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ABSTRACT

Accurate representation of working postures is critical for ergonomic assessments with digital human models because posture has a dominant effect on analysis outcomes. Most current digital human modeling tools require manual manipulation of the digital human to simulate force-exertion postures or rely on optimization procedures that have not been validated. Automated posture prediction based on human data would improve the accuracy and repeatability of analyses. The effects of hand force location, magnitude, and direction on whole-body posture for standing tasks were quantified in a motion-capture study of 20 men and women with widely varying body size. A statistical analysis demonstrated that postural variables critical for the assessment of body loads can be predicted from the characteristics of the worker and task.

INTRODUCTION

Task postures have a strong effect on the outcome of many ergonomic analyses using digital human models (DHM). Assessments of low-back loading, for example, are dependent on accurate prediction of torso orientation, and calculation of shoulder moments during hand-force application is dependent on accurate prediction of hand locations with respect to the shoulders. This paper presents an investigation of the effects of hand force magnitude and direction on postures in standing tasks. The goal of this work is to predict postures adopted during standing high-force exertions based on task and worker characteristics. A validated three-dimensional posture-prediction model would provide analysts with accurate task postures, eliminating the need for analysts to make assumptions about working postures.

In previous research, posture-prediction for standing tasks has been accomplished using a variety of approaches.

The University of Michigan's 3D Static Strength Prediction Program (3DSSPP), a manikin-based task-analysis tool, uses a statistical model, combined with inverse kinematics, to predict force-exertion postures. Regression equations based on data from Kilpatrick (1970) and Snyder et al. (1972) were integrated into a behavioral inverse kinematics algorithm (Beck, 1992). This algorithm defines whole-body postures by predicting body segment positions based on hand location and orientation (supine, semi-prone, or prone), and worker height and weight.

Several strength-based posture-prediction models have recently been developed. The general proposition of these models is that workers will chose postures in which their joints can exert the largest torque. Seitz et al. (2005), building on earlier work by Rothaug (2000), developed an optimization-based approach for posture prediction that is based on human posture and strength data. The algorithm favors postures with low joint torques as well as high joint strength, and includes the effects of passive joint stiffness. The latter improves the ability to predict resting or low-force postures. The Seitz et al. model differs from other optimization approaches in being based on extensive human posture and strength data. Strength functions have been used as a "naturalness" constraint to improve the visual realism of predicted postures (Liu, 2003, Zhao et al., 2005). "Naturalness," a subjective criterion, is necessary but not sufficient validation for ergonomic analysis. More generally, joint-specific human functions have their peaks near the centers of the joint ranges of motion, so a joint-angle-based strength-optimization algorithm is largely equivalent to minimizing joint deviations from "neutral" positions. No validation has been presented that supports the possibility that subject-specific differences in joint strength correspond to differences in task postures.

Seitz et al. (2005) acknowledge that while computed postures are "plausible," a comparison between predicted and actual postures was not presented. Similarly, the work by Liu (2003) and Zhao et al. (2005) has proven capable of predicting "natural" as opposed to "awkward" postures but, naturalness is not a quantitative measure and again predicted postures have not been compared against postures actually used by workers.

Many researchers have proposed that work postures can be predicted by optimization of such factors as potential energy, deviation from neutral joint angles, discomfort, and strength. The general approach is to select, from among the set of postures that are kinematically consistent with the task constraints, the posture that minimizes (or maximizes) an objective function. The recognition that human postures are not, even on casual inspection, consistent with any single optimization criterion, has led to the use of multi-objective optimization. For example, Marler et al. (2005) propose three "key" considerations that they hypothesize are related to human posture selection behavior. Multi-objective optimization for posture prediction relies on the user to change the relative weights or priorities assigned to each objective to produce accurate postures. In effect, this approach substitutes the potentially more tractable problem of choosing a vector of objective weights for the basic problem of choosing joint angles, but does not itself provide a validated solution to the posture-prediction problem.

Posture and motion prediction can also be accomplished by modifying motion-capture data to conform to the requirements of the task (Park et al. 2004). For this approach to be accurate, the underlying dataset must include tasks that are substantially similar to those being simulated, including with respect to the directions and magnitudes of forces. Recent progress in this area (e.g., Dufour et al., 2001) suggests that the method can be effective for tasks, such as vehicle ingress/egress, in which span of the variables affecting the motions is relatively small. However, this approach does not provide a general solution to the prediction of novel tasks.

Reed et al. (2002) and others have presented predominantly statistical approaches to posture and motion prediction. Data from human volunteers performing tasks similar to those that are to be simulated are analyzed to express postural variables as a function of task and operator characteristics. Seidl (1994), in work to develop posturing models for the RAMSIS manikin, created a posture-prediction algorithm that maximizes the likelihood of joint angles relative to a database of human postures for similar tasks. Faraway (2003) has developed statistical methods for motion prediction that can also be used to predict static task postures. These methods provide validated accuracy for tasks similar to those in the underlying dataset, including the effects of task variables. However, all of the statistical approaches are limited in a manner similar to the motion-capture approaches, which is that the prediction accuracy degrades substantially for task conditions outside of the range of the underlying database.

We propose a new approach to the prediction of standing postures with high hand forces that combines many of the advantages of previous approaches with several innovations. One major principle underlying the new method is the recognition that some aspects of posture are much more critical for biomechanical ergonomic analyses than are others. For standing tasks with hand-force exertions, an ergonomist is focused most frequently on low-back and shoulder loading, because injuries to these areas are common and costly. These outcome measures are influenced most strongly by torso inclination relative to gravity and by the position of the hands with respect to the shoulders and low-back. The accuracy of an algorithm for posture prediction that is intended for use in ergonomics should be judged on the basis of its ability to predict outcome measures, such as task-specific joint loading, rather than on global measures of joint angle correspondence.

This paper presents a laboratory study and a preliminary investigation of the effects of hand force magnitude and direction on whole-body postures. Statistical analysis of several biomechanically important measures of posture show that they can be meaningfully predicted from task and operator characteristics.

METHODS

LABORATORY SETUP

The study was conducted in the Human Motion Simulation (HUMOSIM) laboratory at the University of Michigan. Data were obtained using a laboratory setup comprised of four systems: (1) force platforms, (2) force handle, (3) force feedback display, and (4) motion tracking system (Figure 1).

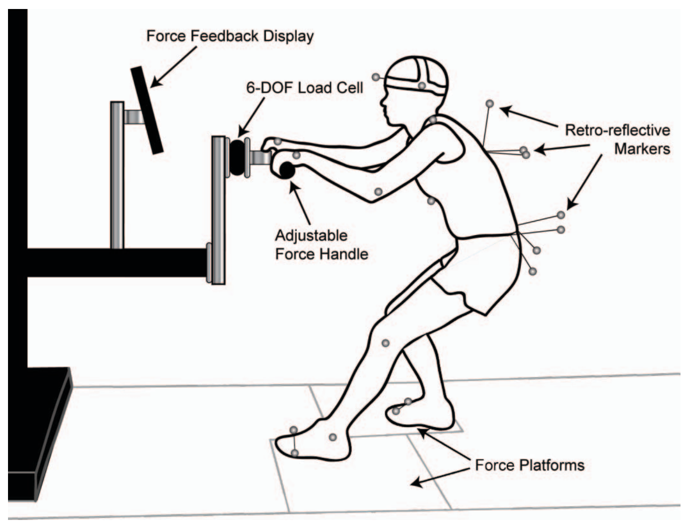

Figure 1: Laboratory configuration.

Because preferred foot placements vary with task parameters (Holbein & Chaffin, 1997) moveable force plates were used to capture ground reaction forces for various stances.

Forces and moments at the hands were measured via an adjustable force handle affixed to a 6-DOF load cell. The handle was a cylindrical, rigid bar 470 mm long and 35 mm diameter. Handle was covered with 5-mm-thick foam rubber that provided a high-friction grip. Hand force feedback was presented visually to the subject allowing subjects to achieve and maintain requested hand forces. It has been reported that without feedback on hand forces, the measured hand force vector differs from that requested (Kerk, 1992). A force feedback display that provides the subject with real-time feedback on hand forces was developed in LabVIEW 7.1 to assist the subject in controlling variations in force magnitude and direction. An eight-camera Qualysis Proreflex 240-MCU optical based motion tracking system was used to quantify whole-body motions and postures.

DATA COLLECTED

Twenty-nine retro-reflective markers were placed on body landmarks (Figure 2). Kinematic data were sampled at 50 Hz and all analog signals sampled at 500 Hz. Video was taken of each trial and synchronized with the kinematic data and the analog data from two AMTI force plates and a JR3 load cell. In addition, anthropometrics, body segment mass estimates, and strength measures were obtained for each subject. Manually digitized body landmark data were combined with the three-dimensional marker data from each trial to create a linkage representation of the human body in the terminal posture (Reed et al., 1999).

Figure 2: Retro-reflective marker set used to track whole-body motion.

TEST CONDITIONS

Participants performed trials at three handle heights and with a wide range of different force magnitudes and directions. For the current analysis, data from two-handed pushing and pulling tasks at elbow height from 15 study participants were extracted from the larger dataset. The current analysis focuses on unconstrained trials, in which participants were told to exert a force forward or rearward, but off-axis forces were not constrained and only the on-axis (i.e., forward or rearward) force magnitude was presented to the subjects.

Prior to the main series of test conditions, participants performed a series of maximal exertions in the assigned direction. Maximal-exertion trials were 6 seconds in duration and were preceded by a practice trial. During the practice trials subjects were encouraged to explore different postural strategies. Practice trials served as an opportunity for subjects to identify their preferred posture and gain familiarity with the force feedback display. Maximum values were recorded and used to define the subsequent force levels.

Submaximal exertion trials were conducted at 25%, 50%, and 75% of the participant's measured maximum in each direction. Submaximal trial durations ranged from 6 to 12 seconds depending on the time required for a subject to achieve the hand force criteria and maintain the criteria for 3 seconds.

Table 1: Test conditions and number of trials analyzed (men / women).

	Force Level (% of maximum)			
Force Direction	25%	50%	75%	100%
Pull	6 / 8	6 / 8	6 / 8	7 / 8
Push	26 / 31	27 / 30	24 / 31	5 / 8

RESULTS

Table 1 lists summary attributes for the participants. All participants were young students (median age 21 years) and relatively thin (median body mass index 23 kg/m^2).

Table 2: Mean (sd) of participant descriptors.

	n	Age [yrs]	Stature [cm]	BMI [kg/m^2]
Men	7	22.6 (3.4)	174.5 (6.1)	23.0 (3.1)
Women	8	20.9 (2.4)	161.7 (6.5)	22.6 (2.6)

QUALITATIVE OBSERVATIONS

The development of this experiment was inspired in part by the informal observation that people can estimate hand force directions and magnitudes fairly well from a static image of a person performing a task. Although most people could not quantify the aspects of posture that reveal the operator's intention, one might say that a person "leans into" the direction of force or "leans back" to pull. A side-view photograph was taken of each trial during the three-second peak-force hold. Figures 3 and 4 show example images that demonstrate this intuitive phenomenon but also show important differences in style among individuals. Figure 3 shows frames from two participants pushing forward with off-axis forces unconstrained. If we consider the torso inclination as "body lean," we see some evidence that individual's lean in the direction of force. But, more strikingly, we see large changes in the position and size of the base of support defined by the foot placements. As the force magnitude is increased, the base of support widens along the axis of the force (fore-aft), and the distance of the rear edge of the base of support to the torso increases. The top and bottom series of images in Figure 3 show two differences in pushing style defined by elbow angle. Both seem designed to reduce the magnitude of active elbow extension moment. At the top, the participant has flexed her elbows maximally, adding passively-generated moments at the elbow and bracing the hands and handle against the torso at the higher force levels. In the bottom image series in Figure 3 the participant is using an extended-elbow strategy that minimizes elbow moment. Note that in both of the strategies depicted in Figure 3, the forward foot is under or forward of the torso. Compared with a posture with both feet together at the position of the rearward foot, this represents a conservative strategy, in the sense that a sudden removal of hand force would not result in a fall.

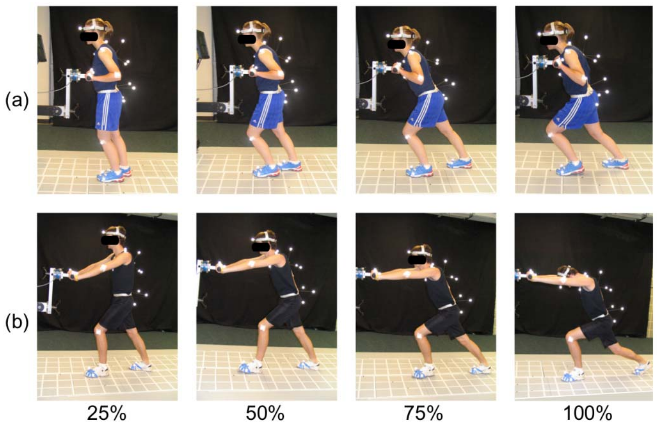

Figure 3: Two-Handed Pushing Strategies: (a) arms flexed; (b) arms extended.

Figure 4 shows a similar photo series for pulling trials. Three strategies are observed. The bottom two rows show two different elbow postures: flexed approximately 90 degrees and one or both elbows straight. Based on the observations from pushing trials, in which participants appeared to try to minimize the consequences of strength limitations at the elbow joint, some of the participants adopted strategies in the pulling trials that seemed to depend on substantial active elbow moments. These elbow joint angles, being near the center of the range of motion of the joint, are probably also approximately at the angle in which the highest moment can be produced. But it remains unclear why these participants would not choose the straight-elbow posture shown in the bottom series. Perhaps the bent-elbow posture protects the elbow or shoulder, e.g., from dislocation. The top photo series in Figure 4 shows a pulling strategy that is less conservative than the others, in that the participant is using a side-by-side foot position, with the torso located well rearward of both feet. This strategy is risky in that a sudden removal of the handle force would likely lead to a fall. In this study, risky strategies were much less common than conservative strategies for positioning the feet.

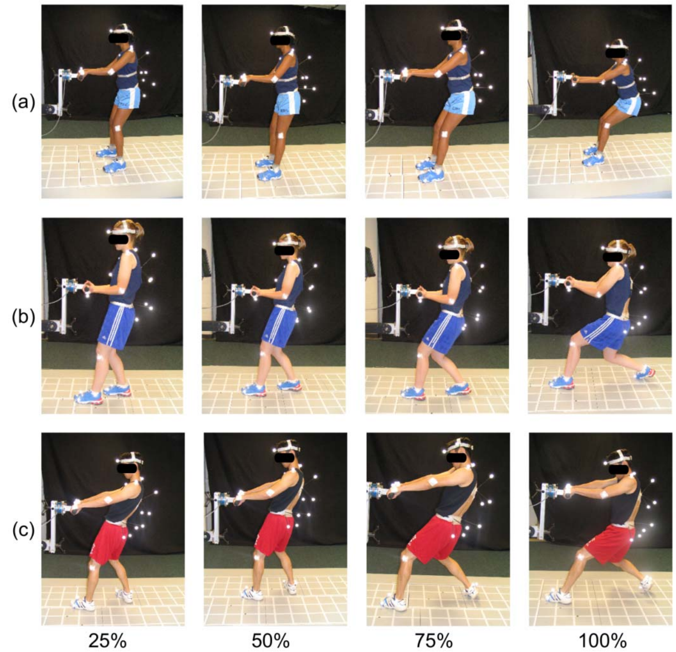

Figure 4: Two-Handed Pulling Strategies: (a) parallel stance, whole-body center-of-mass (COM) rearward of base of support (BOS); (b) split-stance, COM over BOS, arms flexed; (c) split stance, COM over BOS, arms extended.

Unconstrained pushing and pulling tasks resulted in substantial off-axis forces. For all of these trials, the handle height was set to the standing elbow height of the participants. Forces applied to the handle are reported as positive upward and rearward. When pulling (right side of Figure 5), participants tended to exert an upward force in addition to the required horizontal force. As depicted in Figure 4, the shoulder tended to be above the handle in pulling postures, and the vertical component of force indicates that the resultant force vector was oriented closer to the shoulder than a horizontal vector would be. In pushing (left side of Figure 5), the force vector for low force magnitudes has a downward component (negative values on the vertical axis), but high pushing forces include an upward component. Referring to Figure 3, higher push forces are associated with lower shoulder positions. Upward forces at the hands increase the vertical component of the ground reaction force at the feet, allowing higher horizontal forces to be generated within the limits of floor friction.

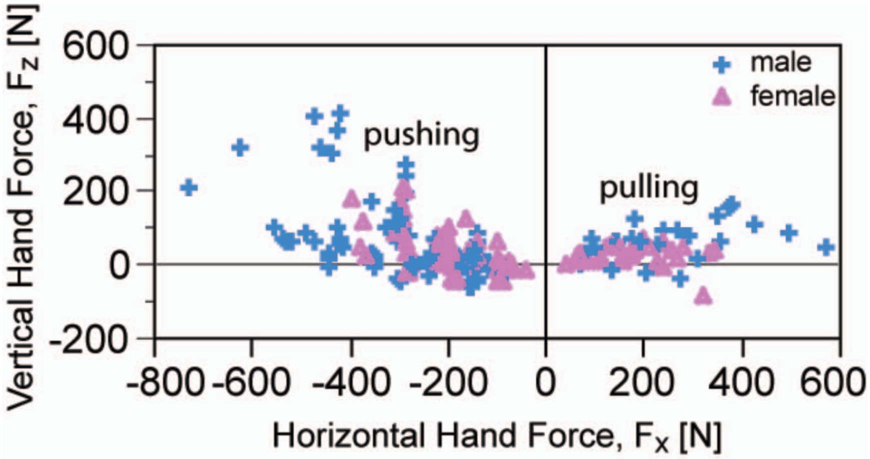

Figure 5: Horizontal and vertical hand force components measured during two-handed push/pull exertions.

QUANTITATIVE ANALYSIS OF POSTURES

A set of planar (side-view) biomechanical variables was calculated for each trial. The origin is defined as a point on the floor directly below the center of the handle. The location of the torso center of mass (COM) was estimated using relationships from de Leva (1996). For men, the torso COM was estimated to lie 41.5% of the vertical distance from the hips to the suprasternale notch in standing. The fraction was 44.9% for women.

Posture metrics are shown in Figure 6, including the front and rear boundaries of the base-of-support (BOS), horizontal distance between the center-of-mass (COM) location and the active boundary of the BOS (front boundary during pulling and rear during pushing), the vertical position of the COM, torso inclination relative to vertical, and the height of the shoulder above the handle. For the current analysis, linear dimensions were normalized by subject stature and force measures were normalized by body weight.

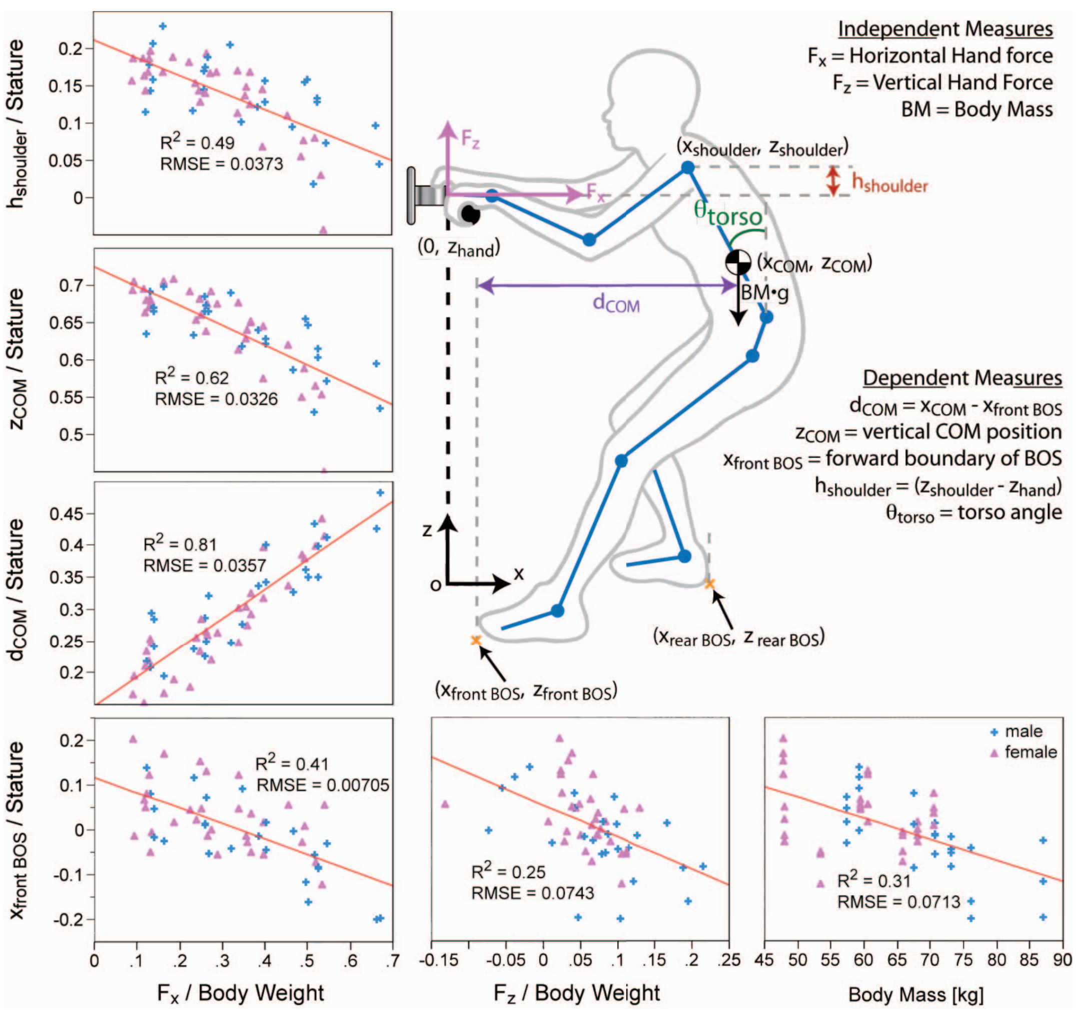

Figure 6: Significant predictors (p<0.0001) of two-handed pulling postures.

PULLING POSTURES

Figure 6 shows that important aspects of pulling postures can be predicted from task and participant characteristics. The strongest relationship is the relationship between the horizontal pulling force and the location of the torso center of mass with respect to the front edge of the base of support (R^2 for the linear regression is 0.81). This observation can be explained through an examination of the means by which a standing person can exert a horizontal force. Consider a point on the base of support closest to the handle ($x_{front\ BOS}$ in Figure 6). The horizontal force exerted against the handle must be exactly balanced by a moment generated by body weight around the same point. Hence, these data show that an increase in pulling force is accompanied by an increase in the fore-aft distance between the front edge of the base of support and the whole-body center of mass (see Figure 4).

The center of mass is lowered as force exertion increases. This may be due in part to the need to spread the feet apart to shift the COM relative to the BOS, but it also has the effect of reducing the moment of the applied force around the shoulder, as shown in the top plot in Figure 6. Repositioning the BOS also causes the forward-most point on the BOS to move closer to and sometimes forward of the handle. This trend is related to the magnitude of vertical force that accompanies the horizontal force, and is also significantly related to body weight. That is, after normalizing the dimensions for stature, participants who have higher body weight tended to place their forward-most foot closer to the handle than did participants with lower body weight. Torso angle in pulling trials did not vary significantly with force magnitude, indicating that participants did not tend to lean their torsos rearward when pulling harder. However, men tended to lean their torsos about 10 degrees rearward across the force range, while women kept their torsos more vertical, on average.

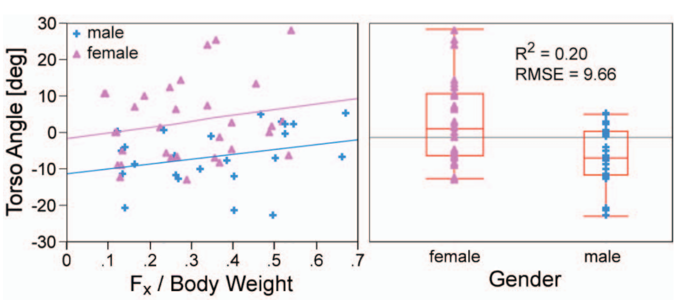

Figure 7: Torso angle during two-handed pulls. The within-gender linear regressions are not statistically significant ($p>0.05$), but the mean difference of 10 degrees between men and women across force magnitudes was significant with $p<0.0001$.

PUSHING POSTURES

Figure 8 presents statistically significant findings for pushing postures. For several variables, significant differences were observed between men and women, so Figure 8 includes box plots showing the distributions of the variables by gender. The strongest relationship was observed between push force (normalized by body weight) and the vertical distance between the handle and the shoulder. (Note that pushing forces are negative, so the data points to the left of the plots in Figure 8 represent large pushing forces.) As the force magnitude increased, the vertical offset between the shoulder and the handle dropped to near zero. There was a small but statistically significant difference between men and women, with women positioning their shoulders lower (closer to the handle height) across the force magnitudes, after normalizing for stature.

As with the pulling trials, a significant trend was observed between force magnitude and the position of the torso COM relative to the boundary of the BOS. For pushing, the relevant boundary is at the rearmost foot. Shifting the body weight forward relative to the posterior margin of the BOS counters the moment produced at by the hand force: "leaning into" the handle. The mean fore-aft offset was slightly larger for women than for men, possibly resulting from a difference in body weight distribution. As with the pulling trials, the vertical position of the COM decreased with increasing hand force. The difference between men and women was consistent with the differences in the fore-aft position of the COM and the smaller shoulder-to-handle offset for women.

Torso angle relative to vertical increased (leaning forward) with increasing push force, but the trend was not as strong across participants as the trends with respect to COM location. Much of the aggregate effect is due to two male subjects whose pushing strategies included substantial torso lean. Removing data from those two subjects reduced the R^2 value to 0.18, indicating only a weak relationship between force magnitude and torso angle.

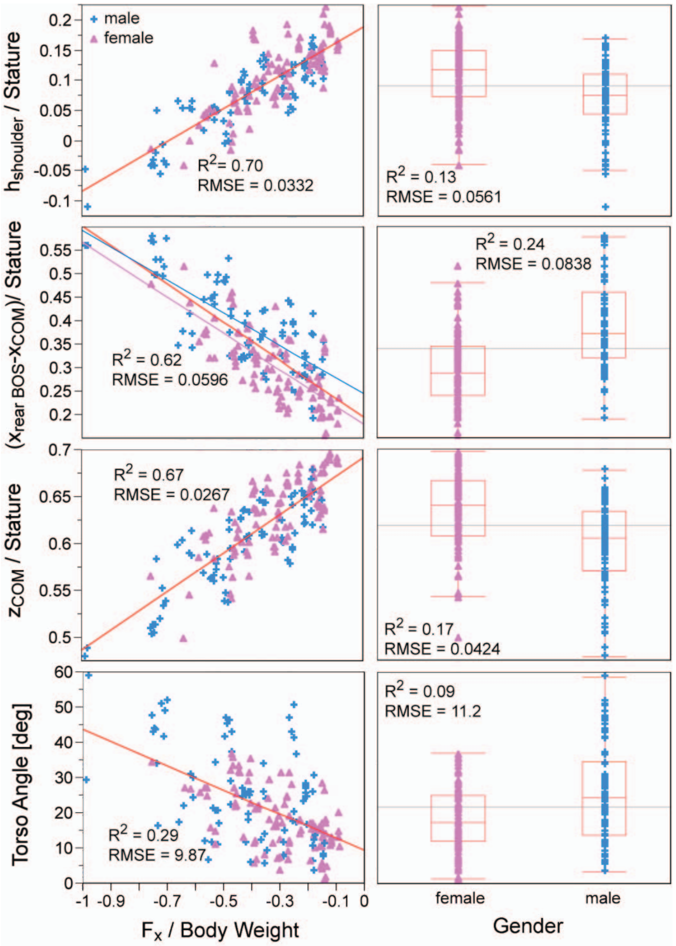

Figure 8: Significant predictors (p<0.0001) of two-handed pushing postures.

DISCUSSION

Through an analysis of laboratory data, pushing and pulling postures have been found to be significantly related to force magnitudes and directions in ways that are consistent with biomechanical explanations. As force magnitude increases, the offset between the torso center of mass and the active boundary of the base of support increases, where the active boundary is the front of the BOS for pulling and the rear for pushing. Torso inclination with respect to gravity remains fairly constant across exertions with a near vertical orientation when pulling and slight forward incline when pushing. This suggests people do not incline their torso to achieve shifts in their center of mass but instead move their pelvis relative to their feet while maintaining a near-vertical torso. The data show that the adjustment of foot positions to enable large forces while maintaining balance is the most salient feature of posture selection for hand-force exertion.

A strong correlation was also found between the vertical location of the shoulder with respect to the hands and force magnitude. The fore-aft location of the shoulders with respect to the hands was found to be more variable due to a presence of different strategies (i.e. arms flexed vs. extended). The statistically reliable results indicate that it is feasible to predict important aspects of pushing and pulling postures using worker attributes and force magnitudes.

The substantial off-axis loads observed in these data are consistent with other research on pushing and pulling (de Looze et al., 2000, Granata & Bennett, 2005, Boocock et al., 2006). For high-force exertions, participants tended to push or pull upward on the handle as well as horizontally, increasing the ground reaction force and hence the magnitude of horizontal force available within the coefficient of friction of the floor. The off-axis forces should be taken into account in any ergonomic assessment of pushing and pulling tasks with high force magnitudes.

The results are not consistent with posture-prediction models that choose postures to maximize available joint torque, whether passive or active. First, the lower-extremity postures appear to be chosen for balance maintenance, not to maximize torque production (Figure 3 and Figure 4(b) & (c)). Second, the upper-extremity postures revealed several strategies, only one of which was consistent with maximizing shoulder or elbow torque (Figure 3(a) and Figure 4(a) & (b)). The straight-arm pushing and pulling strategies did not maximize the torque-production capability of the elbow, for which maximum torque is generated at approximately 90 degrees of flexion (Figure 3(b) and Figure 4(c)). However, this posture is consistent with the dual objective proposed by Seitz et al. (2005), which also considers postures that reduce joint moment. Shoulder flexion also appears to be selected to reduce joint moment, rather than to maximize joint torque. Perhaps a criterion that sought to minimize the ratio between joint torque and available strength would be successful in predicting these postures. Yet, an explanation is needed for the pulling postures that were observed with the elbows flexed approximately 90 degrees.

The current analysis is limited by the test conditions and the lack of diversity in the subject pool. Forces were exerted on a handle with a high-friction grip that was attached to a functionally rigid support. Postures used to apply force to an object that was expected to move as a result of the force could be substantially different. However, de Looze et al. (2000) found no significant difference between force direction and shoulder and L5/S1 torques when pushing a cart versus exerting force on a stationary bar. The relatively high-friction floor may have produced less conservative and quantitatively different postures than would have been observed with a lower-friction floor. Workplace constraints have been shown by Haslegrave et al. (1997) to have a strong influence on posture and force exertion capability. The effects of workplace layout and posture restrictions should be explored in future studies.

The participants were selected to be young and fit so that they could readily endure the long-duration test series. The low body mass index enabled more accurate tracking of the skeleton. More research will be necessary to determine if older or less fit people will produce substantially different postures under the tested conditions. Additional work is also required to determine if the behaviors exhibited by novice participants are consistent with those of experienced operators in industry.

The results of this study suggest that the accuracy of digital human model analyses can be enhanced by improved posture prediction that is based on biomechanical principles and guided by quantitative observations of human behavior. For pushing and pulling tasks near elbow level, torso posture should change little with force magnitude, with most of the postural adjustment occurring through changes in the base of support and adjustments in shoulder position to reduce the moment of the hand force around the shoulder joint. Work is underway to incorporate these findings into the Human Motion Simulation Framework (Reed et al. 2006), a hierarchical, modular set of algorithms for simulating task-oriented human activities.

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