\_mh}$: The pelvis location in the horizontal plane of a coordinate system located at the midpoint between the heels. The fore-aft (X) axis of the coordinate system is equal to the average of longintudinal axes of the feet. The Y-axis is vertical and the Z axis is to the right. This measure quantifies the amount of squat and the translation of the pelvis relative to the feet, which is associated with balance maintenance.

Plan-view distance from hand to shoulder $d_{hs}(left, right)$: The plan-view distance from hand to shoulder (glenohumeral joint) for both left and right hands. This variable is proportional to the object weight (external) moment at shoulder.

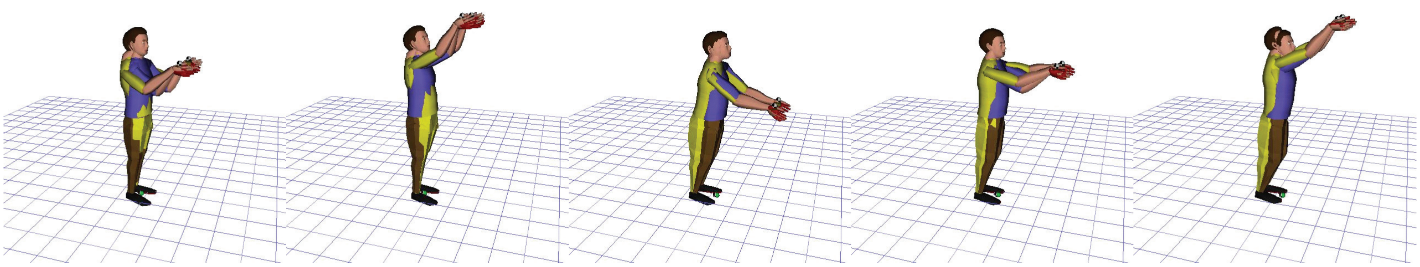
Axial rotation angle of lumbar spine θ_{ls} : The lumbar spine rotation angle is approximated by the angle of the shoulder-to-shoulder vector relative to the lateral axis of the pelvis coordinate system, defined by the vector between the hip joints. Positive indicates axial rotation to the left (left shoulder moves backwards).

RESULTS

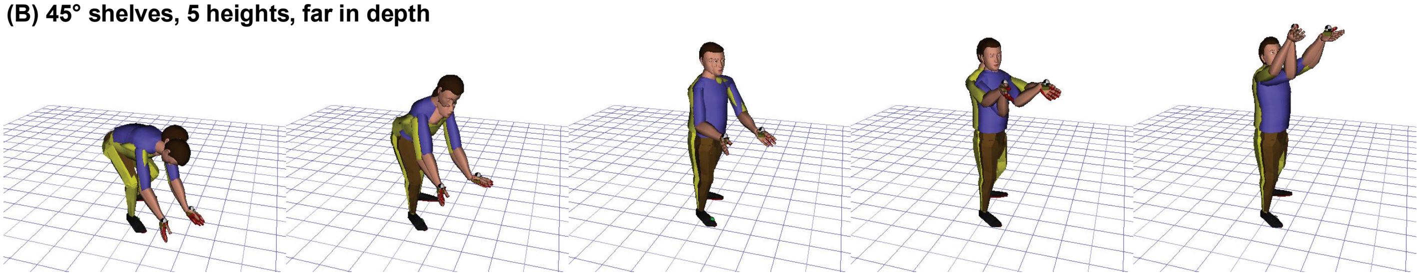
QUALITATIVE VALIDATION – Figure 2 shows predictions for two-handed object transfers by a single subject to 15 of the 26 target locations. Note the large range of postures required, from forward overhead reaches to highly twisted, low reaches. The Framework reproduces the overall postural behavior well, including the amount of torso inclination, pelvis and lumbar spine rotation, and the shoulder-to-hand relationship.

To evaluate the performance of the HUMOSIM Framework predictions across subjects, postures for 8 selected task conditions, spanning across subjects, are presented in Figure 3 and Figure 4. Five subjects are randomly selected for each task condition for illustration. Behavioral variability from subject to subject is observed in the data, in part because the fixed locations represented different relative levels of reach distance for tall and short subjects. The more extreme reaches required of the short subjects resulted in larger shifts in the center of mass and greater torso inclination for the low targets.

(A) Front shelves, 2 heights rear in depth, 3 heights far in depth



(B) 45° shelves, 5 heights, far in depth



(C) 90° shelves, 5 heights, far in depth

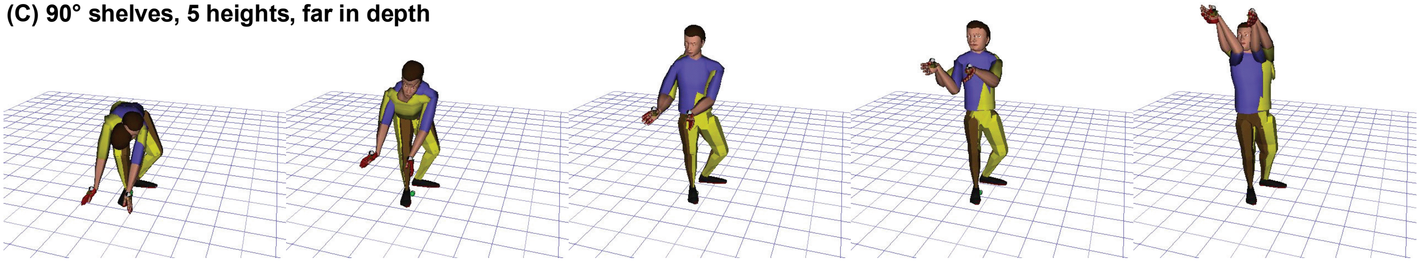


Figure 2. Comparison of observed (yellow shirt), and predicted (blue shirt) standing postures for a single subject, two-hand box transfer task of different target locations. Fifteen target locations are selected for illustration.

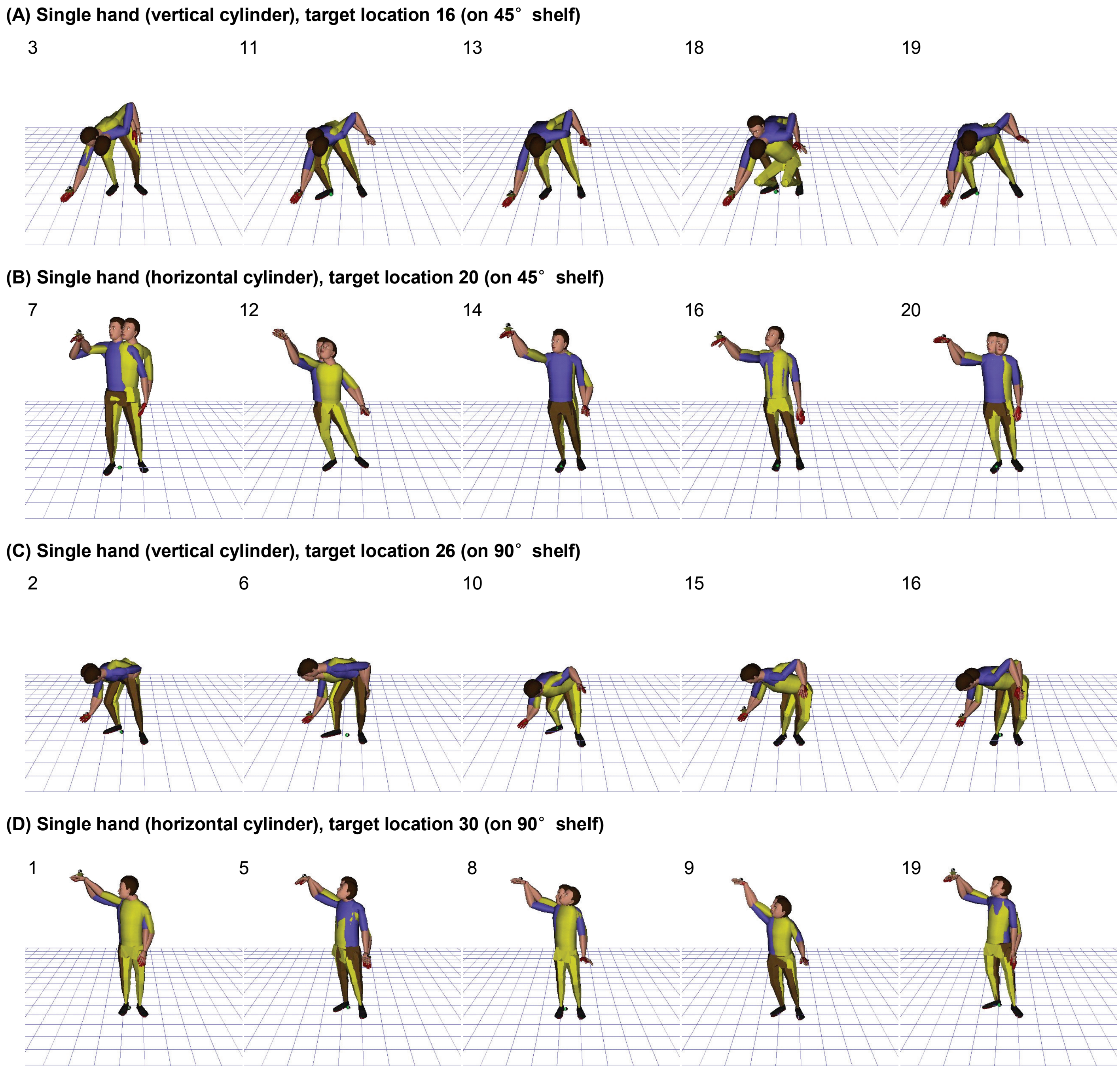


Figure 3. Comparison of observed (yellow shirt), and predicted (blue shirt) standing postures for 4 selected single-hand task conditions across subjects (subject numbers are indicated on each figure). Five subjects were randomly selected from each task condition for illustration.

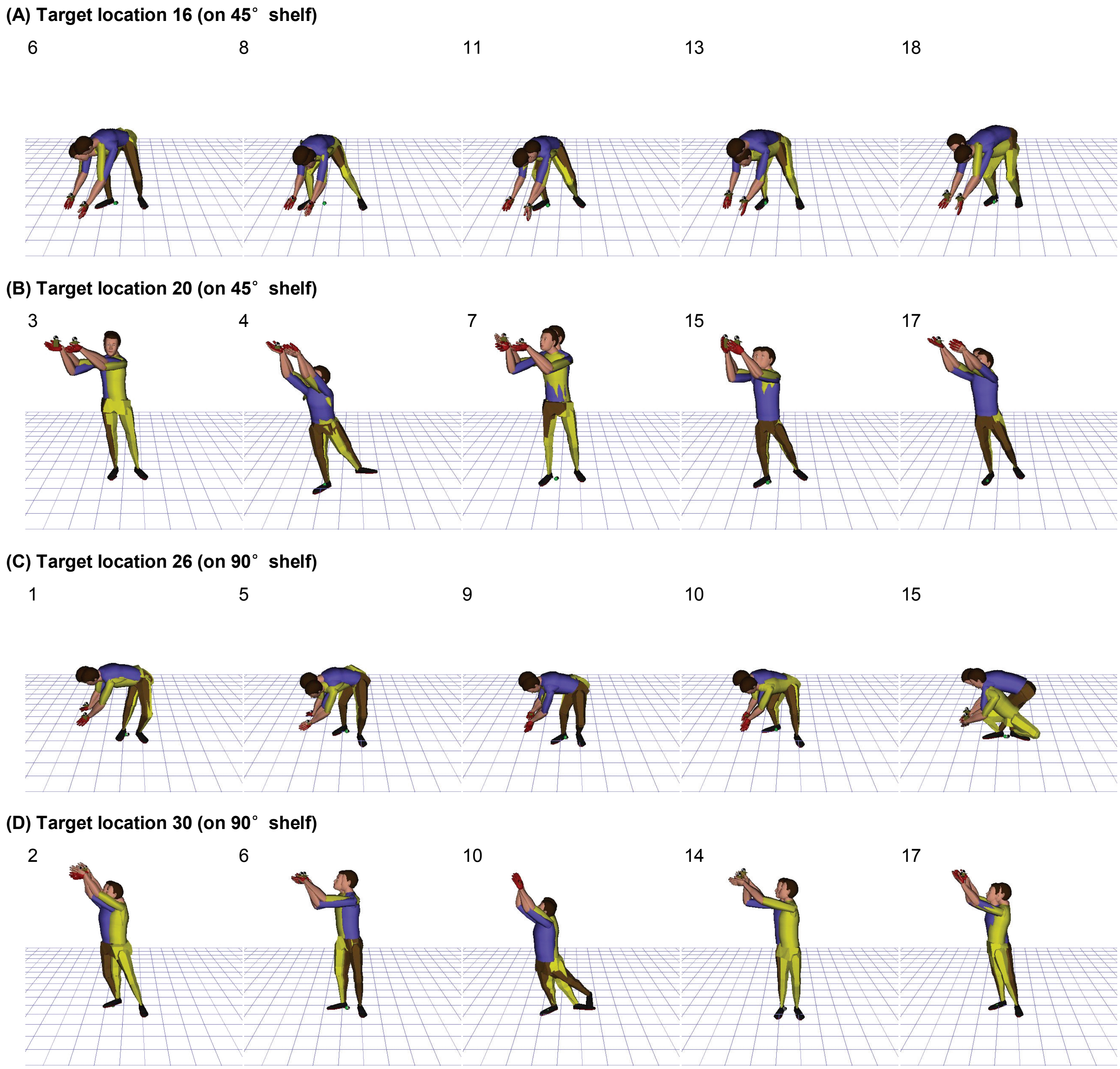


Figure 4. Comparison of observed (yellow shirt), and predicted (blue shirt) standing postures for 4 selected two-hand task conditions across subjects (subject numbers are indicated on each figure). Five subjects were randomly selected from each task condition for illustration.

QUANTITATIVE ANALYSIS – The quantitative measures were calculated for both the predicted and observed standing postures. Correlation coefficients are listed in Table 1, along with root mean square errors. The correlations between the predicted and observed values are strong, indicating a good overall model performance across the range of test conditions. For torso inclination, the correlation exceeded 0.9, indicating that a biomechanical analyses based on these posture predictions are likely to predict fairly accurate low-back moments. The correlations for the distance from the hand to the shoulder are also high, suggesting that external shoulder moment calculations would also be accurate. The comparatively low correlation for lateral pelvis position (r=0.67) is due to a small range in the underlying data, as indicated by the small RMSE value. Observed and predicted values for all trials are shown in Figure 5.

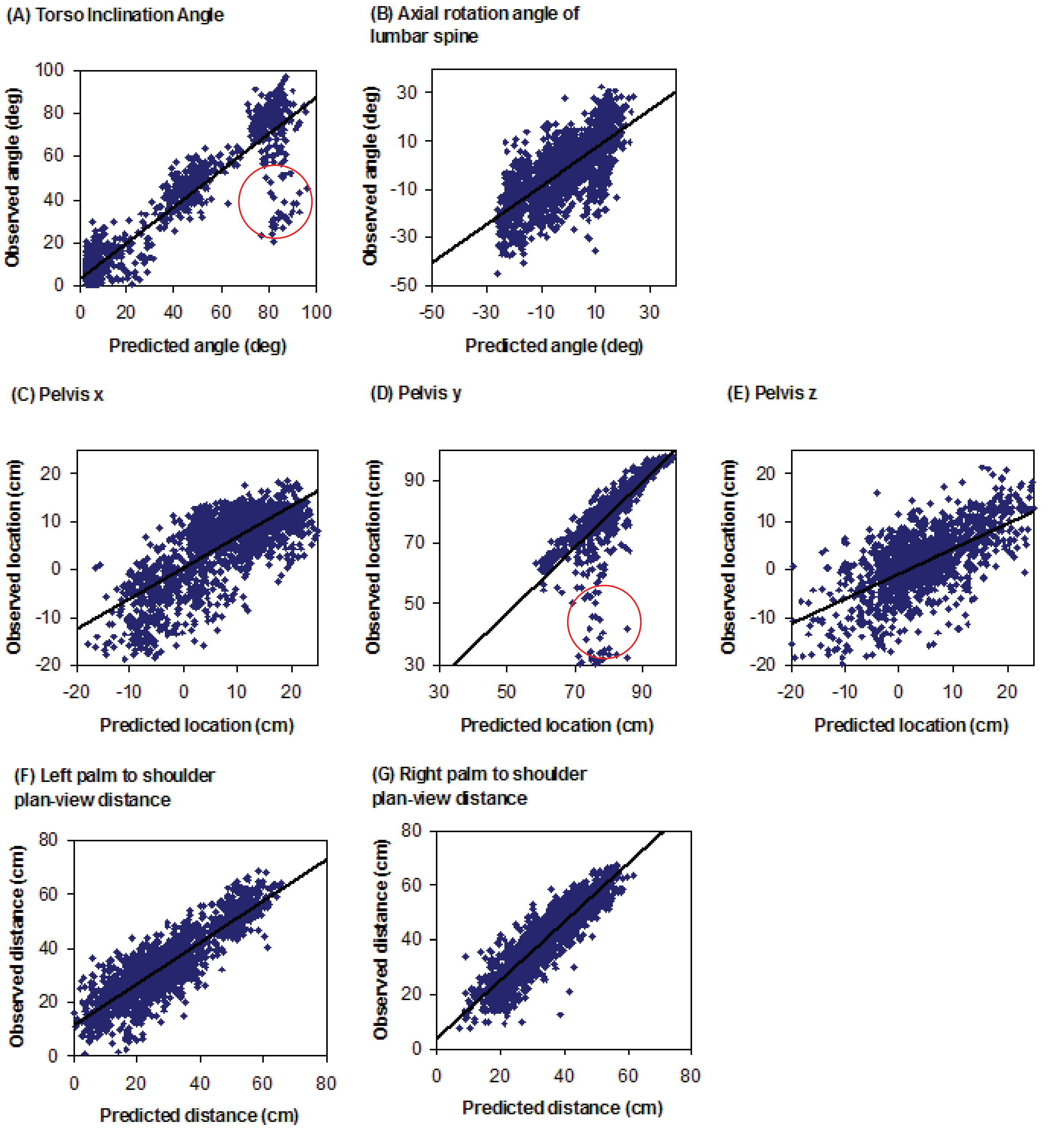


Figure 5. Observed versus predicted axial rotation angle of lumbar spine, torso inclination angle, pelvis location in the mid-heel coordinate system, and plan-view distance from hand to shoulder across all trials grouped on subject. The linear regression lines are also plotted. Outliers in the torso inclination and pelvis y coordinate highlighted by circles are due to variation in squatting behavior – see text.

Table 1. Model performance for quantitative measures

Measure	Correlation coefficient of observed and predicted values	RMSE
θ_{ti}	0.94	9.4 deg
θ_{ls}	0.72	9.6 deg
$\mathbf{x}_{pelvis\_mh}$	0.73	6.5 cm
y_{pelvis_mh}	0.77	6.7 cm
z_{pelvis_mh}	0.67	6.8 cm
$d_{hs}(left)$	0.87	8.5 cm
$d_{hs}(right)$	0.91	8.3 cm

VARIABILITY IN TACTICS – Subjects occasionally use qualitatively different tactics to perform tasks, such as squatting while reaching for low-level targets. Unusually large amounts of squat are observed as the highlighted outliers in the torso inclination and pelvis y (vertical position) plots in Figure 5 (see Figure 3A: subject 18, and Figure 4C: subject 15 for example). Some subjects squatted occasionally and others more frequently, but a statistical analysis did not show any useful means to predict which subjects would squat, with low or no correlations with stature, gender, body weight and task condition observed. Figure 6A shows different squatting behaviors for three subjects for a two-hand object delivery to one target. Using the default behavior in the HUMOSM Framework, only one of these subject's posture is accurately predicted. However, the Framework includes a variety of parameters that control posturing, including ones that influence the propensity to squat. Figure 6B shows the results of adjusting the squat parameter, which greatly improves the predictions for these trials.

DISCUSSION

MODEL PERFORMANCE – The objective of this study was to validate the HUMOSIM Framework posture predictions for standing object transfer tasks. The results demonstrate that the standing postures predicted by the Framework are generally in good agreement with the motion capture data for a large range of one- and two-handed tasks. The Framework accurately captures important aspects of the subject behavior, including torso bending and twisting. High correlations between predicted and observed measures are observed for torso inclination and shoulder-to-hand distance, which are the two most important postural variables for typical analyses of industrial tasks.

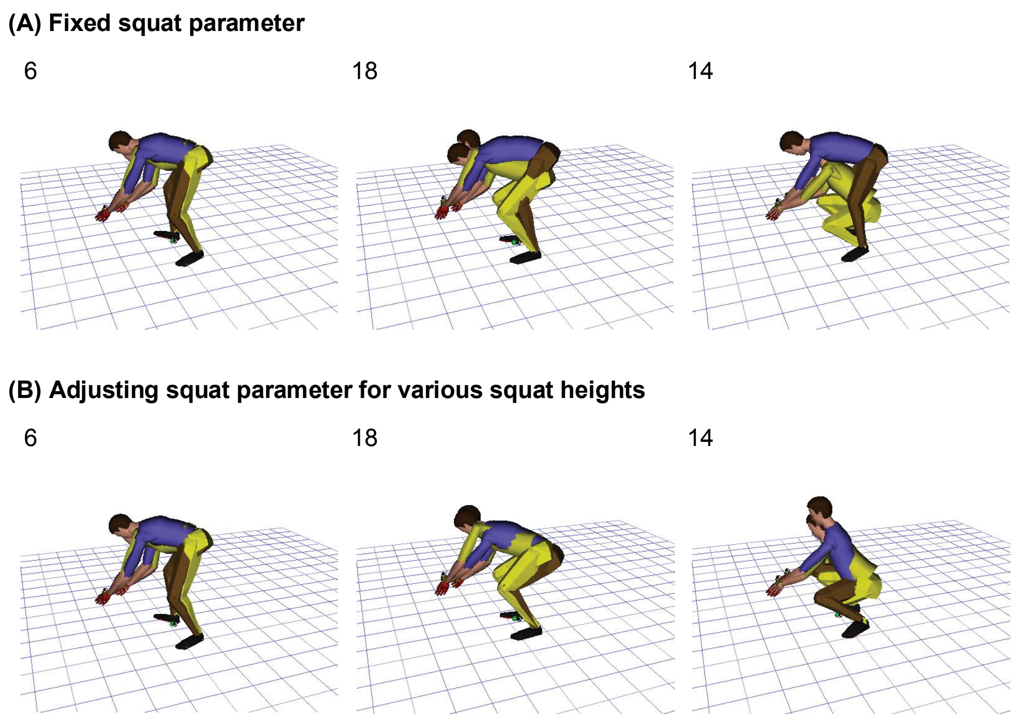


Figure 6. Comparison of observed (yellow shirt), and predicted (blue shirt) squatting postures across subject (subject numbers are indicated on each figure). The behavioral variability in squat heights of different subjects can be captured by adjusting parameters in the HUMOSIM Framework.

FRAMEWORK PREDICTIONS – The HUMOSIM Framework predictions are fundamentally different from most previous approaches to human posture prediction. The Framework posture prediction algorithm is not a unified empirical model created from the validation dataset or similar standing object transfer data (compare to Faraway 2003). The Framework does not directly use motion-capture data, as with many motion simulation approaches (compare to Park et al. 2004 or Dufour and Wang 2005). The Framework predicts the standing postures using the same underlying modeling structure that has been applied to simulating other tasks, including stepping, force-exertion tasks, and vehicle ingress and egress (see Reed et al. 2006). Some individual components of the model are based on statistical analysis of data, but most submodels are based on detailed qualitative analysis of human behavior data. The overall idea is to create a good *null model*, i.e., the default behavior that is obtained without any reference to quantitative data, and then tune the performance to match human data by adjusting a few carefully selected parameters. The parameters of the model are more like high-level control variables than the typical parameters of a statistical fit. Whole-body posture prediction ultimately requires the calculation of a large number of degrees of freedom (38 joint angles and coupled-linkage control variables for the current analysis, which neglects hand posture), but the process is considerably simplified (and more robust) when most degrees of freedom are linked together via behavior-based submodels, and model fitting is performed with high-level control variables rather than at the joint-angle level. Key components of the Framework for the current tasks include the upper- and lower-extremity inverse kinematics systems, torso movement model, and balance maintenance (Reed et al. 2006).

Realistic simulation of balance maintenance behavior is a critical enabler of the accurate prediction demonstrated for these standing object transfer tasks. The model uses heuristics based on detailed observation of human behavior in the laboratory to estimate the location of the center of pressure (CoP) relative to the base of support (The center of pressure is equivalent to the projected center of mass location for tasks without hand loads – see Hoffman et al. 2007). In tasks with relatively large base of support (distance between the feet), such as many of those in the current analysis, the range of possible postures that are in static balance is large. Accurate estimation of the CoP location is a critical step in obtaining accurate postures, particularly for torso inclination and horizontal hand-to-shoulder distances.

Balance predictions for the current tasks incorporate the postural responses to hand loads developed as part of a broader study of force-exertion postures (Hoffman et al. 2007). Comparing to no-load posture, the hand load mainly drives the pelvis backward in order to maintain balance. Due to the relatively light object loadings in this study, the difference between loading and no-loading postures is not large, but the incorporation of the hand-force exertion in the prediction means that the Framework predictions can be extended to higher-force conditions in a smooth and robust manner.

The validation results shown in this paper are the result of extensive model tuning to capture the behaviors exhibited in this and other datasets. During the tuning process, some parameter values were adjusted to match the majority of the data well (for example, the squat parameter demonstrated in Figure 6), and some of the models that produce the default figure behavior was restructured to better capture the observed behavior. For example, the relationships between the target location and the distribution of twisting motion between the pelvis and lumbar spine was adjusted several times. This tuning process should not be misinterpreted as overfitting to this specific dataset, because no subject- or task-specific adjustments were made, and all of the 1685 simulations presented above were performed with a single set of parameter values. The underlying control functions were not statistically fit to the data, although they could be. Using hand-constructed models enforces a model simplicity that emphasizes having a good null model (default behavior) over fitting complex functions to data. A good null model helps to ensure that the overall model will generalize well to novel situations.

The modeling approach used in this paper could be generalized to a large range of tasks in which the end-effector constraints are the primary task-related determinants of posture. In principle, such constraints could include obstacles and line-of-sight requirements. Moreover, the use of the foot positions as inputs in the current work could be relaxed, providing the opportunity to validate foot position prediction.

LIMITATIONS AND FUTURE WORK – The principal limitation of this validation for practical application is that the foot placements were given as inputs to the model, whereas in normal application of human models to ergonomic analysis the foot placements would need to be predicted. The subjects moved the test objects from a specified home location and were instructed to maintain the left foot approximately stationary while performing the motion. The advantage of these instructions is that a wide range of asymmetrical postures was generated, but in a real task situation a worker might take several steps rather than twisting the body. Wagner et al. (2005) showed the critical importance of accurate foot placement for biomechanical analysis of materials handling tasks using digital human models, but Wagner et al. (2006) also showed that foot placements for object transfer tasks are dependent on the locations of the preceding and succeeding tasks, so all evaluations of posture-prediction for object handling are necessarily constrained to the specific task contexts. The validation in this paper demonstrates that the Framework can accurately predict a wide range of task postures if the foot and hand locations are known. Further work is needed to generate accurate hand and foot placements for a wide range of tasks, although considerable progress has been made in the area of foot placement predictions (Wagner et al. 2006, Reed and Wagner 2007).

This study examined only transfers to targets in the sagittal plane and to the right of the subject. The Framework makes symmetric predictions for motions to the right and left, but workers might move differently when moving to targets at the left side, or using the left hand. The data and predictions are for postures held for only short durations, typically less than three seconds. Postures held for longer durations would likely be different. The tasks used relatively small but realistic object weights. More research is needed to quantify postural responses with higher object weights.

The analysis demonstrated that qualitative differences in postural tactics (stooping vs. squatting) pose an important problem for developing, validating, and applying posture simulation. Beginning with the application, methods need to be developed to present the user of ergonomic analysis software multiple postures that exceed some probability threshold for a particular task. Although this is conceptually straightforward, the typical analysis methodology focuses on a few manikins of different sizes with one posture per manikin. Automated simulation methods based on technologies such as the HUMOSIM Framework will allow analysts to quickly consider a large range of tactics and variability within those tactics. The current analysis demonstrates that a single "squat" parameter can account for the primary tactical difference observed in these data.

The current analysis is limited by errors in the motion-capture process and particularly the estimates of joint center locations from the marker data. In particular, intersubject variability in the configuration of the shoulder girdle was not well represented by the mapping between the marker data and the Jack figure. This is a general problem that affects all biomechanical modeling, where a relatively simple rigid-segment model is scaled to fit human data. A related issue is that the mass distribution of the male Jack figure was used for all calculations. On average, female subjects would be expected to have a lower center of mass location, and variations in mass distribution affect the balance calculations directly. Subject-specific body mass distribution estimates may have reduced the residual errors in the pelvis location prediction, but this affect might be overwhelmed by variation in subject tactics for center-of-pressure location.

Another important limitation is the lack of obstacles in the environment. In many industrial task situations, obstructions would influence the worker's posture. The large range of potential obstacles makes validating a general obstacle avoidance algorithm challenging, but future studies will expand validated range of Framework predictions to include common classes of obstacles, including those that can serve as support for the worker's body.

A model with performance as general as the HUMOSIM Framework cannot be declared "validated" in a categorical sense. The HUMOSIM Framework is an evolving constellation of posture and motion prediction and analysis algorithms. Validation analyses, such as those shown in this paper, represent a snapshot of model performance for a particular set of tasks at a particular point in the evolution of the overall model. Ongoing modifications to the Framework to improve the predictions for other types of tasks such as force exertions with obstacles or object transfers with contralateral bracing might change the performance for the current tasks. The automated validation process developed for the current work will allow regular monitoring of performance for a wide range of tasks, so that the posture-prediction accuracy documented in this paper can be maintained.

CONCLUSION

The HUMOSIM Framework accurately predicts whole-body postures for standing object transfer tasks given hand and foot locations as inputs. A set of comparative measures was selected that are closely related to the industrial ergonomic assessments typically performed with human figure models. The Framework captured important qualitative aspect of the subject's postural responses to the tasks, and high correlations were obtained between predicted and observed postural measures. Some of the residual variability is due to variation in tactics, particularly squatting behavior, and the adjustment of a Framework parameter value could account for this variation.

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