CHAPTER 7

PREDICTING FORCE-EXERTION POSTURE BEHAVIORS ASSOCIATED WITH BRACING AVAILABILITY

7.1. Abstract

The objectives of this work were to quantify postural trends during kinematically constrained one-handed force exertions with bracing availability and to develop regression models to predict key aspects of associated postural behaviors. Within the context of the multinomial FGS classification, the effects of task configuration, task hand and bracing forces, and anthropometrics on postures were examined. In a broader sense, this work seeks to determine if the postural behaviors observed during unconstrained isometric exertions uphold within a restricted or kinematically constrained space. Analysis of key postural behaviors associated with braced, force exertions are coupled with the force-generation strategies and support the hypothesized biomechanical principles. Changes in key postural degrees-of-freedom in response to task configuration variables and increasing task hand force were found to be consistent with the five force-generation strategies (FGSs). The fore-aft position of the pelvis was the key postural metric to differentiate FGSs based on the engagement of the lower extremities with the kinematic constraint and influenced by the task configuration. Thigh bracing altered the direction of the task hand force vector, while increased rearward displacement of the pelvis, characterized as a lack of engagement with the kinematic constraint, was observed to increase force-exertion capability. Decrease in the vertical height of the pelvis was also coupled with increased force-exertion capability and task hand force direction more closely associated with nominal for NB and HB FGSs. Torso inclination was related to the kinematic constraint of the task configuration, and accompanied by increased task exertion capability, task hand force direction more closely associated with nominal, and

changes in task shoulder location. Decrease in task shoulder height also resulted in task hand force vectors more closely associated with the nominal direction. Lowering task shoulder height was hypothesized to increase task hand force exertion capability and to maintain task shoulder moment within a criterion level. Changes in contralateral shoulder height were consistent with task shoulder modifications. In general, the postural trends and regression models presented in this chapter provide insight into the biomechanics of FGS selection and associated postural behavior during kinematically constrained force exertions with bracing availability.

7.2. Introduction

Several researchers have examined postural changes in response to force exertion, and have proposed explanations regarding the observed trends. Granata and Bennett (2005) hypothesized that people exert off-axis forces to align the force vector along the spine. Similarly, de Looze et al. (2000) explained small changes in shoulder moments over a range of task conditions by a tendency for subjects to direct the resultant task force vector towards the task shoulder. Observations from the literature regarding postural behaviors associated with force-exertions suggest a strong relationship between task hand force and posture (Haselgrave et al., 1997). Hoffman's (2008) provided a systematic quantification of unconstrained task hand force exertions. Force exertions were found to be consistent with a desire to reduce task shoulder moment while maintaining a relatively upright torso posture. Subjects were observed to adopt two strategies to reduce task shoulder moment: 1) alter the location of the task shoulder with respect to the task handle, or 2) generate off-axis forces to direct that task hand force vector towards the task shoulder joint. Moreover, Hoffman (2008) observed that subjects maintained task shoulder moment within a restricted range across a large range of force levels and task configurations. Alternative strategies, including adopting torso inclination and increasing length of base-of-support were also adopted in an effort to maintain task shoulder moment.

The overall goal of this chapter is to presents systematic quantification of the relationship between task hand force, bracing forces and posture during force exertions that are kinematically constrained by an obstacle in the environment. In a broader sense, this work seeks to determine if the postural behaviors observed during unconstrained isometric exertions uphold within a restricted or kinematically constrained space.

The current study investigates the effects of task configuration variables, which were shown in Chapters Three, Four and Six to have important effects on task-hand force generation capability, on whole-body posture. During the experiment, subjects were asked to exert a force in a specified direction (i.e. backward or forward) and afforded the opportunity to utilize randomized levels of bracing availability, but were not instructed on how to perform the task (i.e. push, pull, or to chose whether to utilize the bracing surface at all). Subjects were also encouraged to select a preferred behavior or bracing strategy to generate the requested task hand exertion. As a result, within in a given test configuration, different force-generation strategies and postural behaviors were adopted. The following analysis is intended to provide an understanding of the individual and interactive effects of: (1) vertical and (2) fore-aft task handle location, (3) levels of bracing availability, (4) nominal task hand force direction and (5) force level on key postural metrics and within the previously defined force-generation strategies (FGSs) classification. The objective of this work is to parameterize key postural behaviors associated with the force-generation strategies, and to develop regression models for use in the integrated force-generation strategy prediction model (Chapter Eight).

As discussed in Chapter Four, five distinct patterns of bracing force generation, termed force-generation strategies (FGSs), were identified.

(i) *No Bracing* (NB): Task hand force exertion performed without any bracing forces from contralateral hand or thigh.

(ii) *Hand Bracing* (HB): Bracing force at the contralateral hand but not the thigh.

(iii) *Hand & Thigh* Bracing-opposed (HTB-o): Bracing forces at both the contralateral hand and thigh. The thigh bracing force acts primarily in opposition to the hand force vector (for example, pulling with the task hand while exerting a forward-directed force on the thigh bracing surface).

(iv) *Thigh Bracing* (TB): Bracing force at the thigh but not the contralateral hand.

(v) *Hand & Thigh Bracing-aligned* (HTB-a): Bracing force at both the contralateral hand and thigh. Thigh bracing force acts primarily in the same direction as the task hand force (for example, pushing with the task hand while leaning against the thigh board, exerting a forward force).

In an effort to quantitatively parameterize key aspects of 3D whole-body postures associated with the force-generation strategy classification, a critical set of kinematic metrics were defined (Table 7.2.1).

Table 7.2.1 Key postural metrics used to quantify whole-body postures in 3D global coordinates.

Postural Metric	Definition
HipX: fore-aft location of pelvis	Horizontal (x) coordinate of mean hip joint location of the pelvis normalized by stature
HipZ: vertical position of pelvis	Vertical (z) coordinate of mean hip joint location of the pelvis normalized by stature
Torso Inclination Angle: planar torso inclination angle	Angle with respect to vertical of a side-view line connecting the mean hip joint to the C7-T1. (angle between the negative z-axis of the global frame and the projection of the vector from C7T1 to mid-hip onto the XZ plane of the global frame; defined + torso extension & - torso flexion to be consistent with definition of torso orientation angles)
TaskShoulderZ: task shoulder height	Vertical (z) location of the task shoulder (right) normalized by stature
BraceShoulderZ: contralateral shoulder height	Vertical (z) location of the brace shoulder (left) normalized by stature

The relationship between task hand force and bracing forces and postural behaviors with respect to force-generation strategy for nominal backward and forward task exertions are hypothesized to be consistent with aforementioned postural behaviors observed for unconstrained isometric task hand force exertions. It is hypothesized that the kinematically constrained isometric forces exertions in the current study will uphold and be governed by the aforementioned biomechanical rationale asserted by Haselgrave et al. (1997) and Hoffman (2008). Table 99.2.2 presents a cross-tabulation of the relationship between the task hand force exertion capability and the associated postural behaviors with respect to force-generation strategies for nominal backward and force exertions.

Table 7.2.2 Relationships between posture behaviors, task hand force exertion capability, and force-generation strategy.

Postural Behavior	Hypothesized Biomechanical Principle	FGS	Affected Variables	Definition
Engage pelvis/thighs with the kinematic constraint	Obtain reaction force to oppose task hand force	TB HTB-o; HTB-a	HipX	Horizontal (x) coordinate of mean hip joint location of the pelvis normalized by stature
Shift pelvis rearward, away from kinematic constraint	Shift body center of mass rearward relative to front edge of base of support to generate a moment that can be used to increase pull force.	NB HB	HipX	Horizontal (x) coordinate of mean hip joint location of the pelvis normalized by stature
Squat (lower centre-of-mass)	Align task shoulder with exertion handle to reduce task shoulder moment while improving alignment between task hand force and requested direction.	All	HipZ	Vertical (z) coordinate of mean hip joint location of the pelvis normalized by stature
Incline torso from vertical	Accommodate kinematic requirements of reach to the handle. Reduce task shoulder moment while improving alignment between the task hand force and requested force direction.	All	Torso inclination angle	Angle with respect to vertical of a side-view line connecting the mean hip joint to the C7-T1.
Alter task shoulder location	Reduce task shoulder moment while improving alignment between task hand force and requested force direction.	All	TaskShoulderZ	Vertical (z) location of the task shoulder (right) normalized by stature
Alter contralateral shoulder location	Reduce contralateral shoulder moment while improving alignment of bracing force with task hand force	HB HTB-o; HTB-a	BraceShoulderZ	Vertical (z) location of the brace shoulder (left) normalized by stature

This chapter is organization as follows. First, the effects of the task configuration variables on the key postural metrics are examined and the postural behaviors associated within each force-generation strategy (FGS) classification are observed for kinematically constrained, nominal backward isometric exertion tasks. Second, integrated prediction models are developed and presented for the critical posture metrics, which encapsulate whole-body postural behaviors for backward tasks and across all FGSs. The outline as presented is repeated for nominal forward tasks.

7.3. Methods: Data Analysis

Postural Metrics

A key set of posture metrics was developed to quantify whole-body postures in 3D global space. Body landmark data were used to calculate the locations of the joints defining a kinematic-linkage representation of the body. These procedures are described in greater detail in Chapter Two. The result body segment positions and orientations were analyzed to determine the effects of the task configuration variables on bracing posture. Five variables of primary interest are defined in Table 7.2.1.

Statistical Analysis of Posture Behaviors Observed

Analysis of the data was conducted in two phases. The first phase explored trends in the data to determine if postures adopted within force-generation strategies were consistent with the postural behaviors and hypothesized biomechanical principles. All linear trends presented in these sections are statistically significant at $p<0.01$.

Integrated Regression Models

In the second phase, regression models were formulated to predict key postural metrics for application to posture prediction in digital human models. Given that the exertion directions represented qualitatively different behaviors that could not be well captured by a unified model, separate regressions models are generated.

Regression analyses were performed using a step-wise procedure similar to that used in the preceding chapter for the purpose of evaluating task and bracing forces. Test configuration and anthropometric variables and two-way interactions between covariates were considered as potential predictors. An automated procedure was applied, using $p<0.25$ to enter and $p>0.10$ to leave. Non-significant terms were only when included when second-order terms were highly significant ($p<0.0001$) and inclusion of the non-significant first-order term was required for a proper model. The choice of predictors in the regression models are not meant to imply causality but rather associations between the postural degrees of freedom and force exertion capability within a FGS. In most cases, parsimonious models with fewer predictors were chosen over more complex models that provided only slightly better fit. In general, the models presented here have adjusted R^2 values within 0.02 of the best model attainable. All terms, and each model, are statistically significant with $p<0.001$. Table 7.4.1 and Table 7.4.3 show the resulting models. Adjusted R^2 and root-mean-squared error values are given in the table. The importance of the regression function terms can be evaluated by multiplying each coefficient by the range of the independent measure that is present in the data. Table 7.4.2 and Table 7.4.4 present the resulting values.

The preceding regression models were generated on 80% of the entire data set. Twenty percent of the trial data was withheld for each subject by randomly sampling across all test configuration variables. Future evaluation of the overall integrated model performance can then be assessed by exercising the regression prediction models across the task configurations and requested nominal task hand force directions.

7.4. Results

Backward Exertions: Postural Behaviors Observed

NB Force-Generation Strategy

The fore-aft hip position was the key postural metric to define the degree to which the lower extremities were engaged at the kinematic constraint and subsequently differentiates force-generation strategies based on thigh bracing. Change in fore-aft location of the pelvis was observed to have a significant relationship with both task hand force exertion capability and hand force direction for backward exertions adopting the NB FGS (Figure 7.4.1). The pelvis horizontal displacement increased with increasing resultant task hand force for all task handle locations. Task hand force direction was also significantly related to the fore-aft hip position at all but the low task handle location.

In backward trials for which the subjects used no bracing (NB), pelvis height was significantly affected by task variables at the task handle locations that imposed the least degree of kinematic constraint (Figure 7.4.1). Increased force levels were associated with lower pelvis positions at the medium-close and low task handle locations. Changes in the hip height were also associated task hand force directions that were more closely associated to the nominal direction.

In NB trials, increased force levels resulted in an increase in the degree of torso inclination at the high, medium-close and medium-far task handle locations (Figure 7.4.1). This trend was unique to the NB FGS.

When torso inclination increased, the task hand force direction was closer to the nominal direction at high, medium-close and medium-far task handle locations (Figure 7.4.1).

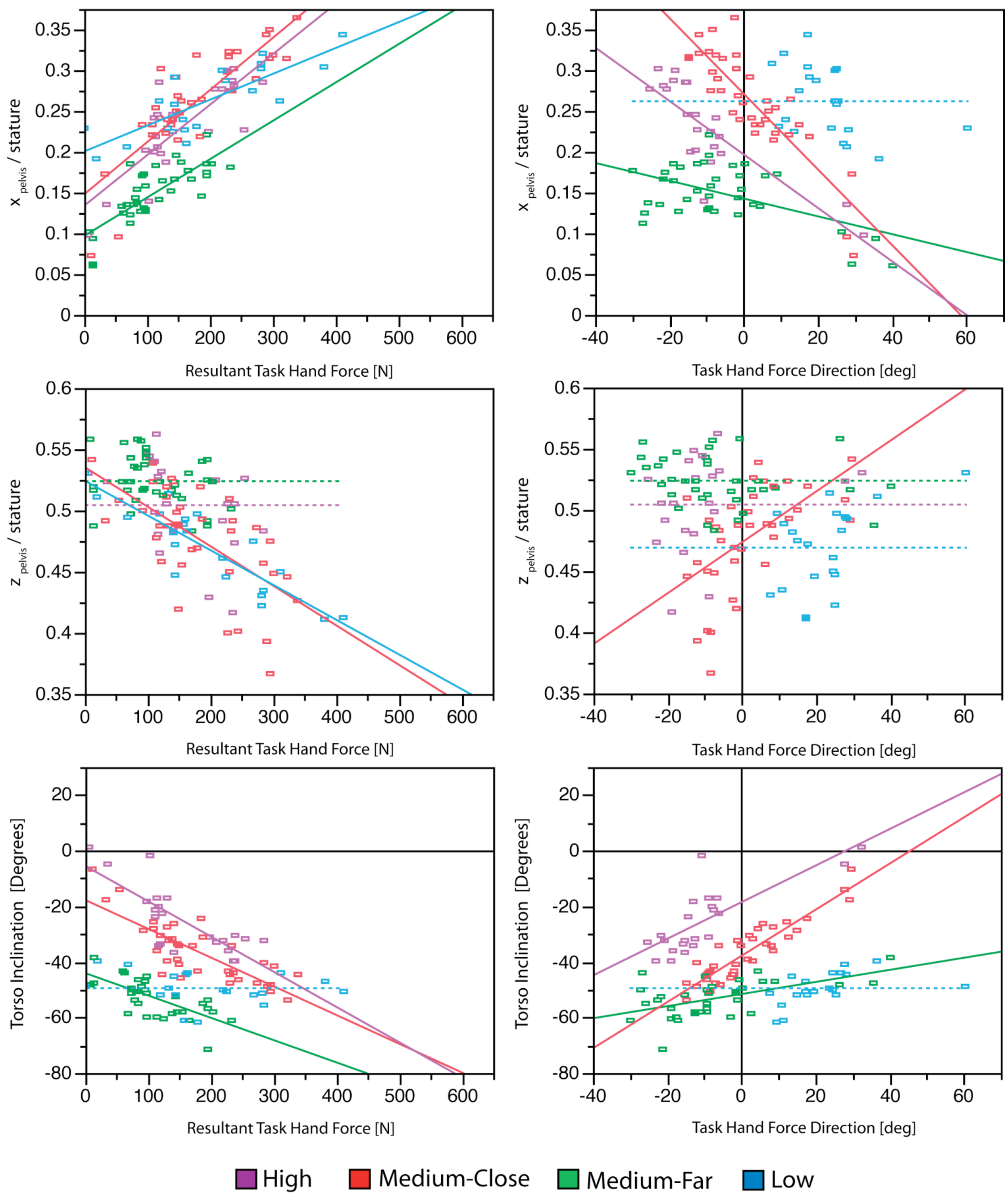

Figure 7.4.1 Change in fore-aft location of the pelvis (x pelvis/ stature), pelvis height (z pelvis/ stature), and torso inclination angle [degrees] with respect to vertical with resultant task hand force and direction, respectively, for backward exertions adopting the NB FGS. Linear relationships denoted by solid fit lines and color-coded for task handle location.

Changes in task shoulder location were quantified for backward exertions across all of the force-generation strategies and task handle locations. For pull tasks performed with NB FGS, lower task shoulder heights were observed with higher resultant task hand force across all task handle locations (Figure 7.4.2). Task shoulder height was correlated with task hand force direction. When shoulder heights were lower, the task hand force direction was closer to the nominal direction (Figure 7.4.2).

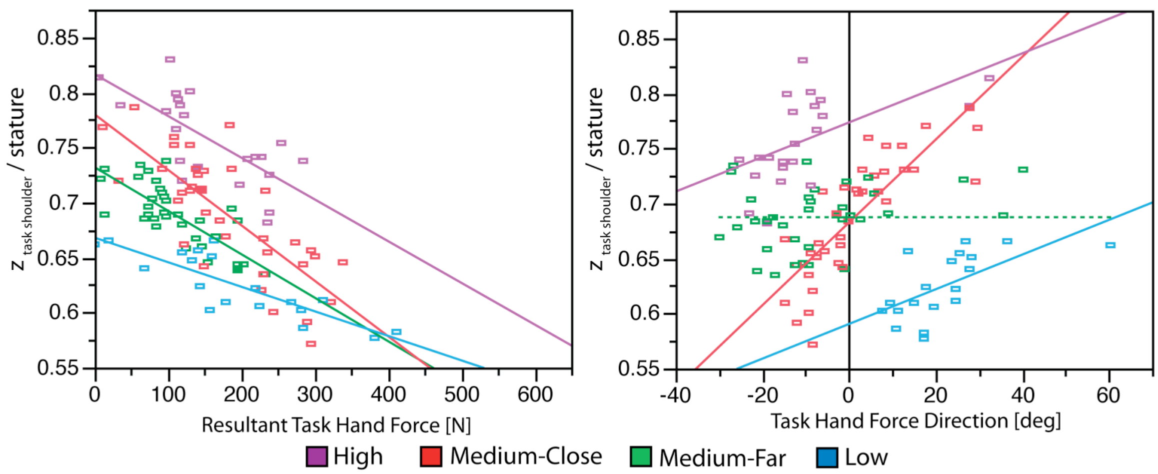

Figure 7.4.2 Change in task shoulder height with increasing task hand force and deviation in task hand force direction during backward exertions adopting NB FGS at high (R^2 = 0.50; R^2 = 0.31), medium-close (R^2 = 0.60; R^2 = 0.66), medium-far (R^2 = 0.59; mean = 0.69) and low (R^2 = 0.72; R^2 = 0.42) task handle locations. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

HB Force-Generation Strategy

Similar to NB trials, change in fore-aft location of the pelvis was observed to have a significant relationship with both task hand force magnitude and direction for backward tasks employing the HB FGS at the medium-close and low task handle locations (Figure 7.4.3). Task hand force directional changes were associated with the fore-aft hip position at the medium-close and low task handle positions.

Similar to NB trials, the task configurations hat imposed the least degree of kinematic constraint, namely medium-close and low. Increased force levels were associated with lower hip heights (Figure 7.4.3). No relationship was observed between vertical pelvis position and task hand force direction at the other more restricted task handle locations (medium-far and high).

In HB trials, increased force levels were not observed to affect torso inclination at any of the task configurations (Figure 7.4.3). However, an increase in torso inclination did result in task hand force vectors that were closely associated with nominal direction for backward trials that employed HB FGS across all of the task handle locations.

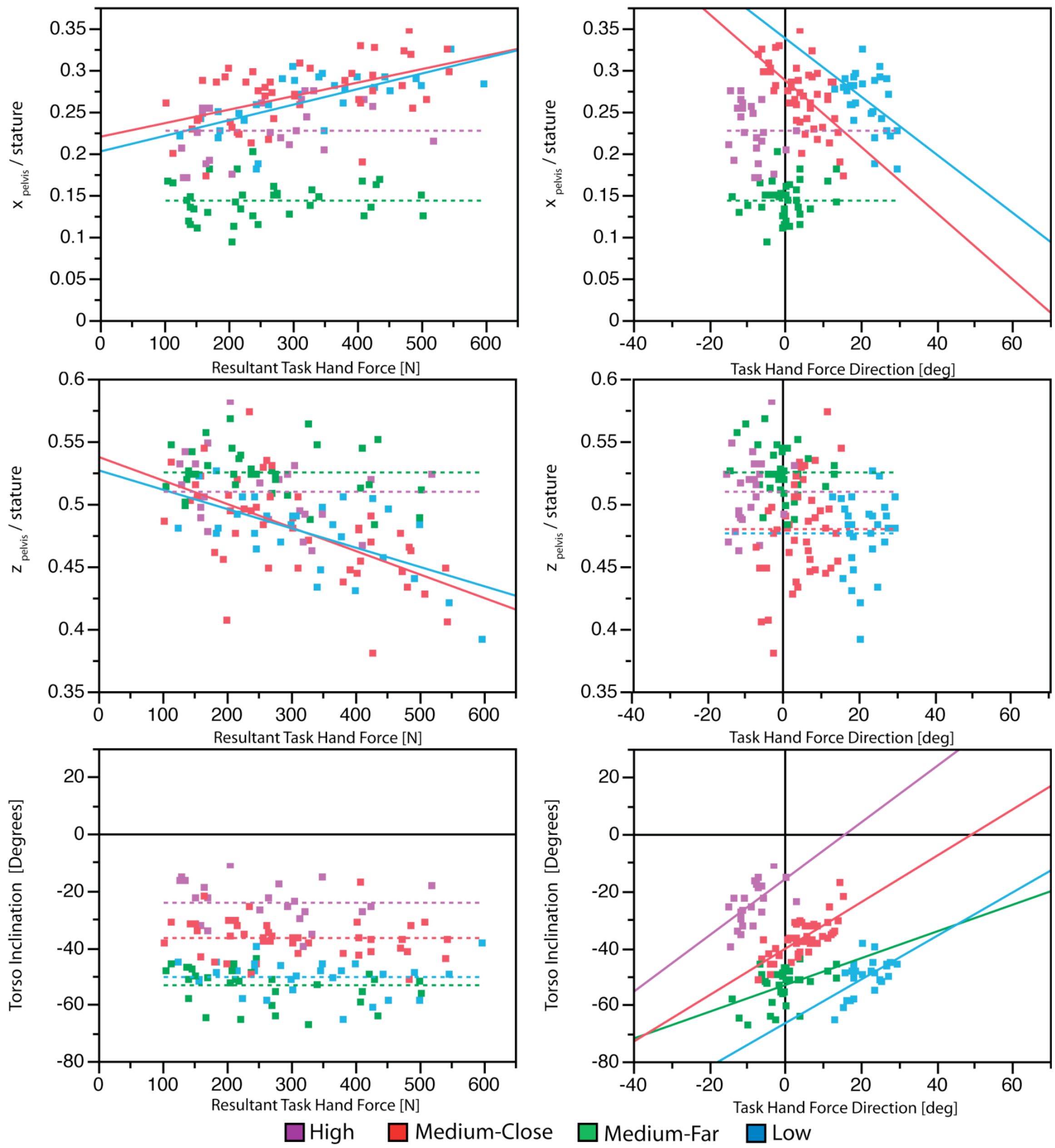

Figure 7.4.3 Change in fore-aft location of the pelvis (x pelvis/ stature), pelvis height (z pelvis/ stature), and torso inclination angle [degrees] with respect to vertical with resultant task hand force and direction, respectively, for backward exertions adopting the HB FGS. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

For backward tasks that employed HB FGS, increased force levels were associated with lower task shoulder positions (Figure 7.4.4). Change in task shoulder location was observed with higher resultant task hand force at all the task handle locations, except the high task handle. Similar to NB trials, lower shoulder heights were observed to exert task hand force vectors that are more closely associated to the nominal direction (Figure 7.4.4). Correlation between task shoulder height and task force direction was significant at high, medium-close and low task handle locations.

Changes in the contralateral shoulder location were quantified for backward exertions as across all FGSs and task configurations. For pull tasks performed with HB FGS lower contralateral shoulder heights were observed with higher task hand force levels across all task handle locations (Figure 7.4.4). When brace shoulder locations were lower, the task hand force vector was directed towards the nominal direction for HB trials at medium-close and low task handle locations.

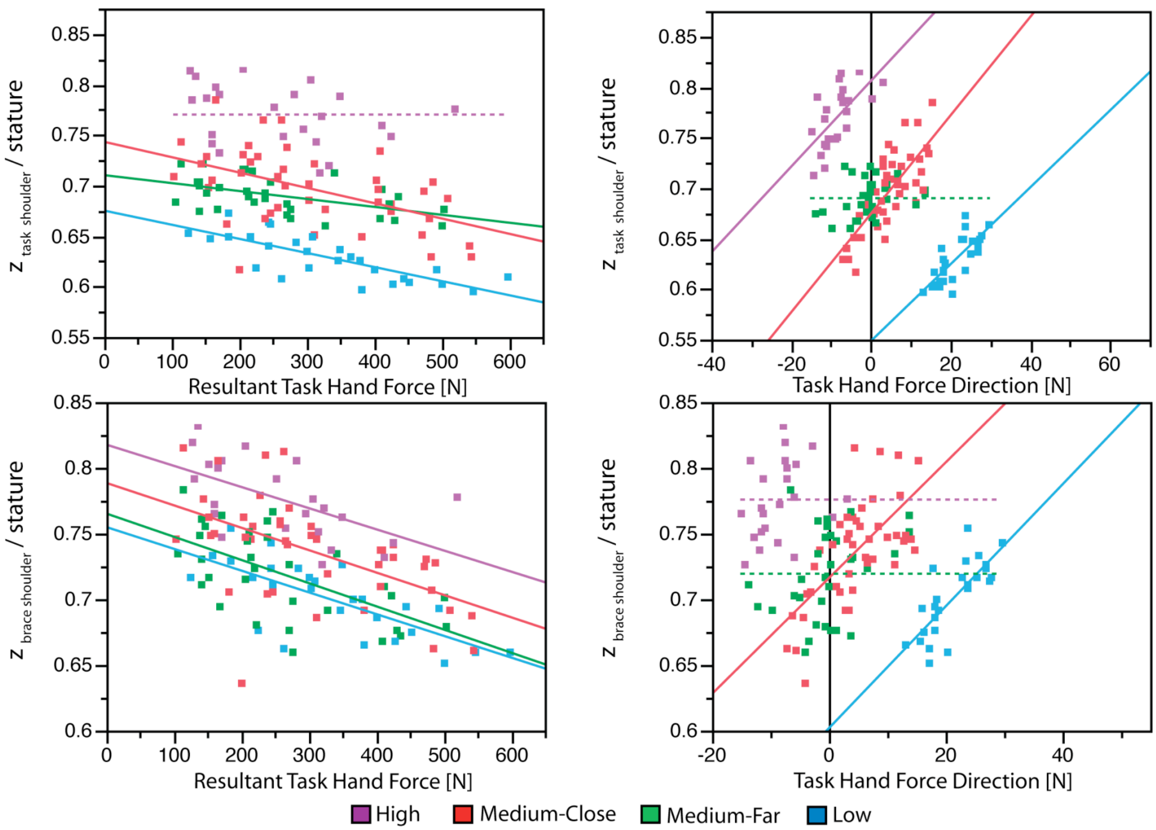

Figure 7.4.4 Variation of task and brace shoulder height with increasing task hand force and deviation in task hand force direction during backward exertions adopting HB FGS. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

TB Force-Generation Strategy

Neither TB nor HTB-o FGS trials revealed significant relationships between the postural degrees of freedom and task hand force exertion capability. Changes in postural metrics were observed however to be associated with directional changes in the task hand force vector.

Change in fore-aft location of the pelvis was observed to have a significant relationship with task hand force direction for backward exertions. As the fore-aft hip position decreased, increasing the engagement of the pelvis at the kinematic constraint, the direction of the task hand force vector was observed to increase directional deviation with respect to nominal direction (Figure 7.4.5). Task hand force direction was significantly related to the fore-aft hip position at medium-close and medium-far task handle location.

In backward trials which the subject engaged the kinematic constraint to generate thigh force (TB), pelvis height was not affected by increased task hand force levels for any of the task configurations. Changes in the hip height had a limited effect on task hand force direction at the medium-close handle position only.

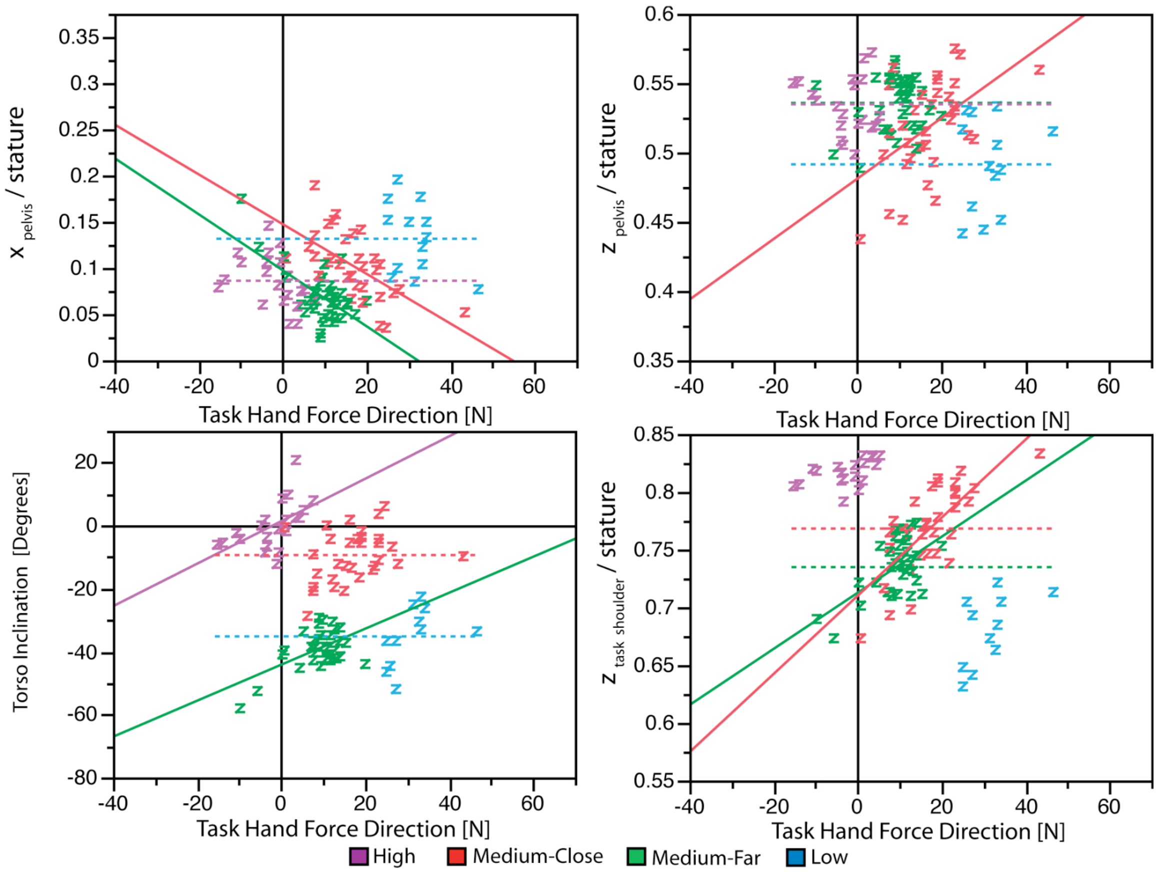

Figure 7.4.5 Change in fore-aft location of the pelvis (x pelvis/ stature), pelvis height (z pelvis/ stature), torso inclination angle [degrees] with respect to vertical, and task shoulder height (z task shoulder /stature) with task hand force direction for backward exertions adopting the TB FGS. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

Engagement of the thigh at kinematic constraint during TB trials yielded a small deviation in torso inclination and subsequently more upright postures. Small torso inclination changes were associated with task hand force vectors more closely associated to nominal for high and medium-far task handle locations only (Figure 7.4.5).

For backward trials that employed the TB or HTB-o FGS, there were no significant changes in task shoulder height associated with increasing task hand force. On average, force-generation strategies that involved thigh bracing resulted in more upright postures due to the kinematic constraint. Change in task shoulder height was correlated with task hand force direction that had were more closely aligned with the nominal direction at medium-close and medium-far task handle positions (Figure 7.4.5).

HTB-o Force-Generation Strategy

The fore-aft hip position and task shoulder height were the only two postural degrees of freedom to have any effect on the direction of the task hand force for backward exertions adopting the HTB-o FGS. A decrease in the fore-aft location of the pelvis was found to result in an increased directional deviation of the task hand force vector with respect to nominal at the medium-close and low task handle locations (Figure 7.4.6).

Change in task shoulder height was also observed with task hand force direction more closely associated with the nominal direction for HTB-o trials at high, medium-close and low task handle positions. This trend was observed across all FGSs and task handle locations, with exception of the medium-far handle position and subsequent extended horizontal reach.

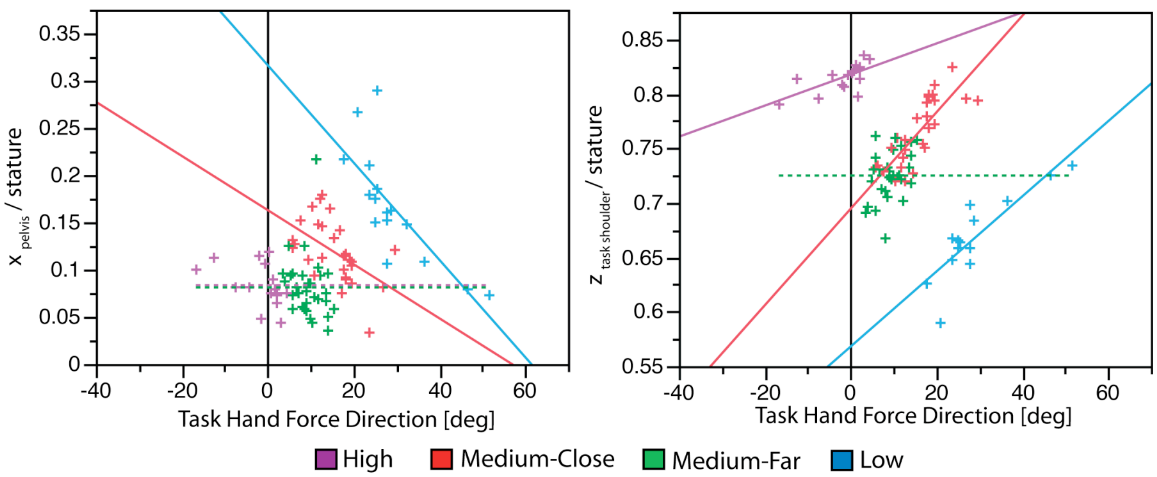

Figure 7.4.6 Change in fore-aft location of the pelvis (x pelvis/ stature) and task shoulder height (z task shoulder /stature) with task hand force direction, for backward exertions adopting the HTB-o FGS. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

It is interesting to note that relationships between contralateral shoulder location and task hand force metrics were not significant for HTB-o exertions. In contrast to HB trials there was no significant change in contralateral shoulder height with increased task force levels observed for pull exertions that employed the HTB-o FGS.

Backward Exertions: Regression Analysis

The foregoing statistical analyses demonstrated that task handle location and requested task hand force magnitude have statistically significant effects on the postural adaptations associated within the force-generation strategies outlined in Chapter Four. These observations are integrated into regression models that predict the key postural variables.

The range estimates, R^2 values, and root-mean-square-error (RMSE) values in Table 7.4.2 indicate the relative importance of task configuration and anthropometric variables in determining postures adopted within the force-generation strategies. The importance of the regression function terms can be evaluated more easily by multiplying each coefficient by the range of the independent measure that is present in the data. Table 7.4.2 shows the resulting values. For example, the range of the fore-aft location of exertion handle, normalized to stature in the data is 0.29 (fraction of stature). Multiplying the coefficients from Table 7.4.1 by 0.29 (fraction of stature) indicate that effect on the fore-aft hip position of varying stature over this range is about 0.12 (fraction of stature), while the effect on the torso inclination is about 34 degrees of forward flexion.

Table 7.4.1: Regression equations predicting key postural variables for nominal backward exertions within force-generation strategies*

Postural Metric	FGS	$Task_x$	$Task_z$	$Task_z^2$	Brace Level#	Task HF	BMI	Stature	DoF	R^2 Adj	RSME	2-way Interactions
HipX		0.43	~	~	-0.02	0.0005	~	~	117	0.83	0.03	
HipZ		-0.13	0.12	~	~	-0.0003	~	0.0001	117	0.59	0.03	$(TaskLoc_z^2)$*(TaskHF): 0.301
TorsoInclin	NB	120.35	227.23	-129.8	2.74	-0.0679	0.7413	~	112	0.85	5.42	
TaskShZ		0.16	0.41	~	~	-0.0004	0.0027	0.0001	112	0.83	0.02	
BraceShZ		~	0.29	~	~	-0.0004	~	~	112	0.55	0.04	
HipX		0.61	-0.11	~	~	0.0001	~	~	132	0.75	0.03	
HipZ		-0.19	0.11	~	~	-0.0001	~	~	132	0.46	0.03	($TaskLoc_x$)*(Brace): -441.495
TorsoInclin	HB	-26.30	84.43	~	10.67	~	-1.73	-0.031	123	0.79	5.82	(BraceLevel)*(BMI): -8.461
TaskShZ		~	0.46	~	~	-0.0001	~	~	123	0.81	0.02	(BraceLevel)*(Stature): -0.092
BraceShZ		0.14	0.24	~	~	-0.0002	~	~	123	0.64	0.03	
HipX		0.21	-0.19	~	~	~	0.0045	~	105	0.39	0.03	
HipZ		-0.15	0.19	~	~	~	-0.0034	~	105	0.37	0.02	
TorsoInclin	TB	159.87	492.82	-320.7	~	~	~	~	97	0.85	6.83	
TaskShZ		0.12	0.47	~	~	~	~		97	0.72	0.03	
BraceShZ		~	0.25	~	-0.02	0.0000	~	~	97	0.39	0.03	
HipX		0.28	-0.37	~	~	0.0000	0.0044	~	90	0.56	0.03	
HipZ		-0.09	0.22	~	~	~	~	~	90	0.37	0.03	$(TaskLoc_z)$*(TaskHF): -0.001
TorsoInclin	HTB-o	152.7	449.79	-278.3	~	~	~	~	86	0.88	6.32	
TaskShZ		~	0.52	~	~	~	~		86	0.70	0.03	
BraceShZ		~	0.29	~	0.05	~	~	~	86	0.42	0.03	

*Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients (columns) and the variable values, plus a constant intercept.

#Brace level is a nominal variable and only one value from each strategy should enter the regression equation at any one time.

$TaskLoc_x$ denotes fore-aft task handle location; $TaskLoc_z$ ($_z^2$) denotes vertical task handle position; Task HF denotes task hand force

Table 7.4.2: Range estimates using regression equations predicting key postural variables for nominal backward exertions within force-generation strategies

Postural Metric	FGS	$Task_x$	$Task_z$	$Task_z^2$	Brace Level#	Task HF	BMI	Stature	DoF	R^2 Adj	RSME
HipX		0.12	~	~	-0.05	0.29	~	~	117	0.83	0.03
HipZ		-0.04	0.04	~	~	-0.18	~	0.03	117	0.59	0.03
TorsoInclin	NB	34.30	80.89	-53.76	8.22	-42.36	10.33	~	112	0.85	5.42
TaskShZ		0.04	0.15	~	~	-0.24	0.04	0.03	112	0.83	0.02
BraceShZ		~	0.11	~	~	-0.23	~	~	112	0.55	0.04
HipX		0.17	-0.04	~	~	0.09	~	~	132	0.75	0.03
HipZ		-0.05	0.04	~	~	-0.08	~	~	132	0.46	0.03
TorsoInclin	HB	-7.50	30.06	~	32.00	~	-24.16	-12.24	123	0.79	5.82
TaskShZ		~	0.16	~	~	-0.07	~	~	123	0.81	0.02
BraceShZ		0.04	0.08	~	~	-0.10	~	~	123	0.64	0.03
HipX		0.06	-0.07	~	~	~	0.06	~	105	0.39	0.03
HipZ		-0.03	0.07	~	~	~	-0.05	~	105	0.37	0.02
TorsoInclin	TB	45.56	175.44	-132.76	~	~	~	~	97	0.85	6.83
TaskShZ		0.03	0.17	~	~	~	~		97	0.72	0.03
BraceShZ		~	0.09	~	-0.05	-0.01	~	~	97	0.39	0.03
HipX		0.08	-0.13	~	~	0.03	0.06	~	90	0.56	0.03
HipZ		-0.03	0.08	~	~	~	~	~	90	0.37	0.03
TorsoInclin	HTB-o	43.52	160.12	-115.23	~	~	~	~	86	0.88	6.32
TaskShZ		~	0.18	~	~	~	~		86	0.70	0.03
BraceShZ		~	0.10	~	0.15	~	~	~	86	0.42	0.03

NB Force-Generation Strategy

The available variables account for a large percentage of variance in the key postural metrics, R^2 values ranged from 0.55 to 0.85, for backward exertions within the NB FGS. Range estimates of the regression models substantiate that higher task hand force levels are by far the most important determinant for all the postural metrics during backward exertions within the NB FGS and across the task configurations studied. Postural degrees of freedom associated with backward tasks executed with the NB strategy were largely affected by the vertical task handle location. The second-order vertical task height term also added substantial predictive ability for torso inclination with respect to vertical. Fore-aft location of the task handle had a strong effect on the fore-aft hip position, 0.12 (fraction of stature) of a 0.29 (fraction of stature) range, which is indicative of the aforementioned relationship with increasing task hand force.

Anthropometric variables, BMI and to a lesser extent stature, affect torso inclination, hip height and task shoulder height for backward exertions employing the NB FGS.

HB Force-Generation Strategy

All of the postural degrees of freedom associated with HB trials are effectively predicted from the task configuration variables. The R^2 values, ranged from 0.46 to 0.81 across the postural metrics, indicating strong relationships between the vertical handle position and task hand force levels. Fore-aft hip position, vertical pelvis location, and contralateral shoulder height were each predicted by a combination of the vertical height and fore-aft position of the task handle positions and increasing task hand force requirement. Torso inclination is the only postural metric that was not significantly affected by task hand force but rather was moderately affected by the anthropometric variables. Unique from the aforementioned postural degrees of freedom, task shoulder height was not affected to the horizontal location of the task configuration. Similar to the NB FGS results, the horizontal task handle location is the most predominate predictor of the fore-aft hip position.

TB Force-Generation Strategy

Torso inclination and task shoulder height are strongly predictive (adjusted R2 values of 0.85 and 0.72, respectively), in comparison with fore-aft and vertical hip variables (adj $R^2 = 0.39$ and adj $R^2 = 0.37$, respectively) and contralateral shoulder height (adj $R^2 = 0.39$), which are only moderately well predicted for backward exertions that employed the TB FGS. Task configuration variables, fore-aft and vertical location of the task handle, contribute as regressors for all of the postural metrics. Subject BMI also affects the fore-aft displacement and hip height within the TB strategy. Similar to NB trials, the second-order vertical task height term also added substantial predictive ability for torso inclination with respect to vertical. Correlation between the task configuration and task hand force level was notably absent for backward exertions within both TB and HTB-o FGSs.

HTB-o Force-Generation Strategy

There is a consistent trend upheld across all the backward exertions and FGSs in that the fore-aft horizontal location and vertical task handle position were important determinants of the key postural metrics. In addition to the task configuration variables, fore-aft hip position is also affected by increasing task hand force level. Torso inclination is again predicted with a second-order vertical task height term, which is observed across all of FGSs with the exception of the TB strategy. The prescribed level of bracing availability did contribute significantly to contralateral shoulder height within the HTB-a FGS.

Forward Exertions: Postural Behaviors Observed

NB Force-Generation Strategy

The relationship between hip height and task hand force exertion capability was found to be significant during forward exertions across all FGSs and most task configuration variables. Increasing task force levels was associated with a decrease hip height at high, medium-close, and low task handle locations (Figure 7.4.7). Task hand force direction was also significantly related to a lower hip height for tasks performed at the low task handle with the NB FGS.

In NB trials, increased force levels and changes to task had force direction were associated with increased torso inclination at the medium-far task handle position (Figure 7.4.7). This trend was unique for both task hand force and direction at the medium far task configuration, which the bracing structure imposed a kinematic constraint and subsequent extended horizontal reach.

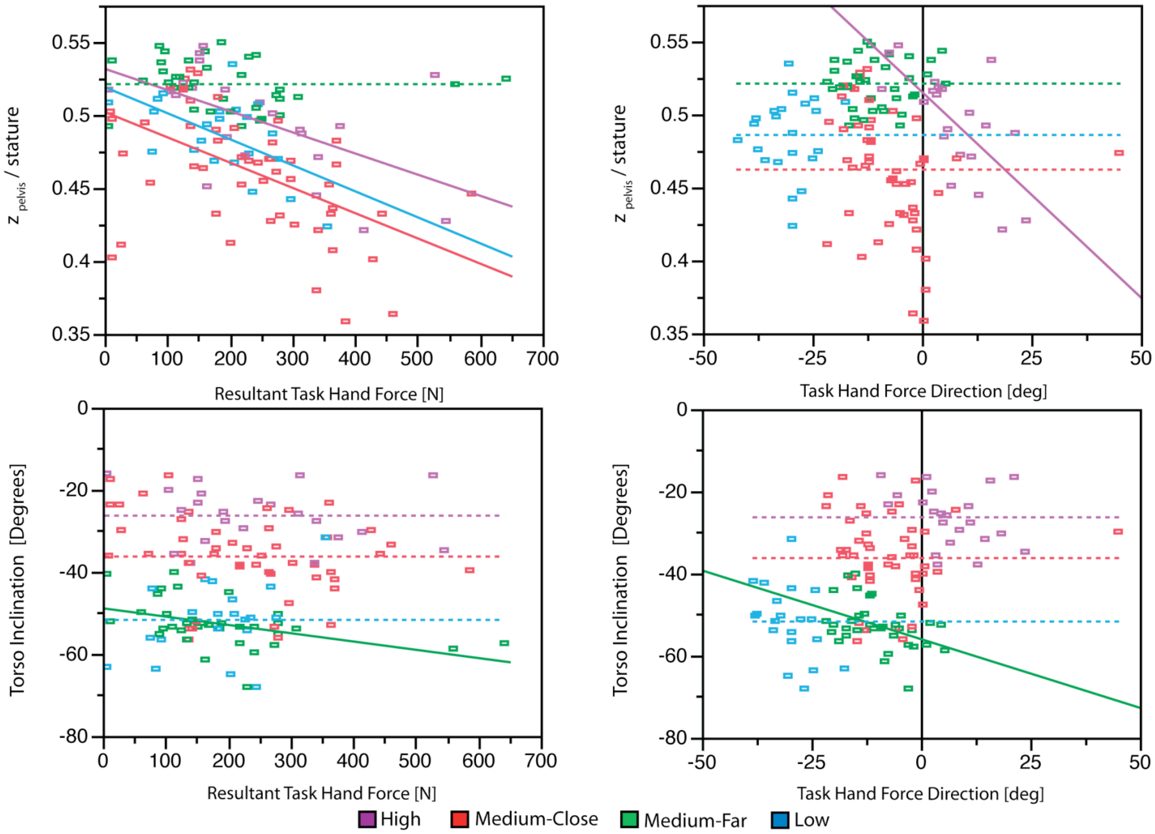

Figure 7.4.7 Change in pelvis height (z pelvis/ stature) and torso inclination angle [degrees] with respect to vertical with resultant task hand force and direction, respectively, for forward exertions adopting the NB FGS. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

Changes in task shoulder were quantified for forward exertions across all FGSs. For NB FGS trials, lower task shoulder heights were observed with higher resultant task hand forces at the medium-close task handle location only (Figure 7.4.8). However, task shoulder height was significantly correlated with task hand force direction for the range of vertical task handle configurations. When shoulder heights were lower, the task hand force direction was closer to the nominal direction across task handle positions (Figure 7.4.8).

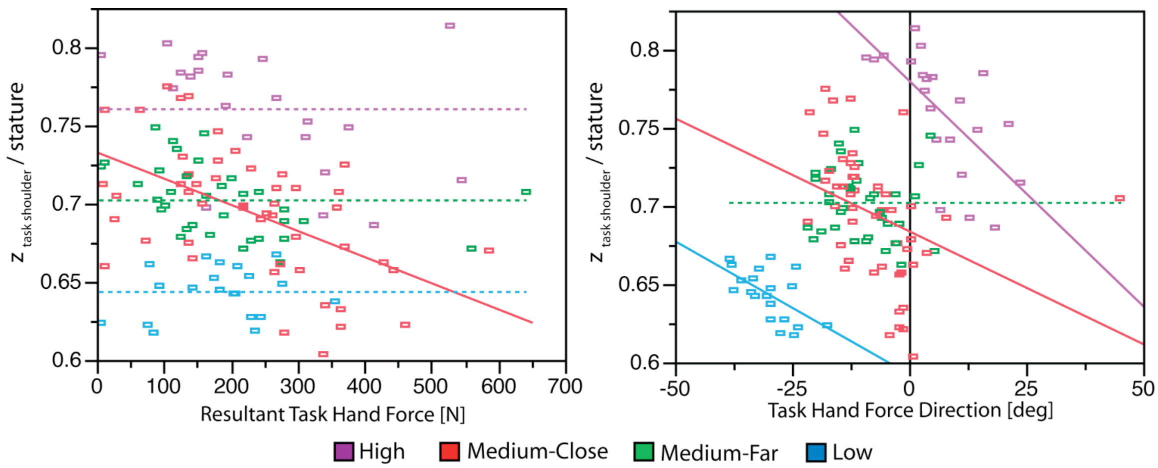

Figure 7.4.8 Change in task shoulder height with increasing task hand force and deviation in task hand force direction during forward exertions adopting NB force-generation strategy at high (mean = 0.76; R^2 = 0.45), medium-close (R^2 = 0.28; R^2 = 0.14), medium-far (mean = 0.70) and low (mean = 0.64; R^2 = 0.33) task handle locations. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

HB Force-Generation Strategy

No significant change in fore-aft hip position was observed with higher resultant task hand force for HB FGS (Figure 7.4.9). Task hand force directional changes were associated with an increasing displaced fore-aft hip position at the low task handle positions.

A consistent trend was observed of for both NB and HB FGS trials. Increased force levels were associated with lower hip heights at high, medium-close, medium-far, and low task handle locations. The relationship between lower hip height and task hand force direction more closely associated with nominal was significant for HB trials at medium-close and low task handle locations.

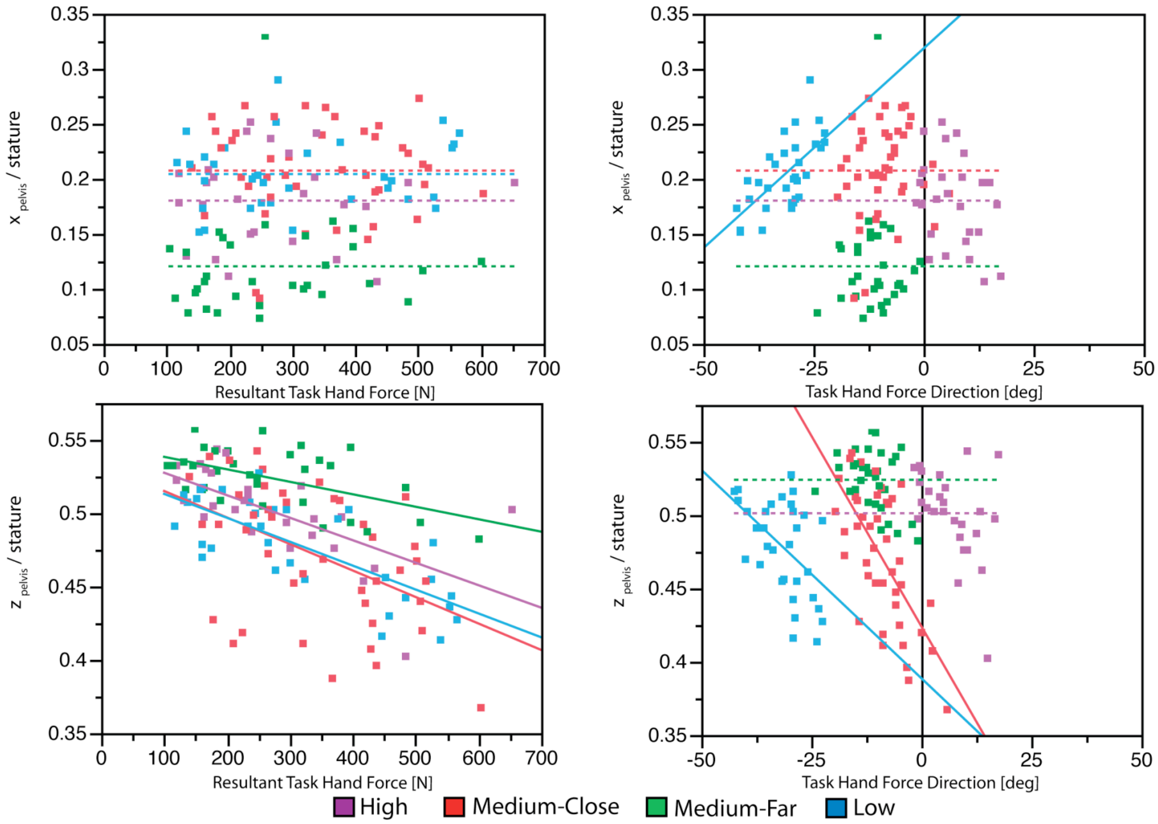

Figure 7.4.9 Change in fore-aft location of the pelvis (x pelvis/ stature) and pelvis height (z pelvis/ stature) with resultant task hand force and direction, respectively, for forward exertions adopting the HB FGS. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

For forward tasks that employed that HB FGS, increased force levels were associated with lower task shoulder positions (Figure 7.4.10). Change in task shoulder height was observed with higher resultant task hand force at high, medium-close, and medium-far task handle locations. Similar to NB trials, lower task shoulder height were observed to exert task hand force vectors that were more closely associated with nominal direction (Figure 7.4.10). Correlation between task shoulder height and task force direction was significant at all task handle locations.

Changes in the contralateral shoulder height were also quantified for forward exertions employing the HB and HTB-a FGSs. For push tasks performed with HB FGS lower contralateral shoulder heights were observed with higher task hand force levels across for the high and medium-far task handle locations only (Figure 7.4.10). Consistent with HB pull trials, contralateral shoulder locations were lower for HB push tasks, and the task hand force vector was found to be directed more towards the nominal direction at medium-close and low task handle locations.

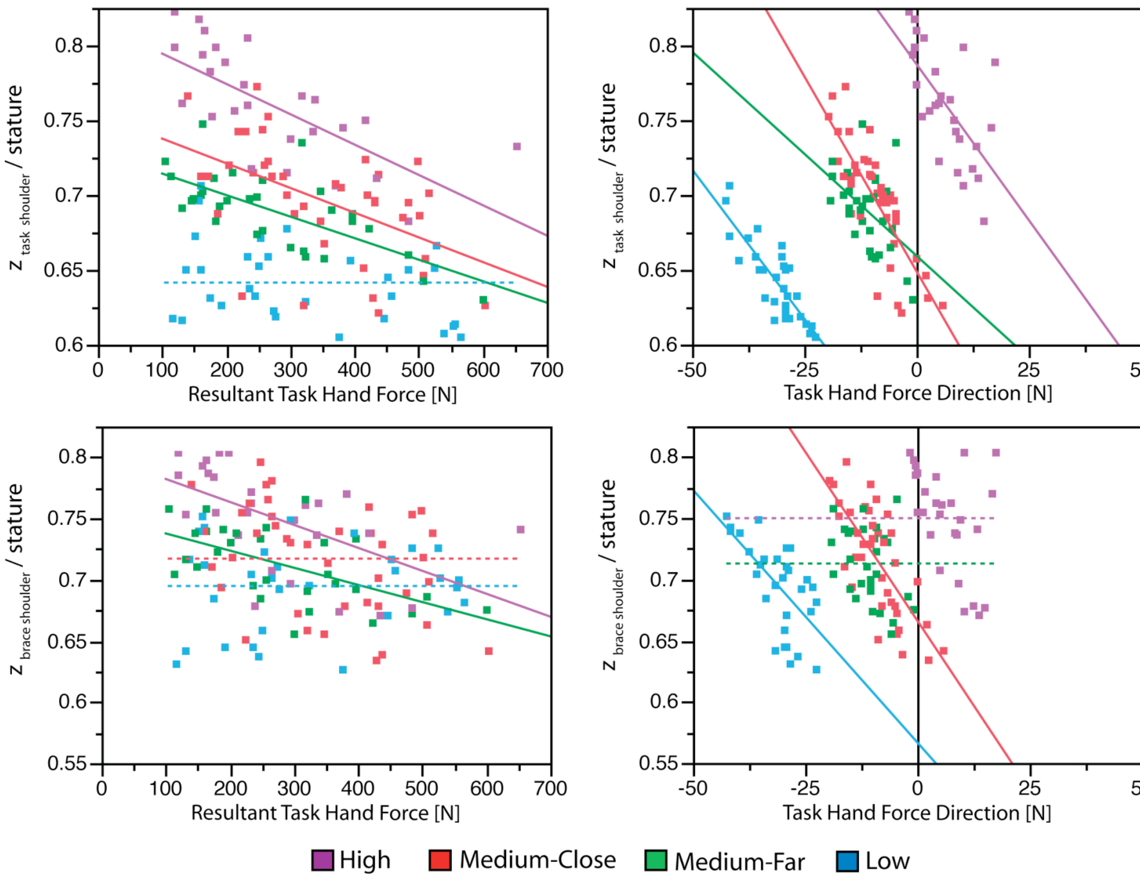

Figure 7.4.10 Variation of task and brace shoulder height with increasing task hand force and deviation in task hand force direction during forward exertions adopting HB FGS. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

TB Force-Generation Strategy

For TB trials, subject were observed to lower hip height with higher task hand force levels (Figure 7.4.11). Consistent with NB and HB FGSs, this was a significant relationship for push tasks performed with thigh bracing only at the high, medium-close and medium-far task handle positions. Changes in the hip height were not found to have a significant effect on task hand force direction at any task handle location.

Consistent with the trend observed for forward exertions adopting the NB and HB FGSs, lower task shoulder height was observed with higher resultant task force levels for

TB trials (Figure 7.4.11). The change in task shoulder height with increasing task hand force levels was significant at high, medium-close, and medium-far task handle positions.

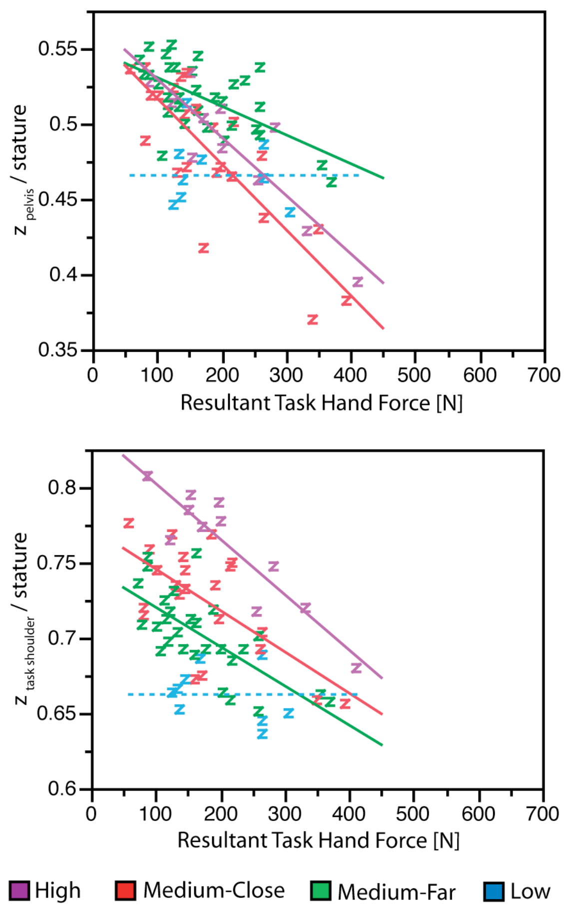

Figure 7.4.11 Change in pelvis height (z pelvis/ stature) and task shoulder height (z task shoulder /stature) with increasing task hand force for forward exertions adopting the TB FGS. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

HTB-a Force-Generation Strategy

The HTB-a strategy was the only FGS to show a significant relationship between the fore-aft horizontal displacement of the pelvis and task hand force levels (Figure 7.4.12). An increase in fore-aft location of the pelvis was found with higher resultant task hand force at the medium-close and medium-far handle positions. No relationship was observed between hip displacement and task hand force direction at any of the task handle locations.

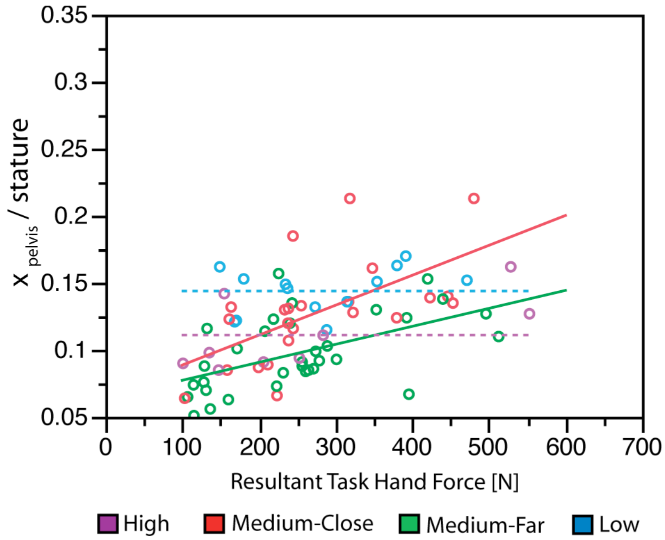

Figure 7.4.12 Variation in horizontal displacement of the hip with increasing task hand force. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

Changes in task shoulder height were also observed with higher task hand levels for HTB-a trials at the medium-far task handle location only, which imposed a kinematic constraint and subsequently an extended horizontal reach (Figure 7.4.13**).** This trend was observed to be statistically significant for both the task shoulder and contralateral shoulder heights. Decrease in task and contralateral shoulder height was also observed with task hand force direction more closely associated with the nominal direction for HTB-a trials at medium-far task handle positions (Figure 7.4.13).

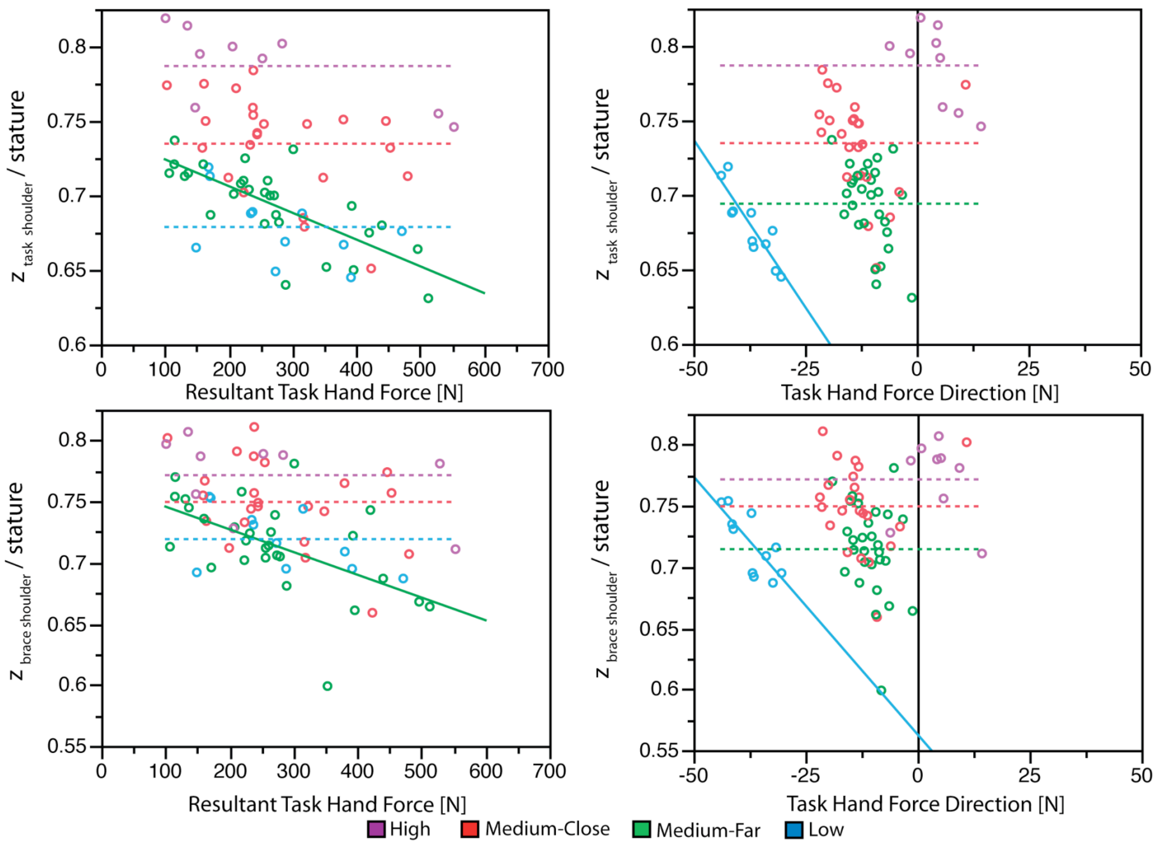

Figure 7.4.13 Variation of task and brace shoulder height with increasing task hand force and deviation in task hand force direction during forward exertions adopting HTB-a FGS. Linear relationship denoted by solid fit lines, and means values (non-significant) denoted by hatched lines, both color-coded for task handle location.

Forward Exertions: Regression Analysis

Integrated models were developed to predict the key postural metrics that parameterize forward tasks within the four FGSs (Table 7.4.3 and Table 7.4.4).

Table 7.4.3 Regression equations predicting key postural variables for nominal forward exertions within force-generation strategies*

Postural Metric	**FGS**	**$Task_x$**	**$Task_z$**	**$Task_z^2$**	**Brace Level#**	**Task HF**	**BMI**	**Stature**	**DoF**	**R^2 Adj**	**RSME**	**2-way Interactions**
HipX		0.48	0.48	-0.49	~		~	0.0000	141	0.60	0.04	(Task-z^2)*(Stature): -0.001
HipZ		-0.21		~	~	0.0001	~	~	141	0.38	0.03	(Task-x)*(TaskHF): 0.001
TorsoInclin	NB	92.75	79.19	~			0.890		132	0.74	6.89	(Task-z)*(BMI): -9.71
TaskShZ		0.44	3.48	-2.67	~	0.0001	0.003	~	132	0.72	0.02	
BraceShZ		0.19		~	~		~	~	132	0.24	0.05	(Task-X)*(Task-z): -55.42
HipX		0.40		~	~			~	126	0.35	0.04	
HipZ		-0.21		~	~	0.0002	~	~	126	0.51	0.03	
TorsoInclin	HB	101.64	72.88		~		~	~	120	0.62	8.57	
TaskShZ		0.39		~	~	0.0001	~		120	0.75	0.03	
BraceShZ			0.35	-0.19		0.0001	~	-0.0001	119	0.49	0.03	(Task-z^2)*(TaskHF): 0.001
HipX		0.18		~	~	-0.0001		~	71	0.35	0.03	
HipZ		-0.20		~	~	0.0003		~	71	0.61	0.03	
TorsoInclin	TB	133.05	72.97		~		~	~	66	0.84	5.85	
TaskShZ		0.12	0.37	~	~	0.0003	0.003		66	0.79	0.02	
BraceShZ			0.18	~		0.0004	~	~	66	0.57	0.03	
HipX		0.15	-0.12	~		-0.0001	~	~	71	0.44	0.03	
HipZ		-0.12	0.14	~	~	0.0001	~		71	0.36	0.03	
TorsoInclin	HTB-o	142.79	64.38					~	64	0.77	6.98	
TaskShZ		0.22	0.41	~	~	0.0002			64	0.75	0.02	
BraceShZ		0.17	0.22	~	~	0.0001	~	~	64	0.39	0.03	

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients (columns) and the variable values, plus a constant intercept.
# Brace level is a nominal variable and only one value from each strategy should enter the regression equation at any one time.
$TaskLoc_x$ denotes fore-aft task handle location; $TaskLoc_z$ ($_z^2$) denotes vertical task handle position; Task HF denotes task hand force

Table 7.4.4 Range estimates using regression equations predicting key postural variables for nominal forward exertions within force-generation strategies

Postural Metric	FGS	$Task_x$	$Task_z$	$Task_z$ 2	Brace Level#	Task HF	BMI	Stature	DoF	R^2 Adj	RSME
HipX		0.14	0.17	-0.20	~		~	0.000	141	0.60	0.04
HipZ		-0.06		~	~	0.07	~	~	141	0.38	0.03
TorsoInclin	NB	26.43	28.19	~			12.38		132	0.74	6.89
TaskShZ		0.13	1.24	-1.11	~	0.04	0.04	~	132	0.72	0.02
BraceShZ		0.05		~	~		~	~	132	0.24	0.05
HipX		0.11		~	~			~	126	0.35	0.04
HipZ		-0.06		~	~	0.12	~	~	126	0.51	0.03
TorsoInclin	HB	28.97	25.94		~		~	~	120	0.62	8.57
TaskShZ		0.11		~	~	0.09	~		120	0.75	0.03
BraceShZ			0.12	-0.08		0.07	~	-0.048	119	0.49	0.03
HipX		0.05		~	~	-0.09		~	71	0.35	0.03
HipZ		-0.06		~	~	0.19		~	71	0.61	0.03
TorsoInclin	TB	37.92	25.98		~		~	~	66	0.84	5.85
TaskShZ		0.04	0.13	~	~	0.17	0.04		66	0.79	0.02
BraceShZ			0.07	~		0.25	~	~	66	0.57	0.03
HipX		0.04	-0.04	~		-0.09	~	~	71	0.44	0.03
HipZ		-0.04	0.05	~	~	0.08	~		71	0.36	0.03
TorsoInclin	HTB-o	40.69	22.92					~	64	0.77	6.98
TaskShZ		0.06	0.15	~	~	0.10			64	0.75	0.02
BraceShZ		0.05	0.08	~	~	0.09	~	~	64	0.39	0.03

HB Force-Generation Strategy

The available variables account for a large percentage of variance in the key postural metrics, R^2 values ranged from 0.35 to 0.75, for forward exertions within the HB for FGS. The integrated regression models substantiate that increasing task hand force requirement, in combination with the fore-aft task handle position were the most important determinants for hip and task shoulder height, while it was the association between vertical handle height and increasing task hand force that predicted the brace shoulder height. Contralateral shoulder height was also affected by stature. Fore-aft hip position and torso inclination were not observed to be affected by increasing task hand force, rather as indicated the horizontal location of the task handle was the most powerful predictor of the fore-aft hip position and torso inclination.

TB Force-Generation Strategy

The effect of increasing task hand force level was a significant predictor of all the postural degrees of freedom with the exception of torso inclination for forward exertions adopting the TB FGS. In addition to task hand force, the fore-aft hip position and height were both affected by horizontal task handle location, although it is notable that the vertical task handle position did not have a significant effect. The remaining postural variables, torso inclination, task and contralateral shoulder heights were determined largely by the combination of task handle height and increasing force levels.

HTB-a Force-Generation Strategy

Forward exertions performed with the HTB-a FGS were observed to follow a similar trend as TB trials; in that a combination of task configuration variables and increasing force level that have substantial predictive ability. Unique to the HTB-a strategy, both the fore-aft and vertical positions of the task handle consistently affected all of the postural metrics. Again, torso inclination was the only postural degree of freedom unaffected by increasing task hand force levels. The R^2 adjusted values range from 0.36 to 0.77, indicating that forward exertions performed by employing the HTB-a FGS are predicted moderately well.

7.5. Discussion

Analysis of key postural behaviors associated with braced, force exertions are coupled with the force-generation strategies and support the hypothesized biomechanical principles. Changes in key postural degrees-of-freedom in response to task configuration variables and increasing task hand force were found to be consistent with the five force-generation strategies.

Principal observations are:

- Fore-aft task handle location and vertical handle height; nominal task hand force and force-generation strategy each have significant, independent and interactive effects on all posture variables.
- The effects of these four variables are mostly independent of body size (stature) and proportion.

- Fore-aft position of the pelvis, the key postural metric to differentiate force-generation strategies based upon the engagement of the lower extremities with the kinematic constraint, is influenced by task handle locations, force-generation strategy and their interactions and task hand force exertion capability.

- Task handle location had the most significant effect on the vertical height of the hip for both nominal task hand exertions.

    - Hip height was constrained by the kinematic constraint for backward exertions that engaged the lower extremities, and varied for force exertions performed without thigh bracing.

    - Hip height did not change with force-generation strategy, but was associated with task hand force exertion capability for forward exertions.

- Torso inclination was affected by task configuration variables and force-generation strategies for both backward and forward exertions.

- Task shoulder height was modified as a function of task handle location for exertions performed in both nominal directions. Force-generation strategies that did not employ thigh bracing also had a significant effect on the vertical location of the task shoulder during backward exertions.

- The vertical position of the brace shoulder was observed to change with task handle location effects only.

The following observations were realized by the cross-tabulation (Table 7.5.1) of the relationship between the postural behaviors and task hand force with respect to force-generation strategies.

Table 7.5.1 Relationships between postural behaviors, task hand force exertion capability, and force-generation strategy (FGS).

(Hypothesized) Relationship with Task Hand Force-Exertion Capability	**Postural Behavior**	**FGS Association**	
		Backward Exertions	*Forward Exertions*
Increase in horizontal displacement, characterized as a lack of engagement with the kinematic constraint, was observed to increase task hand force exertion capability.	**Fore-aft hip location (Hip_X)**	NB HB	HTB-a
Engagement of lower extremities at the kinematic constraint was found to increase the deviation of the task hand force direction with respect to the requested horizontal nominal.		NB HB TB HTB-o	HB
A decrease in hip height was observed with increasing task hand force for medium and low task handle locations.	**Height of the pelvis (Hip_Z)**	NB HB	NB HB TB
Task hand force directions more closely associated with the requested horizontal nominal were observed with lowering hip height.		NB TB	NB HB HTB-a
An increase in torso inclination with respect to neutral standing posture was found to increase task hand force exertion capability.	**Torso inclination from vertical**	NB	NB HB
Forward torso inclination was associated with a decrease in directional deviation of the task hand force vector.		NB HB TB	HB HTB-a
Lowering task shoulder height with respect to the point of force application is hypothesized to increase exertion capability, although not explicitly quantified.	**Vertical position of the task shoulder (Task Sh_Z)**	NB HB	NB HB TB HTB-a
Decrease in task shoulder height resulted in task hand force vectors more closely associated with the nominal direction to maintain task shoulder moment (% criterion threshold).		NB HB TB HTB-o	NB HB HTB-a
Lowering contralateral shoulder height with respect to the point of force application is hypothesized to increase exertion capability, although not explicitly quantified.	**Vertical position of the brace shoulder (Brace Sh_Z)**	HB	HB HTB-a
Decrease in task shoulder height resulted in task hand and brace hand force vectors closely associated with the nominal direction.		n/a	HB HTB-a

Backward Exertions

NB Force-Generation Strategy

Backward exertions that were performed without the availability of any bracing surface, utilized all of the degrees of freedom to increase task hand force exertion capability. Subjects were observed to horizontally displace the pelvis with respect to the kinematic constraint to increase task hand force and affect task force direction. These trends were observed across all of the task handle locations. An increase of forward flexion of the torso about the lumbar spine was also found to increase task hand force capability and reduce directional deviation of the task hand force vector for backward exertions at the high, medium-close and medium-far handle locations. Adopting a squatting posture, exertions performed at the medium-close and low exertion handle locations were also correlated with a lower pelvis height and increased task hand force that was more closely associated with the nominal direction. The vertical position of the task shoulder location was the final degree of freedom to be affected and was found to drop and align with the exertion handle with increasing task hand force. This postural behavior was consistent with the hypothesis of altering task shoulder position to reduce the task shoulder moments, or alternatively produce higher task hand force with the same task shoulder moment.

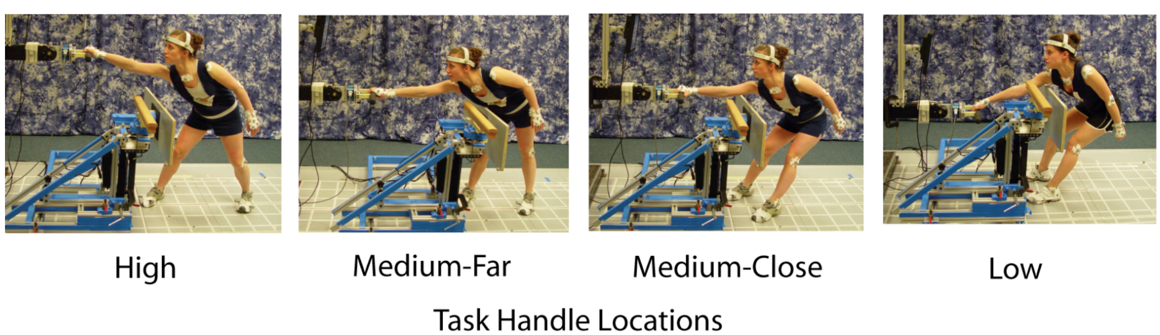

Figure 7.5.1 Representative postural behaviors associated with backward exertions adopting the NB FGS.

HB Force-Generation Strategy

The addition of hand bracing restricted the effect of the position of the pelvis degree of freedom, for the high and medium-far task handle locations. The kinematic constraint of the tasks performed at high and medium-far handle locations also imposed significant change in torso inclination although the only effect was to alter the direction of the task hand force vector. Increasing the horizontal displacement of the pelvis with respect to the bracing structure and lowering the hip height were found to increase task exertion capability and reduction directional task force deviation for backward exertions at the medium-close and low handle locations. The effect of lowering the task shoulder location in an effort to increase task hand force and align the task force vector with the shoulder joint was observed for all task handle locations with the exception of the medium-far location. The brace shoulder was also lowered to increase both task and brace hand force across all of the task handle locations, although it did not reveal any effect on the direction of either the task or brace hand forces.

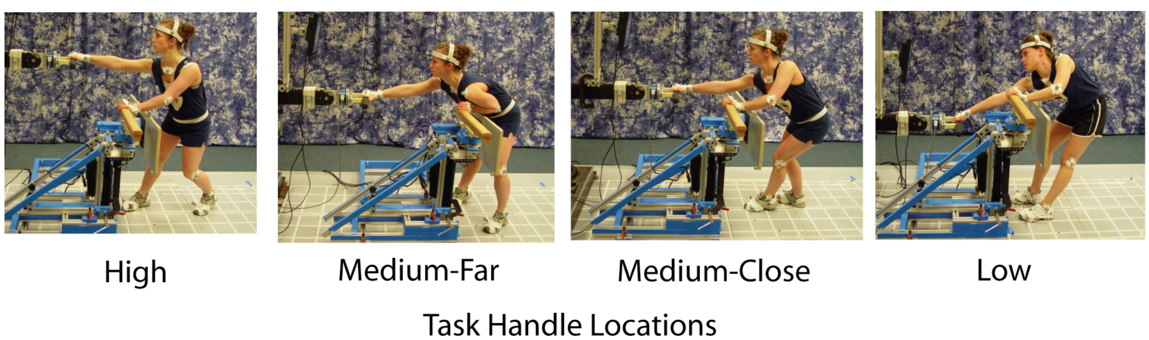

Figure 7.5.2 Representative postural behaviors associated with backward exertions adopting the HB FGS.

TB Force-Generation Strategy

None of the postural degrees of freedom were observed to increase task hand force exertion capability for backward exertions performed by the TB force-generations strategy. Rather for backward exertions at the medium-close handle location, changes in the horizontal displacement of the pelvis with respect to the bracing structure, which were indicative of changes in the rotation of the pelvis that correspond to turning away from the handle or opening up the base-of-support orientation, yielded task hand force vectors that were closely oriented to the nominal direction. Similarly, an increased torso inclination with respect to neutral posture and a lowered hip height resulted in a torso rotation that is hypothesized to reduce low-back rotation moment by reducing the direction of task hand force vector and subsequently reducing the rotational moment arm. The vertical task shoulder modifications were also observed to decrease the directional deviation of the task hand force.

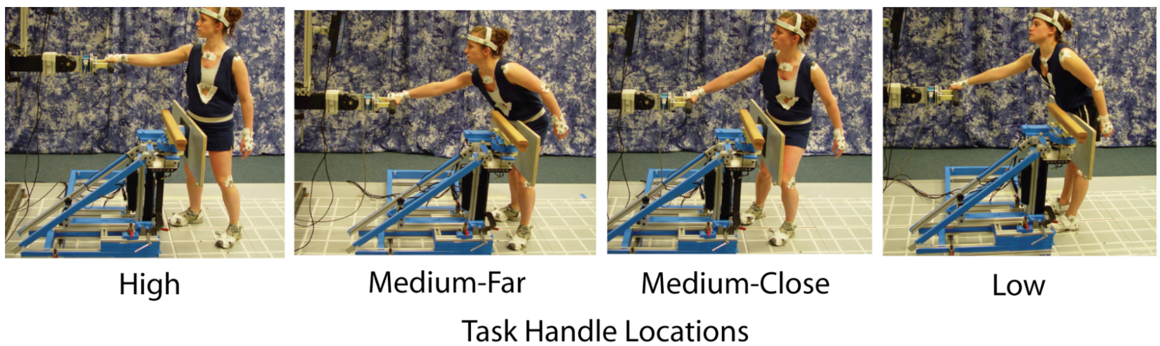

Figure 7.5.3 Representative postural behaviors associated with backward exertions adopting the TB FGS.

HTB-o Force-Generation Strategy

The postural degrees of freedom are largely restricted for backward exertions that employed contralateral hand bracing and engaged the lower extremities at the kinematic constraint. Similar to the TB strategy, there were no significant relationships between the postural behaviors and task hand force exertion capability. Horizontal displacement of the pelvis, akin to the aforementioned changes in torso orientation observed for the TB strategy, was the only whole-body degree of freedom that was associated with a decrease in task hand force direction. Position of the task shoulder was also found to lower in an effort to re-direct the task hand force vector through the task shoulder for tasks at the high, medium-close and medium-far handle locations. It is interesting to note that modifications to the brace shoulder did not reveal any significant relationship with either task or brace hand force.

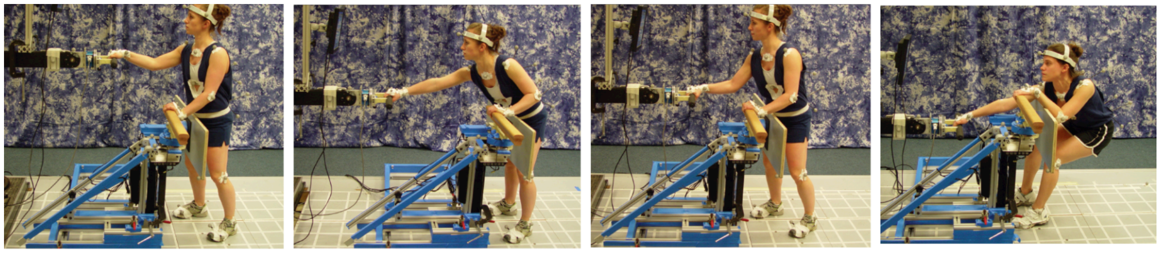

Figure 7.5.4 Representative postural behaviors associated with backward exertions adopting the HTB-o FGS.

Forward Exertions

NB Force-Generation Strategy

There is one critical difference in the available degrees of freedom between forward and backward exertions. The engagement of the thigh and subsequent horizontal displacement of the pelvis has no significant contribution task hand strength capability during forward exertions adopting NB, HB or TB force-generation strategies. This is predicated on the fact that the bracing hand and feet provide the only oppositional, reactive forces relative to the task hand force. Forces exerted by lower extremity engagement at the kinematic constraint are aligned with the task hand force direction. Therefore forward task adopting the NB force-generation strategy are restricted to n-1 degrees of freedom. Lowering the hip height did result in an increase in task hand force exertion capability for forward exertions at high, medium-close and low handle locations; yet the direction of the task hand force vector was only affected by height of the pelvis for tasks performed at the high handle height. Changes in torso inclination were found to significant increase task hand force exertion capability and direct the task hand force closer to the requested nominal direction for tasks performed at the medium-far handle location, which were kinematically constrained by the extended horizontal reach. Adjusting the task shoulder to align with the exertion handle increase exertion capability for forward exertions at medium-close handle height, and enabled modifications to the task hand force vector to direct through the task shoulder for tasks at high, medium-close and low handle heights.

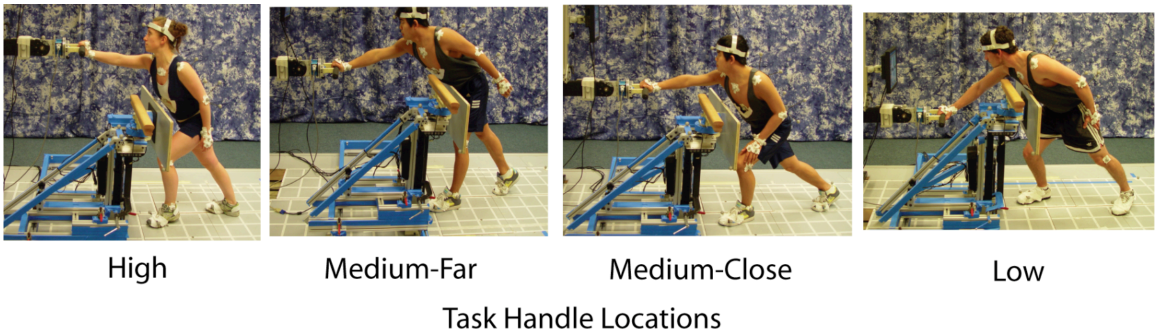

Figure 7.5.5 Representative postural behaviors associated with forward exertions adopting the NB FGS.

HB Force-Generation Strategy

The additional contact at the contralateral hand-bracing surface afforded subjects to adjust the pelvis height across all of the task handle locations in an effort to significantly increase task hand force exertion capability. The medium-close and low task handle locations were the least kinematically constrained tasks and were observed to alter the task hand force vector to nominal horizontal direction. The effect of lowering the task shoulder location in an effort to increase task hand force and align the task force vector with the shoulder joint was observed for all task handle locations with the exception of the low location. The brace shoulder was also lowered to increase both task and brace hand forces for the kinematically constrained tasks, medium-far and high task handles, in contrast to the less constrained task locations, medium-close and low task handle heights, in which the task shoulder was observed to re-direct the task force vector closer to nominal.

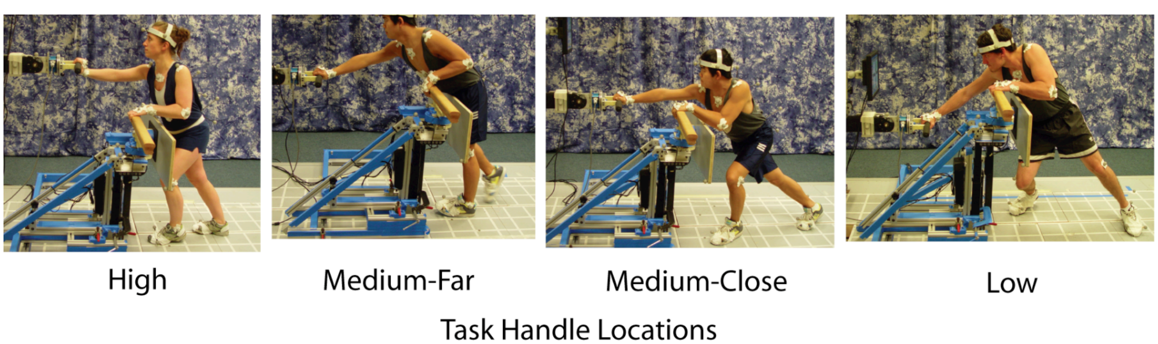

Figure 7.5.6 Representative postural behaviors associated with forward exertions adopting the HB FGS.

TB Force-Generation Strategy

Altering the pelvis height and task shoulder were the only two degrees of freedom that affected task hand force exertion capability for the TB force-generation strategy. Reducing the height of both the pelvis and task shoulder effectively enabled the task hand force vector to be aligned with the L5/S1 joint and task shoulder, in an effort to reduce both rotational moment about the lumbar spine and task shoulder respectively. This relationship was significant for forward exertions at the high, medium-close and medium-far task handle locations.

Figure 7.5.7 Representative postural behaviors associated with forward exertions adopting the TB FGS.

HTB-o Force-Generation Strategy

The HTB-o is the one force-generation strategy that was observed to have a significant relationship between the horizontal position of the hip and task exertion capability. Forward tasks performed at the medium-close and medium-far task handles were observed to adopt rearward horizontal displacement of the pelvis and an open orientation of the base-of-support that were consistent with reducing low-back rotational moments by rotating the torso to reduce the rotational moment arm. The additional kinematic constraint of the medium-far handle location resulted in lowering the task and brace shoulder with increasing task hand force.

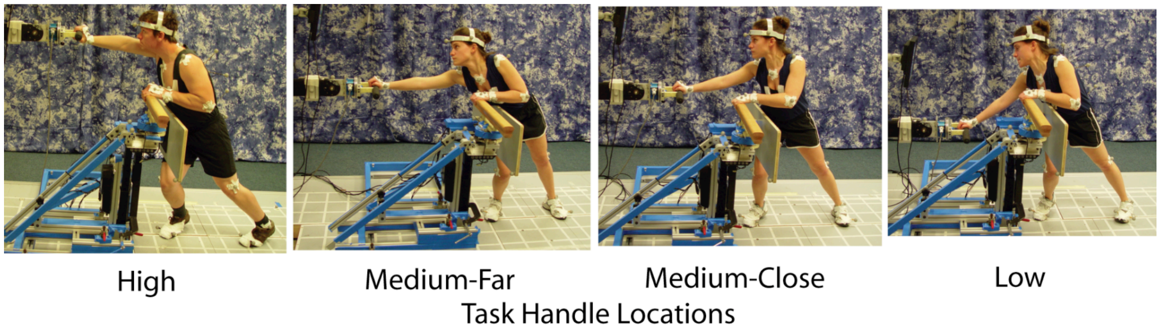

Figure 7.5.8 Representative postural behaviors associated with forward exertions adopting the HTB-a FGS.

Application

Changes in key postural degrees-of-freedom in response to task configuration variables and increasing task hand force-exertion capability were found to be consistent with the multinomial FGS classification of five discrete force-generation strategies across the nominal backward and forward tasks.

- Engagement of the lower extremities with the kinematic constraint, more specifically the fore-aft position of the pelvis, was the key postural metric to differentiate FGS that did or did not involve thigh bracing.
- Torso inclination was affected by the kinematic constraint of the task configuration and FGS selection.
- Alignment between the task shoulder and point of force application were modified by:
    - Modify task shoulder location to align with the vertical task handle location.
    - Improving the alignment between the task hand force and nominal direction.
- Alter contralateral shoulder to improve alignment of bracing force with task hand force.

7.6. Conclusions

Through systematic analysis of laboratory data, pushing and pulling postures are found to be consistent with the multinomial FGS classification and subsequently related with task hand force direction and magnitude. Changes in critical postural metrics were modified in ways that were consistent with biomechanical explanations that have been found to govern unconstrained, force-exertion tasks (Haselgrave et al., 1997; Hoffman, 2008).

7.7. References

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CHAPTER 8

DISCUSSION

8.1. Review of Objectives

The research was conducted with the following objectives:

1. Evaluate the effect of compensatory, bracing forces on task hand force-exertion capability.

2. Develop quantitative criteria for classifying force-generation strategies. Develop a method for representing and classifying bracing forces as contributory or non-effective with respect to task hand force exertion.

3. Develop and empirically validate statistical models to predict force-generation strategies based on task conditions and bracing availability.

4. Determine the quantitative effects of anthropometric and task configuration variables on force-exertion capability and associated postural behaviors.

5. Identify and analyze biomechanical aspects of force-generation strategies and associated postural behaviors for the purpose of developing an integrated conceptual model of force exertions with bracing availability.

All of these objectives have been met through the work presented in the preceding chapters. This chapter summarizes the findings, highlights the principal contributions of the research, discusses applications of the findings, and addresses the limitations and opportunities for future research.

8.2. Summary of Findings

The general objective of this dissertation is to understand the effects of a kinematic obstruction on strength and posture behaviors in perform one-handed exertions, both when the obstructions can be used for bracing and when bracing is not permitted. A qualitative model of the force generation strategy and posture behavior prediction, shown in Figure 4.3.1, was developed to guide this work. The environmental obstruction (bracing fixture) limits posture, but also provides the opportunity to exert bracing forces that may augment task hand force capability.

The research in this dissertation provides an empirical parameterization of the model depicted in Figure 4.3.1. The effects of changes in several task configuration and kinematic constraint variables were quantified through statistical analysis of laboratory data. These observations formed the foundation for statistical models of bracing forces and associated postures.

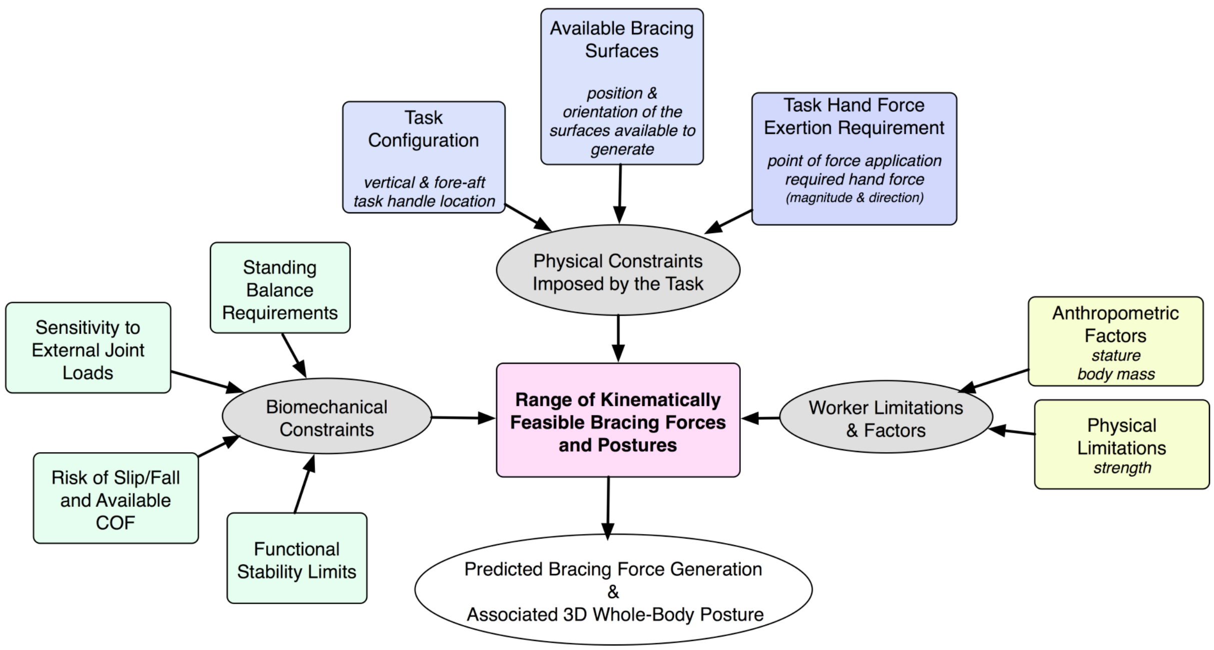

Figure 8.2.1 Schematic of proposed force generation strategy and posture behavior prediction process.

The experimental manipulation of the task configuration variables led to several important conclusions. Vertical task handle position, fore-aft horizontal task handle location, levels of bracing availability, nominal task hand force and direction have important independent and interacting effects on bracing forces and associated postural behavior. These effects were examined for three discrete task force directions in the sagittal plane (backward, forward, and upward).

The principal findings are:

- Bracing with the contralateral hand and/or thighs significantly increased one-hand force exertion capability, by 40% on average (Chapter 3).

- Both the magnitude and direction of task hand forces changed with levels of bracing availability (Chapters 3 & 6).

- Five distinct patterns of bracing force generation, termed *force-generation strategies*, were identified. A force-generation strategy (FGS) classification identifies the bracing forces (hand and/or thigh) and whether the thigh force is aligned or opposed with respect to the task hand force vector (Chapter 4).

- Relative contribution of the opposing and non-opposing components of bracing forces are varied significantly across FGS during nominal *backward* and *upward* exertions (Chapter 4).

- Bracing forces, exerted at the contralateral hand or thigh, did not change significantly with FGS during nominal *forward* exertions (Chapters 4 & 6).

- Brace hand force direction is largely unaffected by the handle location and task force level (Chapter 6).

- Task configuration variables, and most importantly the levels of bracing availability and task hand force magnitude, have significant independent and interacting effects on FGS selection (Chapter 5).

- Task hand force was a significant predictor of contralateral hand bracing forces across all of the nominal task hand force directions (Chapter 6).

- Task hand force was observed to predict body-bracing forces at the thigh during nominal *backward* and *upward* exertions (Chapter 6).

- Changes in posture in response to task configuration variables and increasing task hand force were consistent with behaviors implied by the five force-generation strategies (Chapter 7).

- The effects of these task configuration variables are mostly independent of body size (stature), proportion and strength subject characteristics (Chapters 5; 6; & 7), after normalizing the task geometry for subject stature.

Table 8.2.1 shows the relationships of the bracing forces at the hand and thigh with the task hand force magnitude and the FGS.

Table 8.2.1 Bracing force relationships with task hand force exertion capability and force-generation strategies*

Bracing Force	Relationship with Task Hand Force Exertion Capability	FGS Association Backward Exertions	Forward Exertions	Upward Exertions
Contralateral Hand Brace	Increase in task hand force was associated with increase in task bracing force (both opposing & non-opposing force components).	The relative contribution to task hand force exertion (opposing component) of hand bracing was 50% higher for HB vs. HTB-o FGS.	Only the non-opposing component contributes the increase in brace hand force with increase in task hand force [HB & HTB-a FGS].	The relative contribution to task hand force exertion (opposing component) of hand bracing was 72% higher for HB vs. HTB-o FGS.
Thigh Bracing	Increase in task hand force was associated with increased bracing force at the thigh, but only for nominal backward & upward exertions.	Opposing component was strongly influenced by the extended reach to the furthest fore-aft task handle location for backward exertions performed [TB & HTB-o FGS].	Task hand force is not a significant predictor of thigh force for forward exertions. Opposing thigh forces were also not affected by task configuration variables.	Opposing component was strongly influenced by the extended reach to the furthest fore-aft task handle location for backward exertions performed [TB & HTB-o FGS].

*HB denotes Hand only FGS; TB denotes Thigh only FGS; HTB-o denotes Hand & Thigh-opposed FGS; HTB-a denotes Hand & Thigh-aligned FGS.

Table 8.2.2 demonstrates the coherence of the observations regarding bracing force, force generation strategy, and posture. The table demonstrates that the behavior-based approach to Force-Generation Strategy (FGS) classification is a useful concept that encapsulates observations regarding bracing force and posture. Within each FGS, the force observations are consistent with the posture observations and vice-versa.

Table 8.2.2 Relationships between posture behaviors, task hand force exertion capability, and force-generation strategy*

Postural Behavior	(Hypothesized) Relationship with Task Hand Force-Exertion Capability	FGS Association	
		Backward Exertions	*Forward Exertions*
Fore-aft hip location (Hip_X)	Increase in horizontal displacement, characterized as a lack of engagement with the kinematic constraint, was observed to increase task hand force exertion capability.	NB HB	HTB-a
	Engagement of lower extremities at the kinematic constraint was found to increase the deviation of the task hand force direction with respect to the requested horizontal nominal.	NB HB TB HTB-o	HB
Height of the pelvis (Hip_Z)	A decrease in hip height was observed with increasing task hand force for medium and low task handle locations.	NB HB	NB HB TB
	Task hand force directions more closely associated with the requested horizontal nominal were observed with lowering hip height.	NB TB	NB HB HTB-a
Torso inclination from vertical	An increase in torso inclination with respect to neutral standing posture was found to increase task hand force exertion capability.	NB	NB HB
	Forward torso inclination was associated with a decrease in directional deviation of the task hand force vector.	NB HB TB	HB HTB-a
Vertical position of the task shoulder (Task Sh_Z)	Lowering task shoulder height with respect to the point of force application is hypothesized to increase exertion capability, although not explicitly quantified.	NB HB	NB HB TB HTB-a
	Decrease in task shoulder height resulted in task hand force vectors more closely associated with the nominal direction to maintain task shoulder moment (% criterion threshold).	NB HB TB HTB-o	NB HB HTB-a
Vertical position of the brace shoulder (Brace Sh_Z)	Lowering contralateral shoulder height with respect to the point of force application is hypothesized to increase exertion capability, although not explicitly quantified.	HB	HB HTB-a
	Decrease in task shoulder height resulted in task hand and brace hand force vectors closely associated with the nominal direction.	n/a	HB HTB-a

*HB denotes Hand only FGS; TB denotes Thigh only FGS; HTB-o denotes Hand & Thigh-opposed FGS; HTB-a denotes Hand & Thigh-aligned FGS.

Figure 8.2.2 provides a visualization of representative postural behaviors associated with the five distinct force-generation strategies, including NB, HB, TB, HTB-o, and HTB-a, adopted during maximal backward and forward exertions performed at the medium-close task configuration. Opposing contralateral hand force defines the vertical axis and opposing thigh force defines the horizontal axis. Solid lines denote opposing force contribution; while hatched lines denote no force contribution. The figure demonstrates the observed relationships between posture behaviors, task hand force exertion capability, and force-generation strategy.

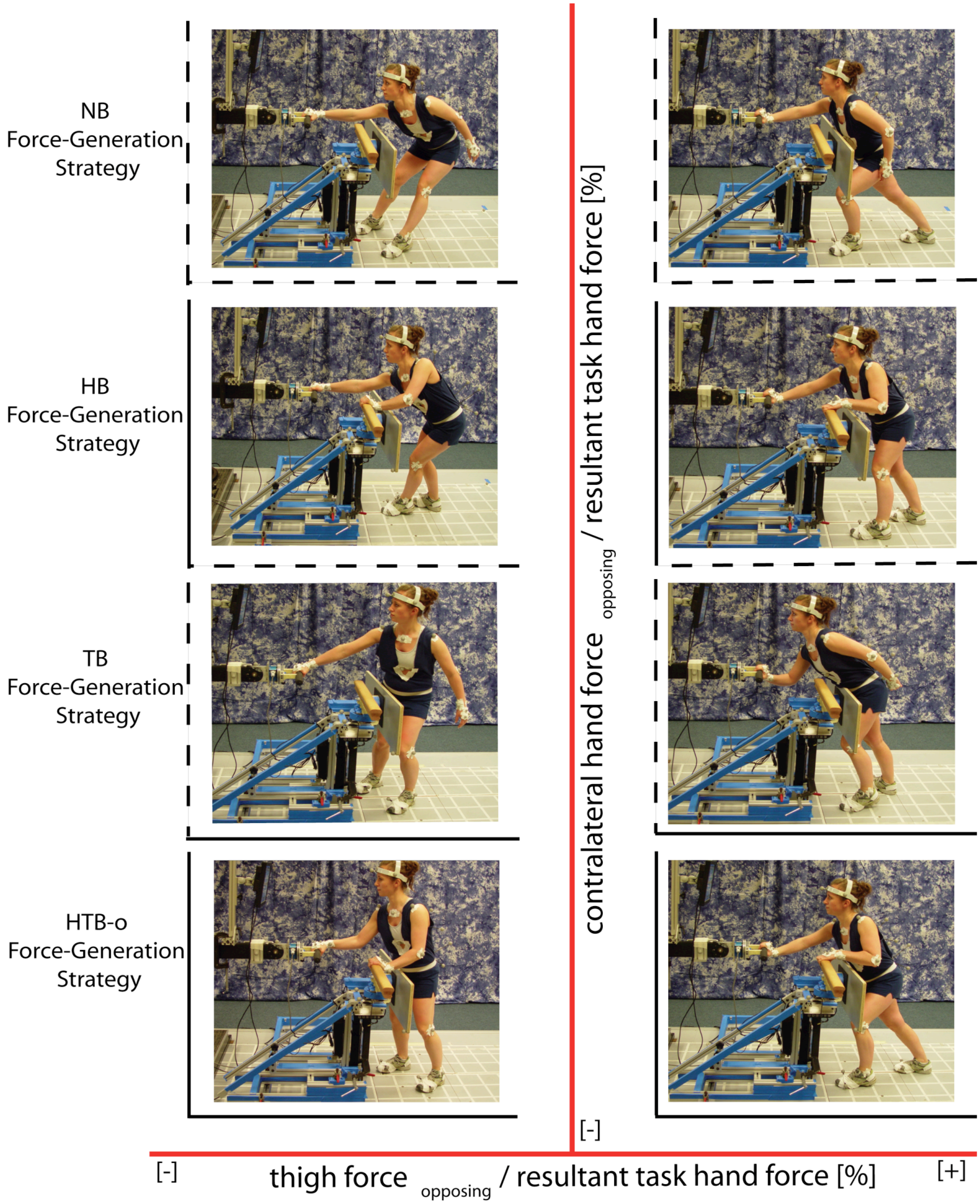

Figure 8.2.2 Representative postural behaviors associated with the five distinct force-generation strategies, including NB, HB, TB, HTB-o, and HTB-a, adopted during maximal backward and forward exertions performed at the medium-close task configuration. Opposing contralateral hand force defines the y-axis and opposing thigh force defines the x-axis. Solid lines denote opposing force contribution; while hatched lines denote no force contribution.

No-Bracing (NB) Force-Generation Strategy

The NB FGS is defined as task hand force exertion performed without any bracing forces from hand or thigh.

This FGS was characterized by a lack of engagement with the fixture, and subjects tended to move their hips rearward, which enables a moment to be generated about the base of support that can be used to increase task hand force capability. This postural behavior was coupled with a decrease in hip height and increase in torso inclination, which would tend to increase force exertion capability for forward and backward exertions by reducing shoulder moment. Change in task shoulder location with respect to point of force application resulted in directional changes to the task hand force vector (Figure 8.2.3; Figure 8.2.4). Task hand force vectors were found to deviate fairly consistently from the nominal horizontal direction. These findings are consistent with the biomechanical hypothesis that people tend to choose hand force directions and shoulder locations that maintain shoulder moments at relatively low levels. Such a strategy is consistent with those observed during unconstrained pulling tasks (Haselgrave et al. 1997, 2007; Hoffman et al, 2008).

Similar to backward exertions performed without bracing availability, decrease in hip height and increase in torso inclination was associated with increase in task hand force exertion capability for forward exertions. Changes in torso orientation and the vertical location of the task shoulder were both consistent with reducing the vertical offset between the task shoulder and the exertion handle to reduce task shoulder moment (Figure 8.2.2; Figure 8.2.4).

Hand-Bracing (HB) Force-Generation Strategy

The HB force-generation strategy (FGS) is defined as bracing force at the hand but not the thigh.

Bracing hand force provides an opportunity to generate opposing forces relative to the task hand force by creating a closed chain across the upper body. Alternatively, bracing hand forces could be used to support the body in advantageous postures without contributing forces directly opposing the task hand force. However, the results strongly supported the hypothesis that bracing hand forces are primarily used to generate forces opposing the task hand force, rather than to support the body.

Contralateral hand brace forces were observed to be associated with increase in task hand force-exertion capability across the nominal task hand force directions. The addition of hand bracing enabled subjects to adjust the hip position in an effort to increase task hand force exertion capability. Changes to hip height permitted subjects to align the task shoulder with exertion handle to reduce task shoulder moment while improving alignment between task hand force and nominal direction (Figure 8.2.2). Change in torso inclination was adopted to accommodate the kinematic constraint of the task configuration. These postural behaviors were observed for both nominal backward and forward tasks. Increasing the horizontal displacement of the pelvis with respect to the bracing structure (Figure 8.2.2) was also found to increase task exertion capability and reduce directional task force deviation for backward exertions.

Coupled with forward torso inclination and changes in hip position with respect to the kinematic constraint, task shoulder location was altered to reduce task shoulder moment and improve task hand force alignment with respect to nominal. The contralateral brace shoulder was also lowered to reduce contralateral shoulder moment while improving alignment of bracing force with task hand force with an increase in force level. This postural behavior was substantiated by a significant increase in the contralateral hand bracing forces for both backward and forward exertion performed with the HB strategy compared to HTB-o and HTB-a trials respectively (Figure 8.2.3; Figure 8.2.4). The task configuration that imposed the least degree of kinematic constraint (medium-close) was associated with task hand vectors closer to nominal. It is also noteworthy that the opposing component of hand bracing was significantly greater (~50%) for backward trials that adopted the HB FGS as compared to HTB-o FGS. Bracing hand forces adopted during forward exertions were found to have a greater contribution from the non-opposing component (Figure 8.2.4).

TB Force-Generation Strategy

The TB force-generation strategy is defined as bracing force at the hand but not the thigh.

In backward trials, the engagement of the pelvis or thighs with the kinematic constraint generated a reaction force that opposed the task hand force. The engagement of the thigh at the bracing structure resulted in a more upright, erect whole-body postures.

Therefore, none of the remaining postural degrees of freedom were observed to increase task hand force exertion capability for backward exertions performed by the TB strategy. When subjects adopted the TB FGS, efforts to align the task shoulder with the exertion handle to reduce task shoulder moment were predominately derived from directional changes of the task hand force vector (Figure 8.2.3; Figure 8.2.4). In other words, the TB FGS required a more upright posture that precluded lowering the shoulder to reduce shoulder moment. Instead, subjects increased the vertical component of the task hand vector, effectively pulling upward more than was the case for subjects who adopted the HB strategy (with no thigh bracing). This observation further supports the proposition that subjects alter the hand force vectors orientation to maintain shoulder moments in an acceptable range. Subtle changes in the horizontal displacement of the pelvis were indicative of pelvis rotation that corresponds to turning away from the handle or opening up the base-of-support orientation. This postural behavior was associated with task hand force vectors more that were closely oriented to the nominal direction.

Thigh bracing contact with the structure during forward exertions generated forces that were in alignment with the task hand force vector and hence did not contribute to opposing the task hand force. Altering the pelvis height and task shoulder were therefore only two degrees of freedom that affected task hand force exertion capability for the TB force-generation strategy. These findings are consistent with other research on unconstrained pushing tasks (Grieve and Pheasant, 1981, Pheasant et al, 1982, Hoffman et al, 2008). The aggregate effect of reducing hip height and vertical task shoulder height postural behaviors were adopted in an effort to align task shoulder with exertion handle to reduce task shoulder moment. The thigh bracing force in forward tasks is consistent with bracing used for postural support rather than for generating opposing force.

HTB-opposed & aligned Force-Generation Strategies

The HTB-opposed (HTB-o) force-generation strategy is defined as bracing forces at both the hand and thigh. The thigh bracing force acts primarily in opposition to the hand force vector (for example, pulling with the task hand while exerting a forward-directed force on the thigh bracing surface).

The HTB-aligned (HTB-a) force-generation strategy is defined as bracing force at both the hand and thigh. Thigh bracing force acts primarily in the same direction as the task hand force (for example, pushing with the task hand while leaning against the thigh board, exerting a forward force).

Posture is substantially restricted for backward exertions that employed contralateral hand bracing and thigh bracing at the kinematic constraint. As was the case with the TB strategy, no significant relationships were observed between the postural behaviors and task hand force exertion capability. Therefore, efforts to align the task hand force vector with the shoulder are primarily resulted in directional changes of the task hand force vector rather than changes in shoulder position (Figure 8.2.3).

Both backward and forward tasks performed with HTB-o and HTB-a force-generation strategies respectively were observed to increase the horizontal location of the hip with respect to the kinematic constraint and adopt an open orientation of the base-of-support. These small changes to the horizontal hip displacement and task shoulder location provided the only degrees of freedom to reduce task shoulder moment and improve alignment between task hand force and nominal force direction. It is also interesting to note that task or brace hand forces or directions did not affect the contralateral brace shoulder location for this FGS.

Figure 8.2.3 and Figure 8.2.4 provide a graphical depiction of the aforementioned relationships between upper extremity postural behaviors, task hand force exertion capability, and force-generation strategy. These upper extremity force vector 2D visualizations illustrate a sagittal view of the task hand and contralateral hand force vectors in the 2D XZ plane (global fore-aft and vertical plane). Force vectors are positioned with respect to the task and contralateral shoulder (x, z) locations. The purpose of these plots is to visually evaluated the biomechanical hypothesis which suggests that postural behaviors modifications are associated with an effort: 1) to improve alignment between task hand force vector and nominal force direction; 2) improve alignment of bracing force with task hand force. Individual trial data presented for backward exertions adopting each of the force-generation strategies at the medium-close task handle location, stratified by sub-maximal (50%) and maximal task hand force exertions. Task and brace hand force are denoted as black vectors (magnitude and direction); blue asterisks denote location of task and contralateral shoulders. Red vectors visualize the alignment between the task and brace force applications and task and contralateral shoulder locations.

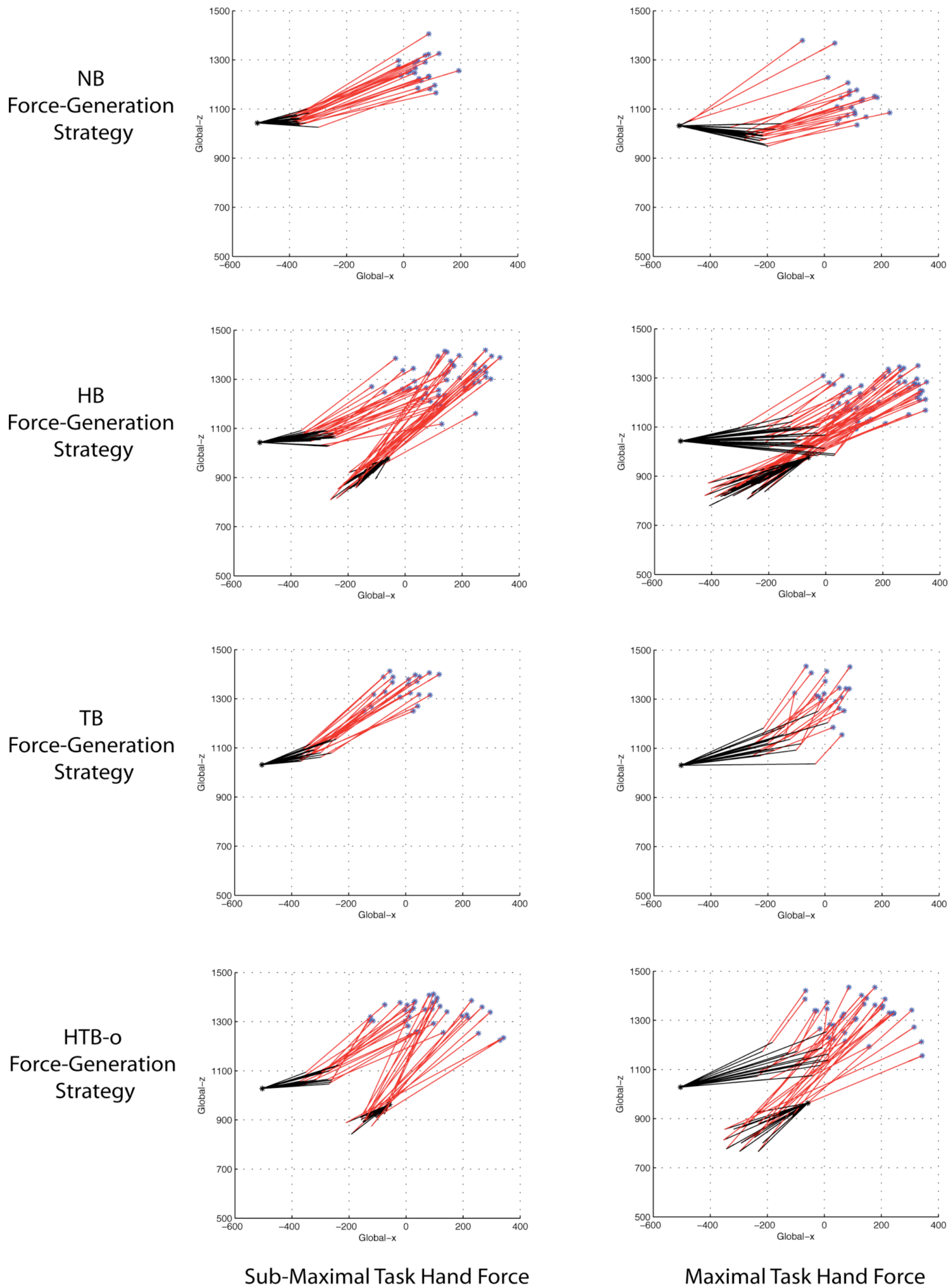

Figure 8.2.3 Upper extremity force vector 2D visualization (XZ sagittal plane) examining the biomechanical hypothesis which suggests that postural behaviors modifications are associated with an effort: 1) to improve alignment between task hand force vector and nominal force direction; 2) improve alignment of bracing force with task hand force. Individual trial data presented for *backward* exertions adopting each of the force-generation strategies at the medium-close task handle location, stratified by sub-maxima (50%) and maximal task hand force exertions. Task and brace hand force are denoted as black vectors (magnitude and direction); blue asterisks denote location of task and contralateral shoulders. Red vectors visualize the alignment between the task and brace force applications and task and contralateral shoulder locations.

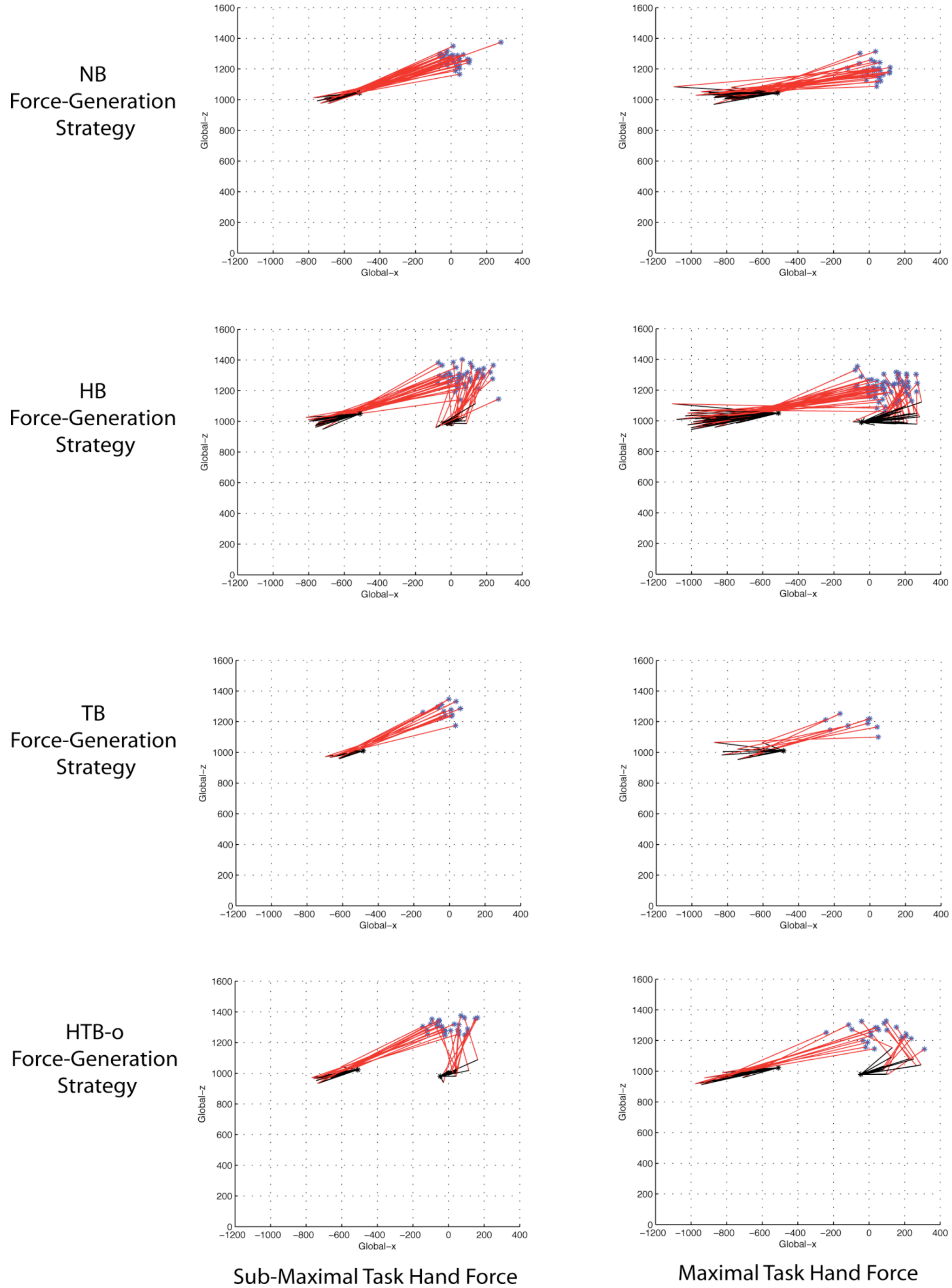

Figure 8.2.4 Upper extremity force vector 2D visualization (XZ sagital plane) examining the biomechanical hypothesis which suggests that postural behaviors modifications are associated with an effort: 1) to improve alignment between task hand force vector and nominal force direction; 2) improve alignment of bracing force with task hand force. Individual trial data presented for *forward* exertions adopting each of the force-generation strategies at the medium-close task handle location, stratified by sub-maxima (50%) and maximal task hand force exertions. Task and brace hand force are denoted as black vectors (magnitude and direction); blue asterisks denote location of task and contralateral shoulders. Red vectors visualize the alignment between the task and brace force applications and task and contralateral shoulder locations.

Statistical Prediction of Bracing Force and Posture

Force-generation strategy classification identifies the bracing forces (contralateral hand and/or thigh) and whether the thigh force is aligned or opposed. One advantage of identifying and predicting discrete FGS within this task regime is that the prediction of posture and force exertion behavior within FGS may be easier, more accurate, and more precise than would be the case without this segmentation. Park et al. (2005) argue that an effort should be made to qualitatively identify and study alternative movement techniques with the objective of incorporating this source of natural variability into force-exertion and posture prediction models to enhance performance. Indeed, cluster analysis based upon behavioral strategies has been previously applied to the classification of human movements and postures. Examples include alternative lifting techniques (Park and Singh, 2004), a bimodal distribution of elbow angles adopted during unconstrained force exertions (Hoffman, 2008) and foot placements in manual material handling tasks (Wagner et al., 2010).

Application: Guidelines for Ergonomic Practitioners

An extension of this dissertation work is to provide a series of guidelines for practitioners to account for bracing forces within existing biomechanical models (i.e. 3DSSPP). The knowledge that bracing increases force-exertion capability, depending on nominal task hand force direction, task handle location and bracing availability, has significant implications for current ergonomic analysis. Constraints imposed by task configuration; particularly where access restricts reach distance to the task hand and the surfaces available for bracing, affect the force-exertion capability. Within the context of the multinomial FGS classification and the experimental conditions in this study, guidelines for practitioners to account for the effects of brace hand and body-bracing forces on task-exertion capability are as follows:

- People use five distinct force-generation strategies across nominal task hand direction, task handle location and bracing availability.
- Transformation and normalization of bracing forces relative to the task hand force vector provides an effective method to parameterize the effect of bracing forces on task-exertion capability and express as a percentage of task hand force.

- Task configuration conditions were the most effective parameters at eliciting distinct force-generation patterns. Classifiers associated with FGS selection or exclusion include:
  - level of bracing availability,
  - increase in task hand force, and
  - fore-aft task handle location.

  Knowledge of the most influential classifiers associated with FGS selection or exclusion across the nominal task hand force directions and task handle locations can provide guidance to practitioners with respect to critical aspects of product or task design and assembly requirements (i.e. task hand force exertion requirement), and providing necessary environmental affordances in the workstation (i.e. bracing availability). Practitioners will be required to consult the quantitative models to determine the effects of individual classifiers.
- Task configuration requirements, specifically vertical and horizontal task handle location, alter the direction of the task hand force vector. These results should encourage caution by ergonomists in interpreting nominal task hand forces as those that a person would actually exert. Consistent with previous research, task hand forces were nearly always appreciably different from the nominal direction, and these deviations could be predicted reliably from task variables.
- Bracing forces, exerted at the contralateral hand and thigh, increase with increased task hand force levels across all FGS, force directions, and magnitudes. These results show that for short-duration, relatively high – magnitude force exertions, bracing is not used primarily to support body weight, but rather to generate force to oppose the task hand force.
- Changes in key postural degrees-of-freedom in response to task configuration variables and increasing task hand force-exertion capability were found to be consistent with the multinomial FGS classification of five discrete force-generation strategies across the nominal backward and forward tasks. Guidelines to posture linkage or DHM manikin:

- Fore-aft location of the pelvis differentiated FGSs that did or did not involve body-bracing. Position the hip to engage the lower extremities with kinematic constraint for FGS strategies that employ thigh-bracing, and increase the horizontal displacement between the fore-aft position of the hip and the environmental obstruction for FGSs that do not employ thigh-bracing.
- Incrementally increase the degree of torso inclination to accommodate the horizontal reach to task handle location or as degree of kinematic constraint task. Changes in torso inclination are adopted during FGSs that do not employ body-bracing.
- Align task shoulder and point of force application by:
    - Positioning the task shoulder location height to align with the vertical task handle location.
    - Alternatively, modifying the task hand force vector with respect to nominal direction to improve the alignment.
- Position the contralateral shoulder to align the brace and task hand force vectors.

This dissertation work contributes substantially to the understanding of bracing and the ability to accurately account for bracing forces and associated postural behaviors in any ergonomic assessment of a kinematically constrained isometric force exertion with bracing availability. It also rejects the assumptions on which current modeling of bracing, supported tasks are based (3DSSPP; Chiang et al. 2006). Bracing forces have been found to interrelate with both task hand force exertion capability, task hand force direction relative to nominal, and postural modifications, which are largely unaccounted for in previous approaches. The results are not consistent with the assumption that people generate bracing forces and/or task forces to maximize available joint torque, whether passive or active, or available strength capability.

Integrated Conceptual Model of Bracing Force Generation and Posture

This dissertation provides knowledge that will be valuable in the development of biomechanical model of bracing force generation and the associated postures. A model that explains the force-generation strategy selection process, patterns of bracing force generation, and the subsequent posture behaviors will allow for biomechanical analysis, simulation and prediction of human capability. Figure 4.3.1 shows an overview of factors influencing bracing during kinematically constrained one-hand isometric force exertions. Generally influential factors include the physical constraint imposed by the task, worker characteristics, and key biomechanical constraints, which collectively determine the range of kinematically feasible bracing forces and postures.

As stated by Haselgrave (1992) "as a simple biomechanical analysis will show, the posture adopted when exerting a force is important for two reasons: it affects both the strength which a person is able to exert and the resultant loading on his/her body, since it determines the geometry and mechanical advantage of the muscles involved in the exertion, and equally importantly affects the stability while performing the task". Data from this work substantiate a biomechanics-based approach to posture-prediction for unconstrained isometric exertions presented by Haselgrave (1992) and Hoffman (2008). Results from this quantitative parameterization of bracing and associated postures suggest that the choice of force-generation strategy and posture behaviors are indeed governed by two key biomechanical criteria. Posture selection and force-exertion directions appeared to be substantially influenced by shoulder moments, but subjects did not appear necessarily to minimize shoulder moment, but rather to choose a posture that gave an acceptable shoulder moment while otherwise remaining close to a neutral standing posture. These observations are consistent with those of Hoffman (2008) who developed a biomechanical posture-prediction model centered on similar observations from unconstrained standing exertions.

Overall, force-generation strategies and associated postures measured in this study were found to be consistent with the following biomechanical hypotheses:

- Force-generation strategies were performed in a manner to reduce moment about the task shoulder by:
  - Altering the direction of the task hand force vector towards the task shoulder moment, and/or
  - Modifying the task shoulder location to decrease the task shoulder moment arm and align the task hand force and nominal direction.

- Force-generation strategies were performed in a manner to reduce moment about the contralateral brace shoulder by:

    - Altering the direction of the contralateral hand force vector towards the contralateral shoulder moment, and/or

    - Modifying the contralateral shoulder location to decrease the moment arm and improve the alignment between the brace and task hand force vectors.

- In forward exertions with the HTB-a FGS, thigh bracing force provided support for the body but did not oppose the task hand force. In all other situations, bracing forces provided primarily opposing forces rather than posture-support forces.

- Horizontal hip displacement away from the kinematic constraint is associated with shifting the center of mass rearward relative to the front edge of the base of support to generate body weight moment, and precludes thigh bracing.
- Lateral pelvis positioning was consistent with reducing the net rotational moment about the inferior-superior axis of the lower-back produced by the hand forces.

- Torso inclination was adopted to accommodate the kinematic constraint of the task configuration.

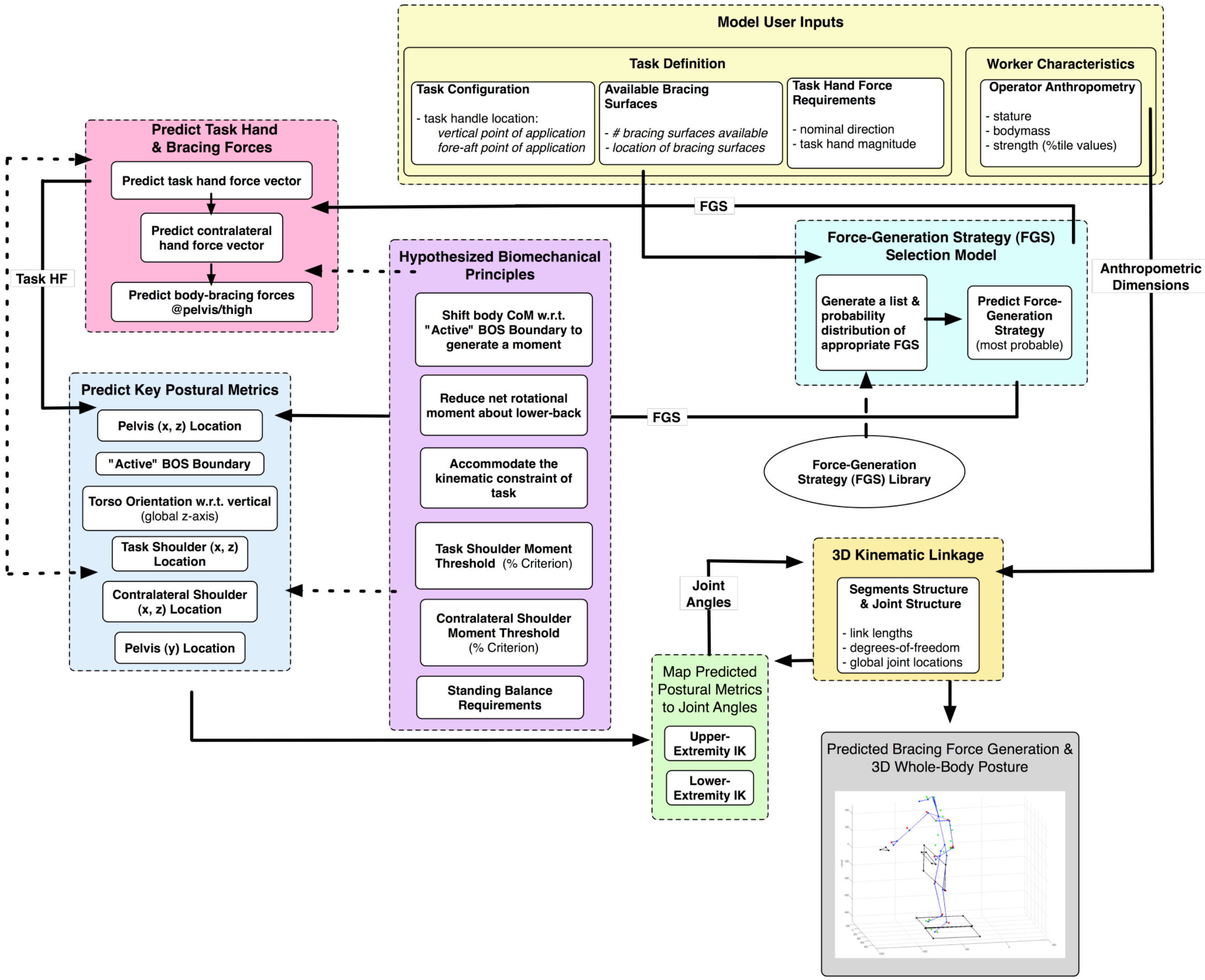

Figure 8.2.5 Integrated Conceptual Model for the Prediction of Bracing Force Generation and Posture

8.3. Limitations

The laboratory study was conducted to elicit a range of force exertions and postural behaviors under kinematically constrained task conditions. However, the generality and applicability of the findings to the industrial domain are limited in some important ways.

Subject pool

The subject pool consisted of a young, student based population (average age ~21), thin (average BMI ~ 24 kg/m^2) and relatively fit individuals, with no industrial experience. An attempt was also made to stratify the subject pool by anthropometric and strength capability. The subjects were selected to be young and fit so that they could readily endure the long-duration experimental conditions. The low BMI values also enabled more accurate tracking of the skeleton. For example, only one subject from the subject pool had a BMI over the normative population average, which ranges from 26.9 to 30.0 kg/m^2 (CDC, 2011). However, when the subject strength values were compared to population strength values in the literature (Chaffin et al., 2006), most of the subjects were found to be relatively weak compared to the population. The homogeneity and demographics of the subjects are not representative of industrial workers.

Force-generation strategies and postural behaviors adopted by the current student subject pool may not be consistent with those of experienced industrial workers. However, subjects performed a series of practice trials prior to performing the assigned exertions. During the practice trials subjects were encouraged to explore the bracing options and different postural strategies. A minimum of one practice trial was conducted for each test condition and was repeated until the subject indicated that they were comfortable with their posture. Practice trials served as an opportunity for subjects to identify their preferred postures and to gain familiarity with the force feedback display. Furthermore, behaviors observed in the laboratory were similar across individuals and qualitatively consistent with those observed in the field survey at an automotive assembly plant. More research will be necessary to determine if older or more experienced industrial workers will produce substantially different postures, or exert different bracing forces.

Twenty-two subjects (10 females and 12 males) participated in the study. Certainly, a sample size of N = 22 provided sufficient statistical power for this exploratory laboratory studies, and it is not clear that the results would be meaningfully different if a larger sample were used. A larger sample would be useful only if it contained subjects who behaved qualitatively differently, for example used different force-generation strategies and employed them with different frequency. With respect to the number of statistic hypotheses test being considered from the current study, it is plausible that some effects were evaluated as "significant" by chance (Type-I error). However, a conservative criterion ($p<0.001$) was selected to reduce the likelihood of chance findings. Also, with the relatively large number of trials, an erroneously "significant" finding will have a small (negligible) effect size and hence have a minimal effect on the conclusions and predictions.

Given the duration and nature of the laboratory study, subjects may have become physiologically or cognitively (attention) fatigued over the course of the study, which could have affected observed behaviors. To minimize the effects of fatigue, rest breaks were also provided to subjects between trials. Strength measurements taken pre- and post- test did not reveal any significant decrease in strength indicative of fatigue, nor did the subjects report feelings of fatigue at anytime during the test sessions.

Nominal task requirements

Isometric exertions performed in this study are characterized as short-duration exertions that were held for 3 seconds. In the field, workers often perform exertions dynamically to take advantage of inertial effects. Dynamic behaviors could accentuate or reduce the directional orientation of the task hand force vectors observed in the study. The task hand force requirements area also considered high-force exertions, performed at 50% and 100% maximal volitional capability for given task configuration. Such high forces are not common in auto assembly work, but may be more frequent in other occupations, such as construction. Observations from the field survey of automotive assembly tasks suggest that experienced workers modify their posture in response to changes in task hand force requirements. The effect of dynamic and lower task hand force exertions on force-generation strategies and associated postural behavior is an additional factor to consider in future studies. An additional factor not studied is the effect of changing task accuracy requirements on bracing. Hoffman (2008) determined that the accuracy of task force component (i.e. constrained task hand forces) affected task-exertion performance during kinematically unconstrained tasks. The effects task accuracy during tasks with environmental and spatial restrictions should be explored in future studies.

Kinematic constraint & task configuration

Task handle locations and bracing surface configurations were normalized to stature in an effort to ensure all subjects experience a similar range of kinematic constraint and subsequent postural requirements. Literature values were used to define the task handle heights as a percentage of stature. In an effort to normalize the close and far horizontal positions of the fore-aft task handle location, each subject's $65^{th}\%$ and 100% functional reach were measured using a specified protocol. The measurements were standardized by the measuring the angle of torso inclination with respect to vertical and normalized to express as a percentage of stature. Due to differences in body-size proportions across individuals the percentages used to define the task configuration variables may not have been equivalent to intended anthropometric dimension for all subjects.

Design of the bracing structure, specifically the handrail designated for contralateral hand bracing and the vertical planar surface denoted as the thigh-bracing surface, is a critical component in the bracing force-reactive surface couple. Pilot data collection, subsequent prototype designs, and results from the field survey of the automotive assembly tasks, were informative as to the effect that geometry and materials properties of the contact surfaces on bracing forces. The bracing interface of the obstruction was designed to be transferable across different domains of application by using generic, simple shapes. Therefore, some additional factors regarding the design of the kinematic constraint and bracing force-obstruction couple might be considered in future studies. For example, additional bracing surface geometric contours and material properties, positions and orientations relative to the subject, might be examined in relation to brace force generation and alignment with respect to task hand force. An additional limitation not studied in this research was the effect of the interaction of bracing surface co-efficient of the friction (CoF) and stiffness with anatomic location used to brace (i.e. knee cap vs. lateral mid-thigh).

One inherent drawback to laboratory experiments is that it places the subject in an unnatural environment. The ability to reliably and accurately capture motion in the workplace would be valuable, but it is currently difficult to accomplish reliably. The laboratory poses some unavoidable noise artifacts (i.e. motion capture markers are affixed to subject skin) that may result in errors in postures or motions. Force plates were recessed in the floor was used to capture ground reaction forces. Subjects' attention was not directed towards the force plates, however over the experiment some subjects became aware of their purpose and may have altered their foot placements as a result. The fact that the subjects were aware that their force-exertion and postures were to be measured should also not be overlooked.

8.4. Principal Contributions

The research in this dissertation, summarized in the preceding paragraphs, resulted in a number of substantial contributions to the knowledge of force exertions. The contributions are discussed in the context of the research objectives.

1. **Evaluate the effect of compensatory, bracing forces on task hand force-exertion capability.**

Bracing with the contralateral hand and/or thighs significantly increased one-hand force exertion capability. Analyses of one-hand maximal push forward, pull backward, and lift upward tasks demonstrated that bracing surfaces available at the thighs and contralateral hand enable participants to exert increase task hand force exertion capability by 40%, on average. Substantial off-axis forces were also observed, consistent with previous studies on unconstrained task exertions (de Looze et al., 2000; Hoffman et al., 2010). Importantly, both the magnitude and direction of task hand forces changed with varying levels of bracing availability.

2. **Develop quantitative criteria for classifying force-generation strategies. Develop a method for representing and classifying bracing forces as contributory or non-effective with respect to task hand force exertion.**

The method presented in Chapter Four categorized bracing forces with respect to their contribution to task hand force generation. Expressing bracing forces in the task-based coordinate reference frame and normalizing relative to task hand force magnitude further clarified the relative contribution of each bracing force.

Subjects braced with their hands and thighs in five distinct force-generation strategies that each increased force-exertion capability. A force-generation strategy classification identifies the bracing forces (hand and/or thigh) and whether the thigh force is aligned or opposed. A set of simple quantitative criteria was developed to classify the force-generation strategy observed in each trial.

This technique also enabled decomposition of the bracing force vectors into opposing and non-opposing components relative to the task hand force vector. Imposing this dichotomous relationship onto bracing force components distinguishes the bracing forces that create closed-chain opposition to the task hand force with those components that serve ancillary purposes, such as providing postural support or reducing shoulder moment. The deviations of bracing forces from the ideal (most effective) orientation (that is, directly opposed to the task hand force) provide considerable insight into the subjects' strategies for posture selection and bracing force generation.

3. **Develop and empirically validate statistical models to predict force-generation strategies based on task conditions and bracing availability.**

The models presented in this work provide, for the first time, a quantitative method to predict the FGS that a person will choose to perform a range of one-hand, isometric force exertions. Multiple logistic regression models define the association between task configuration and subject characteristic variables, and predict the likelihood of adopting each of the FGS for task hand force exertions performed in the sagittal plane.

4. **Determine the quantitative effects of anthropometric and task configuration variables on force-exertion capability and associated postural behaviors.**

This study demonstrated the effects of levels of bracing available, vertical task handle position, fore-aft task handle location, nominal task hand force and direction on bracing force patterns and associated postural behavior. Based on the analysis and distribution of force-generation strategies across a set task constraints, regression models are derived to predict bracing forces and postures. These results will provide quantitative input to the development of biomechanical models to analyze and simulate these tasks.

5. **Identify and analyze biomechanical aspects of force-generation strategies and associated postural behaviors for the purpose of developing an integrated conceptual model of force exertions with bracing availability.**

Quantitative parameterizations of bracing and associated postures measured in this study were found to be consistent with hypothesized principles. Force directions and postures were consistent with the proposition that people act to maintain moments at their shoulders below acceptable limits while also maintaining their torsos as close as possible to a neutral standing posture.

Recommendations for future research

The following are brief research questions that would complement the body of knowledge established by the research presented in this dissertation. While these may address some of the specific limitations discussed previously or create information to develop the proposed integrated conceptual biomechanical models, my intention is to suggest new research avenues inspired by this work.

1. Explicitly evaluation of the proposed biomechanical principles and shoulder moment threshold criterion.

2. Computational modeling efforts to develop a biomechanics-based model to predict the posture and force-generation behaviors documented in this study.

3. Consider variable task hand force requirements in an effort to define “bracing” further:
   i. Evaluate the effect of dynamic tasks and subsequent inertial effects on bracing.
   ii. Evaluate the effect of lower task hand force magnitudes on bracing.
   iii. Evaluate the effect of changing task accuracy requirements on bracing.

4. Within the context of the multinomial FGS classification, investigate the effect of a more diverse subject pool:
   i. Evaluate a less fit subject population with a BMI that is more closely representative of the normative population.
   ii. Study the industrial workers with experience in completing manufacturing tasks that may elicit different force-generation strategies.

5. Investigate a wider range of task configurations to examine the multinomial force-generation strategy (FGS) classification.
   i. Consider workplace constraints, the effects of workstation layout and alternative spatial/postural restrictions.

6. Investigate the effects of task and contralateral hand support orientation, object type and hand-object coupling and grasp on posture.
   i. Evaluate the “mode” of handgrip / brace couple.
   ii. Evaluate the effect of the interaction of bracing surface CoF and stiffness with the anatomic location used to brace (i.e. knee cap vs. lateral mid-thigh).

8.5. References

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