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Postural Behaviors during One-Hand Force Exertions

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ABSTRACT

Posture and external loads such as hand forces have a dominant effect on ergonomic analysis outcomes. Yet, current digital human modeling tools used for proactive ergonomics analysis lack validated models for predicting postures for standing hand-force exertions. To address this need, the effects of hand magnitude and direction on whole-body posture for standing static hand-force exertion tasks were quantified in a motion-capture study of 19 men and women with widely varying body size. The objective of this work was to identify postural behaviors that might be incorporated into a posture-prediction algorithm for standing hand-force tasks. Analysis of one-handed exertions indicates that, when possible, people tend to align their bodies with the direction of force application, converting potential cross-body exertions into sagittal plane exertions. With respect to the hand-force plane, pelvis position is consistent with a postural objective of reducing rotational trunk torques. One-handed task postures are characterized by axial rotation of the torso towards or away from the point of force application.

INTRODUCTION

Digital human figure models (DHM) allow human-product and human-process interactions to be assessed virtually by bringing the human, product, and work cell geometry together in a computer-aided design (CAD) environment. Historically DHMs have been used to statically assess reach capability, line-of-sight, and clearance for people of various size and shape (Chaffin, 2001). Existing tools work well for these types of analyses, but manual manipulation of the human figure makes even simple analyses time consuming, and can result in postural inconsistencies within and across analysts. Task postures have a strong effect on the outcome of many ergonomic analyses using DHMs; thus, postural differences result in poor repeatability and reproducibility of analysis outcomes. Posture is especially critical when assessing jobs involving forceful exertions since joint loads are dependent on the location and orientation of body segments with respect to hand loads. Improved posture and motion simulation capabilities would increase the utility of DHMs by decreasing simulation time and eliminating the need for analysts to make assumptions about working postures.

There are several challenges associated with developing DHM tools for use in industry. Existing ergonomic analysis tools are used to guide design decisions and, when proven, can be used to justify potentially costly changes in product design, tooling, and job layout. To be seen as credible, however, posture-prediction models intended for ergonomic evaluation of industry jobs must produce accurate postures for the range of task conditions observed in industry. The model must be capable of replicating the different postural strategies prevalent in industry, and ergonomic evaluation of predicted postures must yield outcome measures consistent with analysis of actual working postures. Posture-prediction for standing tasks has been accomplished using a variety of approaches but none of the previous methods have resulted in a model that satisfies all of these criteria.

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. Predictive equations are based on postural data collected under no-load conditions, thus the effects of hand force on posture are not reflected in model predictions.

Observations from the literature regarding posture selection and postural changes during forceful exertions suggest a strong relationship between hand force and posture (Haslegrave et al., 1997), although this relationship has not been systematically quantified. Furthermore, previous research on force-exertion postures has mainly focused on two-handed tasks (Gaughran & Dempster, 1956; Dempster, 1958; Schibye et al., 2001; de Looze et al., 2000; Okunribido & Haslegrave, 2003 & 2008). Several researchers have examined postural changes in response to hand forces, and have proposed explanations regarding the observed trends. Granata et al (2005) hypothesized that people exert off-axis forces to align the hand force vector with the lumbar spine. Similarly, de Looze et al. (2000) explained the lack of large changes in shoulder moments over a range of task conditions by a tendency for people to direct the resultant hand force vectors toward their shoulders.

This paper presents an investigation of the relationship between hand force and posture during one-hand standing force-exertions. The objective of this work was to identify postural behaviors that might be incorporated into a posture-prediction algorithm for standing hand-force tasks. In a laboratory study, posture data were gathered for one-hand exertions with a range of force directions and magnitudes.

METHODS

PARTICIPANTS

Nine men and ten women were recruited from a student population and paid for their participation. All were required to be right-hand dominant and none had a history of musculoskeletal disorders, low-back pain, shoulder pain, or reduced mobility. All participants were young (median age 21 years) and relatively thin (median body mass index 23 kg/m^2). An attempt was made to recruit men and women with widely varying body size and strength capabilities. Male participants ranged from 6th %tile to 94th %tile by stature and female participants ranged from 11th %tile to 93rd %tile by stature (Roebuck, 1995). Participant whole-body strength capabilities were characterized by standardized arm, torso, and leg lift strength tests (Stobbe, 1982). Functional strength tests were used to quantify specific isolated elbow and shoulder strengths.

FACILITIES

The study was conducted in the Human Motion Simulation (HUMOSIM) laboratory at the University of Michigan. Posture data were obtained using a passive optical motion tracking system (Figure 1).

Forces and moments at the hands were measured via an adjustable force handle affixed to a 6-DOF load cell (JR3, Woodland, CA). The handle was a cylindrical, rigid bar 470 mm long and 35 mm in diameter. The 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.

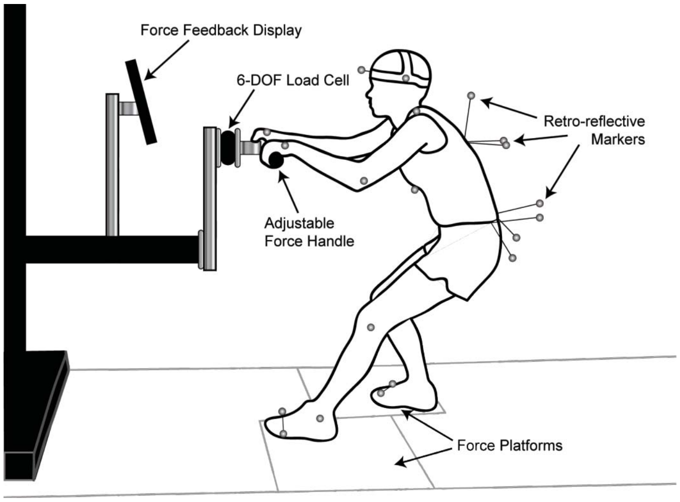

Figure 1: Laboratory configuration with visual force feedback display, 6-DOF load cell, and moveable force platforms for measuring forces and moments at the hands and feet respectively.

An eight-camera Qualysis Proreflex 240-MCU optical based motion tracking system was used to quantify whole-body motions and postures. Twenty-nine retro-reflective markers were placed on the subject at pre-defined body landmarks (Figure 2) and a digitization procedure followed. Optical marker locations are used in conjunction with twenty-six digitized points to capture whole-body postures. Digitization is used to define the location of additional body landmarks on the head, torso, pelvis, and feet with respect to the optical markers. Digitized points are later combined with three-dimensional marker data to create a linkage representation of the human body (Reed et al, 1999). 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 analog data from the two AMTI force plates and a JR3 load cell.

Figure 2: Retro-reflective marker set used to capture whole-body postures.

TEST CONDITIONS

Three handle heights were chosen to span the range of working heights common in industry. Handle height was scaled for each subject to standing elbow height (63% of stature), mid-thigh height (41% of stature), and 0.1 m overhead. A total of six different force directions were studied in order to capture force exertion postures under various symmetric (i.e. sagittal) and asymmetric (i.e. cross-body) loading conditions (Table 1). Exertions were performed on a raised platform with the requirement that subjects remain on the gridded region of the platform during all exertions (Figure 3).

For all trials, participants were required to achieve a desired force level in the requested direction. Participants were instructed to exert a force in the requested direction but off-axis forces (i.e. forces in directions other than that requested) were not constrained and only the on-axis force magnitude was presented to the subjects. Exertions were performed at 25, 50, 75, and 100% of each subject's maximum capability. During the exertions subjects were allowed to brace off their own body but were not permitted to brace externally off the testing apparatus.

Table 1: One-hand force exertion test conditions with analyzed trials shaded. All conditions performed at 25, 50, 75, and 100% of maximum capability.

Experimental Design	Handle Height	Requested Hand Force Direction
I	Overhead	Right
		Left
		Up
		Forward (push)
		Back (pull)
I / II	Elbow	Right
		Left
		Up
		Down
		Forward (push)
		Back (pull)
II	Mid-thigh	Right
		Left
		Up
		Forward (push)
		Back (pull)

Each trial began with the subject at the end of a raised platform requiring them to take a few steps to approach the force handle. This decision was made in an attempt to ensure the foot placements were adapted to each exertion. Given the large number of conditions to be tested a split-plot design was employed. Subjects were distributed between experimental designs in a manner that yielded two groups approximately equivalent with respect to strength and body dimensions. All subjects performed elbow height exertions. In addition, subjects assigned to Design I performed overhead exertions and those assigned to Design II performed exertions at a mid-thigh handle height (Table 1).

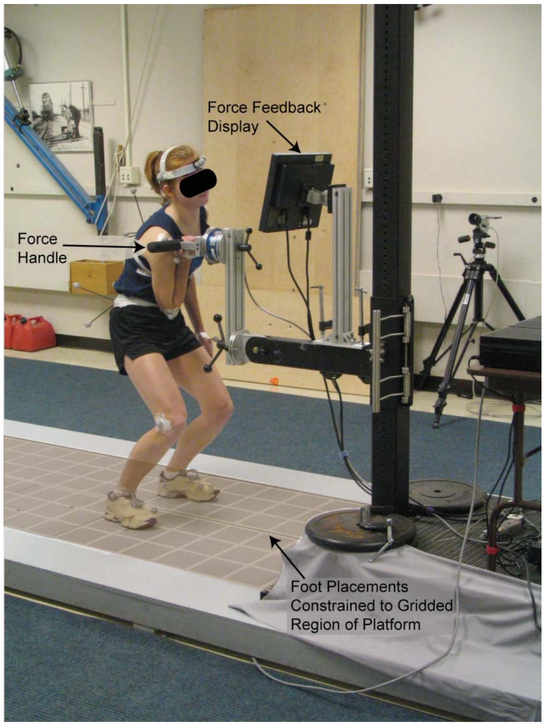

Figure 3: Participant in the laboratory performing an upward exertion on a fixed force handle while receiving visual feedback on hand force via an LCD screen. The force handle is shown in a horizontal orientation. Minimal constraints were imposed on foot placements by requiring subjects to keep their feet within the gridded area of the platform.

Prior to conducting the submaximal trials subjects completed a series of maximal exertions at the two assigned handle heights. Trials were blocked on handle height and maximum values were obtained for the principal force directions only. Maximal 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. A minimum of one practice trial was conducted for each test condition and practice trials were repeated until the participant indicated they were comfortable with their posture. 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 submaximal force levels.

Upon completion of the maximal trials, each subject then performed a series of submaximal exertions at the two assigned handle heights. Trials were again blocked on handle height. For each trial condition, exertions were performed in order of increasing force level. 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.

ANALYSIS

For the current analysis, data from one-handed push/pull exertions performed on an elbow-height handle were used. Subjects exerted forces spanning from 25% to

100% of their maximum capability in the forward (push) and back (pull) directions. The force handle was oriented horizontally during all trials analyzed (Figure 3).

A hand force plane, defined as the vertical (x-z) plane containing the measured hand force vector, was determined for each data trial (Figure 4). The z-axis of the hand-force frame was defined to be coincident with the global z-axis. The global orientation of the x and y-axes of the hand-force frame was obtained by rotating the global frame about the z-axis so that the x-axis lies in the vertical plane of the actual hand force vector. The rotation matrix mapping the global hand force vector to the hand-force plane was computed and used to map the three-dimensional kinematic data into the hand-force plane reference frame.

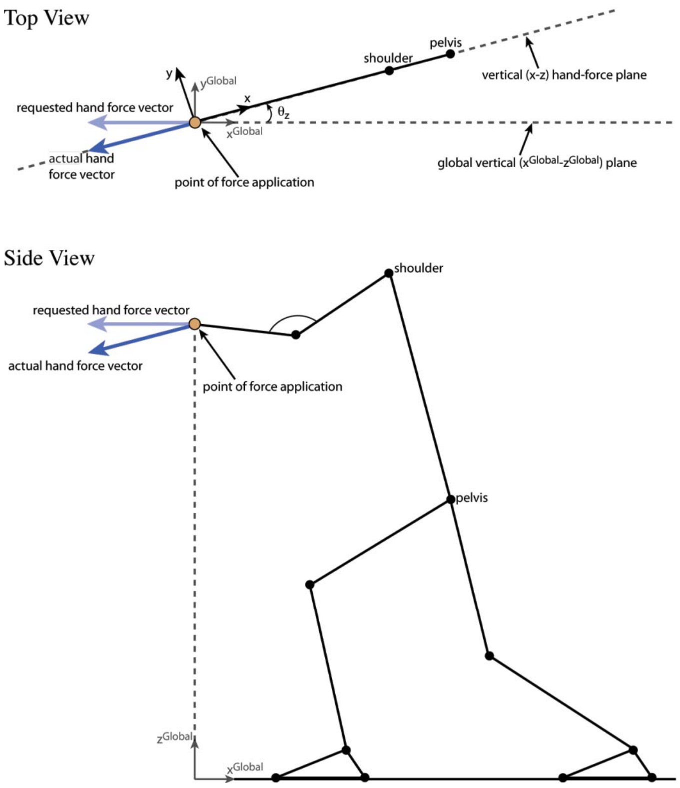

Figure 4: Top and side view of hand-force plane defined by actual hand force vector.

Whole-body postures were quantified by a set of postural metrics defined with respect to the hand-force plane and analyses conducted within each postural category to determine the effects of worker and task parameters on posture.

One-hand force exertion postures are characterized by a torso rotation angle (Figure 5), defined as the angle between the lateral (y-axis) of the hand-force plane and the projection of a vector from the left to right shoulder onto the horizontal plane. Positive rotation corresponds to rotating to the left, i.e. turning away from the force handle or "opening up" the torso for these right-handed exertions. Conversely, a negative rotation angle corresponds to rotating the left (contralateral) shoulder toward the force handle, "closing up" the torso rotation angle. Right and left foot orientations (Figure 6) define base-of-support (BOS) orientation, which is used to further characterize torso postures.

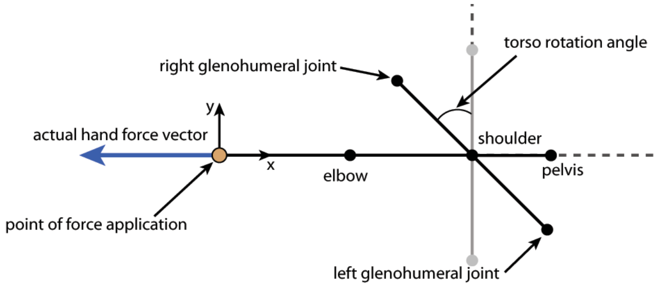

Figure 5: Top view of right-to-left shoulder segment relative to hand-force plane illustrating torso rotation angle used to categorize torso postures as open, closed, or neutral.

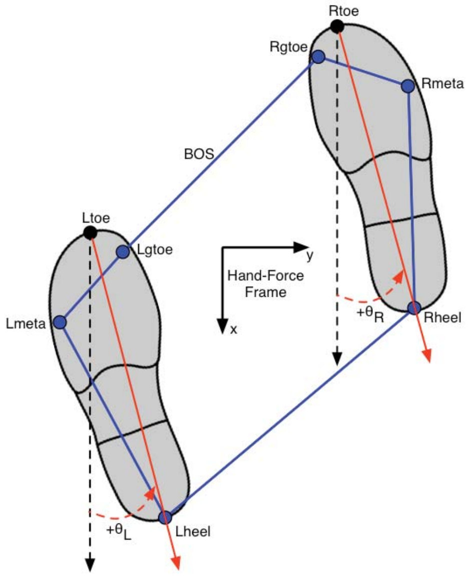

Figure 6: Base-of-support (BOS) and right (θ_R) and left (θ_L) foot orientations used to define torso postures as open, closed, or neutral.

The torso rotation angle (Figure 5), pelvis and BOS orientation, defined by the orientation of the right and left foot, (Figure 6) were used to categorize a posture as being open or closed. Postures with a positive torso rotation angle, positive pelvis yaw angle, and BOS rotated towards the left, with respect to the hand-force plane, were defined as open. A closed posture corresponds to rotation of the torso, pelvis, and BOS to the right. Postures are considered neutral if torso, pelvis and BOS rotations are in opposing directions.

RESULTS

During the experiment participants were asked to exert a force in a specified direction but were not instructed how to perform the exertion. Participants were also encouraged to select their preferred posture. As a result, within a given task condition, different postural strategies were used.

OPEN VERSUS CLOSED TORSO ORIENTATION

Figure 7 presents examples of one-hand force exertion postures characterized by open, closed, and neutral torso orientations. All three torso strategies were observed during push and pull exertions.

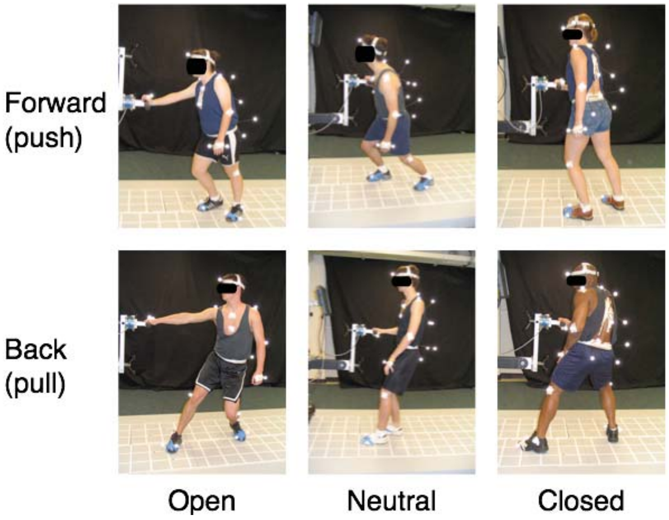

Figure 7: Open, neutral, and closed torso strategies used across one-hand elbow-height forward (push) / back (pull) exertions.

Prevalence of open, closed, and neutral strategies across forward and back exertions was quantified and is presented in Figure 8. All three strategies are prevalent during push/pull exertions with a preference towards open pulling (49%) and pushing (50%) postures compared to closed pulls (24%) and pushes (20%).

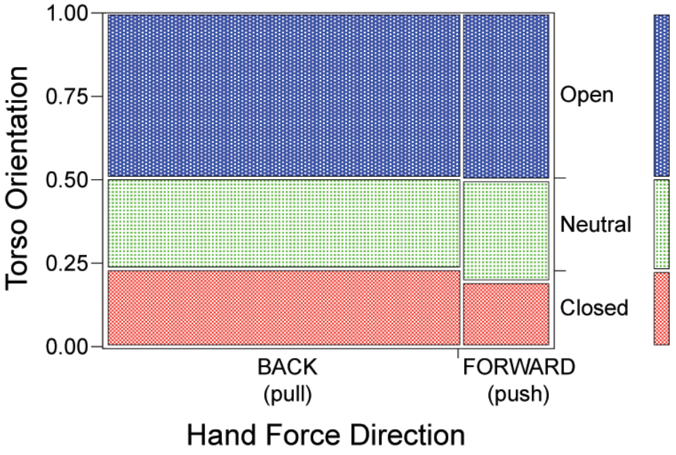

Figure 8: Prevalence of torso orientation strategies within push / pull exertions, horizontal axis proportional to number of trials.

TORSO ROTATION ANGLE

Torso rotation angles and low-back rotational moments during one-hand exertions were examined to determine if postures are consistent with the hypothesis of reducing low-back rotation moments by rotating the torso to reduce the rotational moment arm. The distribution of low-back moments computed for one-hand exertions is presented in Figure 9.

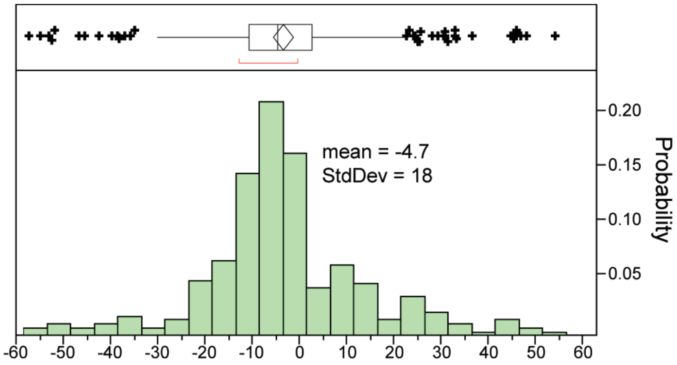

Figure 9: Axial rotation moments [Nm] about the lumbar spine during one-hand elbow-height push/pull exertions.

Torso rotation angles quantified during one-hand push/pull exertions are summarized in Figure 10. On average, torso rotation angles were found to be smaller during push exertions than pull exertions and forward push exertions were characterized by a slightly open torso posture. An open torso orientation was also utilized during one-hand pulls back.

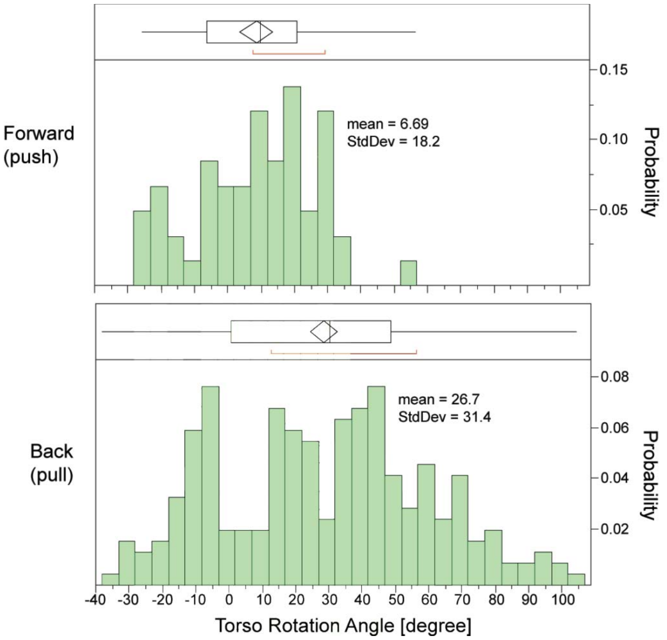

Figure 10: Distribution of torso rotation angle during one-hand elbow-height push/pull exertions.

A significant relationship was observed between hand force and torso rotation angle during one-hand back exertions performed with an open torso orientation (Figure 11). When pulling backward at elbow height an increase in torso rotation angle was observed with increasing pull horizontal force. This is consistent with the hypothesis that people are opening up (i.e. rotating towards the left) to reduce the low-back rotational moment. This strategy also acts to shift the L5/S1 joint laterally towards the hand-force plane. No significant relationships were found between horizontal hand force and torso rotation angle for one-hand forward push exertions.

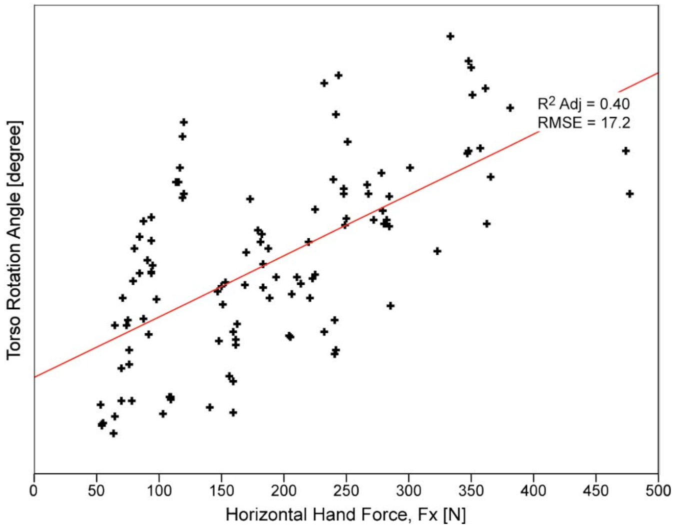

Figure 11: Relationship between torso rotation angle and horizontal hand force during one-hand elbow-height pulls in the back direction performed with an open torso strategy ($p < 0.001$).

DISCUSSION

The findings of this paper suggest, that as with two-handed tasks (Hoffman et al., 2007), the biomechanics of one-hand force exertions can be used to predict key postural metrics required for development of a whole-body posture prediction model. Postural trends unique to one-hand exertions include axial rotation of the trunk, particularly during high-force pulls. On average, both one-hand pushing and pulling postures are characterized by an open torso strategy (Figure 10) with torso rotation angle increasing significantly with increasing hand force during one-hand pulls (Figure 11). Greater variation in torso rotation angle is observed for one-hand pulls with rotation angles ranging from -40 to 105 degrees. This behavior reduces the moment arm from the point of force application to L5/S1 and is consistent with a desire to reduce low-back rotational moments.

Rotational moments about the low-back were hypothesized to be a significant determinant of posture during one-hand force exertions. As the level of force increased participants appeared to rotate their torso in a manner consistent with reducing the low-back rotation moment. This trend was significant for one-hand pulls, however; the relationship between torso rotation angle and hand force is not significant during one-hand push exertions. During one-hand push exertions, moments about the low-back may instead be reduced by shifting the pelvis laterally towards the hand-force plane as the level of required force increases.

Rotational moments about the low-back were quantified and found to be small with moments less than or equal to +/-10 Nm during approximately 50% of trials (Figure 9). Maximum twisting moments in both symmetric and asymmetric postures have been quantified by Marras et al. (1998) and shown to range from approximately 50 to 60 Nm with maximum moments being greatest in symmetric postures. These values suggest that the rotational moments observed during this study are small and perhaps consistent with the strategy of minimizing the low-back rotational moment. However, the effect of pelvis twist on asymmetric loading of the low-back was examined by Kingma et al. (1998) and change in pelvis orientation was not found to produce a significant reduction in low-back loads.

The current analysis is limited by the test conditions. Forces were exerted on a stationary handle while standing on a relatively high-friction floor. 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 low-back moments when pushing a cart versus exerting force on a fixed bar. Postures may be dependent on the available friction at the shoe-floor interface. Future work should include analysis of the ground reaction forces quantified during the experiment to determine the effects of foot traction on push/pull postures.

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