BRACING DURING KINEMATICALLY CONSTRAINED ONE-HAND ISOMETRIC FORCE EXERTIONS: PREDICTING FORCE AND POSTURE FOR ERGONOMIC ANALYSIS

by

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To Klara

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ABSTRACT

Workers performing industrial tasks routinely encounter obstructions in their environment that limit the postures that they can achieve. However, many obstacles also provide an opportunity for bracing with a hand or thigh. Observations of automotive workers have shown that hand or thigh bracing is common during assembly tasks, suggesting that bracing may increase worker capability or decrease stress. Biomechanical analyses of tasks with bracing are difficult to conduct because the addition of the unknown bracing forces produces a mechanically indeterminate system. To address this issue, force and posture data were gathered in a laboratory study of 22 men and women with a wide range of body size. Subjects exerted one-handed isometric backward, forward, and upward exertions at four task-handle positions in the presence of a kinematic constraint that afforded thigh and hand bracing opportunities. Bracing with the contralateral hand or thigh was hypothesized to improve force-exertion capability, and both postures and bracing forces in the presence of kinematic constraints were hypothesized to depend on task conditions and bracing availability. Bracing with the contralateral hand and/or thighs significantly increased one-hand force exertion capability by 40% on average. A method was developed to categorize bracing forces with respect to their contribution to task hand force generation. Decomposition of the bracing force vectors into opposing and non-opposing components enabled patterns of bracing forces to be classified into five distinct Force-Generation Strategies (FGS). Each FGS was associated with a particular posture pattern. Statistical models were developed to predict specific FGS and to predict posture variables and the magnitudes and directions of the task hand and bracing forces within each FGS and nominal task hand force direction. A conceptual model based on biomechanics principles was developed that accounts for the observed behaviors and forms a template for development of posture- and force-prediction models for use in industrial ergonomics. Guidelines for practitioners are presented to account for the effects of bracing forces on task-exertion capability.

CHAPTER 1

INTRODUCTION

1.1. Thesis Statement

Workers performing industrial tasks routinely encounter obstructions in their environment that limit the postures that they can achieve. These obstructions can also provide an opportunity for additional postural support by providing a bracing surface for a non-task hand, thigh, or other body part. Bracing may improve task performance capability, particularly when the posture is constrained. In spite of the common practice of such braced and obstructed push-pull tasks, there is little data or guidance in the literature on how to account for such contralateral hand and body-bracing forces and the associated postural behaviors during biomechanical analysis. It is proposed that force-generation strategies and associated postural behaviors can be better understood by examining the effects of task configuration and subject characteristics on distribution patterns of force generation at the task hand and available bracing surfaces. For one-hand force exertions, task hand force and bracing force and posture prediction models based on laboratory measurements can accurately predict feasible kinematically constrained force exertion postures, demonstrate the quantitative tradeoffs between force-generation strategies, and provide insight into a more integrated force-generation strategy and posture selection process.

1.2. Applied Problem and Motivation

Common manual tasks often involve bracing the body while performing one handed lifting, pushing or pulling exertions. Obstacles in the environment constrain postures while also providing an opportunity for additional support, such as bracing with a hand, thigh or other body part. Representative automotive assembly tasks that involve kinematically constrained, approximately isometric exertions with bracing availability are illustrated in Figure 1.2.1.

Figure 1.2.1 Representative automotive assembly tasks that involve kinematically constrained, approximately isometric exertions with bracing availability.

Realistic and valid biomechanical analyses and simulations of such tasks require accurate prediction of bracing forces and postural strategies. Biomechanical analyses of tasks with bracing are difficult to conduct because the addition of the bracing forces produces a mechanically indeterminate system. That is, even after accounting for the primary (task) hand force and body weight effects, the forces at the bracing hand and other externally braced contact points cannot be determined from the posture. Consequently low back, shoulder, and other important moments cannot be computed, as there is little data or guidance in the literature in this area upon which meaningful ergonomic guidelines can be based and on how to account for such contralateral hand and body-bracing forces. To obtain an initial understanding of bracing behaviors, a field survey was conducted in an automobile assembly plant (Jones et al., 2008). The objective of this research was to qualitatively determine where, when and how workers brace, and to use this information as guidance for a quantitative laboratory study. The field study classified and enumerated the distribution of industrial bracing postures adopted by a large number of workers performing automotive assembly tasks.

There were 20 operations in this study, 13 from a large truck assembly plant and 7 from a small car plant assembly plant. A total of 570 bracing tasks performed by 30 different operators were observed and qualitative assessments were made based on video of force exertions (Figure 1.2.1). A classification system was developed to characterize bracing postures and determine their relative frequency. The classification system included postural descriptions for whole body kinematics, choice of hand used to complete the assembly task, and/or to provide support, subsequent hand posture taxonomy, and geometric and mechanical properties of contact surfaces (Armstrong et al., 2003; McAtamney and Corlett, 1993).

These field data showed that pelvis (44% of observed task performances), abdomen (21%) and thigh (11%) bracing is prevalent in auto assembly. Jones et al. (2008) determined that of the one-handed exertion tasks sampled in an industrial environment, 53% were performed with additional support by the contralateral hand. Within the one-handed tasks, 40% were observed to have an additional point of contact or bracing beyond the reactive forces exerted at the contralateral hand. During two-handed exertions, 33% exhibited bracing at an additional body part. Among all of the postures observed, 85% were found to have some form of upper body or lower extremity bracing.

It was concluded that tasks involving forceful exertions, specifically pushing and pulling while standing in a restricted environment were common in this study (Jones et al., 2008). Workers frequently leaned on obstacles in the environment when given the chance, which suggests that biomechanical analyses that don't take such compensatory forces into account are not accurately representing many postures used in industry, nor the stresses on the body of workers using such bracing postures. These observations are of tremendous consequence given that the available biomechanical models do not account for the reaction forces at these additional points of contact. Therefore, in spite of the common practice of such braced and obstructed push-pull tasks, there is little literature in this area upon which meaningful ergonomic guidelines can be based.

Accurate representation of such force exertions and working postures are essential for accurate ergonomic assessment of worker capabilities (Chaffin and Erig, 1991), given that the risk of injury is greatly increased when job strength requirements approach worker capabilities (Chaffin et al., 1978). Existing ergonomic analysis tools are used to guide design decisions and justify potentially costly changes in product design, tooling and workstation layout. To be seen as credible, however, models intended for ergonomic evaluation of industrial jobs must produce accurate force-exertion capability assessment and posture prediction for the range of task conditions observed in industry. The model must be capable of replicating different force-generation strategies and postural behaviors prevalent in industry, and ergonomic evaluation of predicted strategies must yield outcome measures consistent with analysis of actual working force exertions and postures.

The University of Michigan's 3D Static Strength Prediction Program (3DSSPP), a manikin-based, task-analysis tool, uses a statistical model, combined with inverse kinematics algorithm, to predict force-exertion postures. Predictive equations are based on postural data collected under no bracing conditions, thus the effects of task hand and bracing forces on posture are not reflected in model predictions. To simulate bracing tasks with the 3DSSPP the user must iterate through incremental additions of bracing or external supporting forces (i.e. applied at the contralateral hand, elbow, shoulder, L5S1, hip, knee, ankle) until the % MVC population strength capability is maximized.

There are a number of researchers who have presented predominately statistical approaches to posture and motion prediction (Reed et al., 2002; Seidl, 1994; Faraway, 2003). These methods provide validated accuracy for tasks that are within the range of the underlying dataset. However, to date none of these statistical models account for compensatory force and moment affects on load distribution across the body. Other researchers have proposed strength-based, posture-prediction models that assume workers will choose postures in which their joints can exert the largest torque (Seitz et al., 2005) or can be predicted by optimization of such factors as joint angles, potential energy, deviation from neutral joint angles (Lui, 2003; Zhao et al., 2005; Marler et al., 2005). Again, these models do not account for bracing forces observed in activities of daily living and industrial tasks. Hoffman (2008) developed an approach to prediction of whole-body postures for a wide range of standing hand-force exertions based empirical findings and biomechanical principles. Specifically, Hoffman demonstrated the postures used for short-duration one- and two-hand static force exertions tend to maintain shoulder moments below a threshold and to minimize lower-back rotational moments, while also maintaining torso orientation near vertical. However, the influence of obstructions in the environment that would limit postures was not considered.

Chiang et al. (2006) is a static strength prediction algorithm that has implemented an automated inverse kinematic algorithm to predict support force exerted at the contralateral hand (Figure 1.2.2). If the user identifies either hand as a supporting hand, the software iterates through increasing hand loads applied to the support hand first until the percent strength capability threshold (%Cap) of the associated upper extremity is reached. This force magnitude is then fixed for the contralateral support hand as a second iteration begins with the task hand. This analysis is based upon the assumption that workers will attempt to share the load as much as possible between the joints. However, the model remains invalidated and limited to two-handed tasks. Additional bracing forces at alternative body parts are also not appropriately included or considered in the biomechanical model.

Manual iterative and automated modeling of bracing support forces outlined for both 3DSSPP and Chiang el al. (2006), solve for non-task hand force independent of task hand force and do not consider postural adjustments that result in response to force generation strategies with bracing availability. The approach by Chiang et al. (2006) is also based on the assumption that bracing forces are increased to a magnitude that satisfies the maximal strength capability of the shoulder (% Cap), which is contradictive to observations by Hoffman (2008) that static force exertions tend to maintain shoulder moments below a threshold.

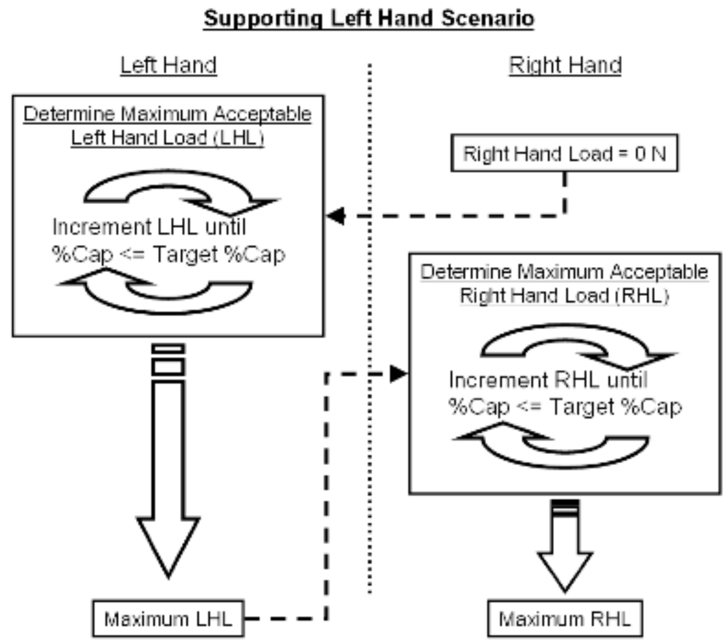

Figure 1.2.2. Software model for determining applied loads at the contralateral hand proposed by Chiang et al., (2006). The supporting (left) hand load is first determined and then used to determine the task (right) hand load.

1.3. Theoretical Problem

An understanding of the patterns of bracing forces and posture selection process, including factors and the tradeoffs workers make when selecting force generation strategies and task postures, is critical for prospective biomechanical analysis. Several different task and subject configuration variables are hypothesized to influence compensatory force generation and the associated postural behavior, and are summarized in Figure 1.3.1. The process of adopting a force-generation strategy during kinematically constrained one-hand isometric force exertions depends on a complex interaction and simultaneous effects of, at least, standing balance requirements, sensitivity of external joint loads (specifically at the task shoulder), task parameters, subject anthropometrics and strength (Grieve 1979a and 1979b; Garg et al., 1982; Kerk et al., 1994; Hoffman, 2008). Each of these individual factors have been extensively researched and governed by biomechanical principles. The extent to which these principles apply under the context of kinematic constraints is not understood. There is little data or guidance in the literature on how to account for such contralateral hand and body-bracing forces and the associated postural behaviors during biomechanical analysis.

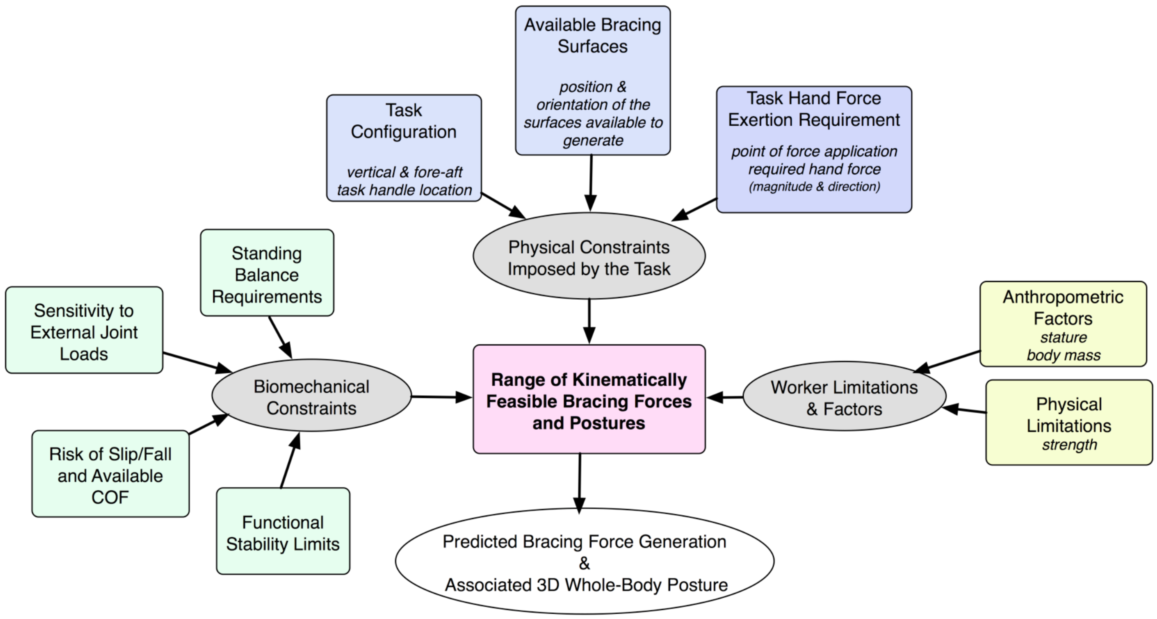

Figure 1.3.1. Factors hypothesized to affect force-generation strategy and the associated postural behavior for kinematically constrained one-hand isometric force exertions with bracing availability.

Previous studies of push and pull tasks performed in unconstrained environments where bracing is not available have documented the effect of variables such as body weight, height of force application, distance between body and point of force application, coefficient of friction between floor and footwear, and volitional postures on the mechanical loading of the low back and shoulders (Grieve and Pheasant, 1981; Pheasant et al., 1982; Chaffin et al., 1983; de Looze et al., 2000; Hoozemans et al., 2004; Granata and Bennett, 2005; Boocock et al., 2006). Numerous studies also have found that the exertion handle location at which push-pull forces were applied has a significant affect on maximum hand force capability (Martin and Chaffin, 1972; Ayoub and McDaniel, 1974; Chaffin et al., 1983; Kumar, 1991; Gagnon et al., 1992). Fothergill et al. (1992) reported a significant effect of handle type and handle position on push-pull strength. Martin and Chaffin (1972) constructed contours of force exertion capability as a function vertical height and horizontal distance between hands and ankles, based upon biomechanical simulation of human strength in the sagittal plane. They found that vertical hand heights of between 50 and 90 cm allowed maximum pushing capability. Kumar (1995) also found that a medium height handle enables maximal pushing and pulling force production, and that both decline with increasing or decreasing heights. Chaffin et al. (1983) investigated the effect of foot position and found that participants displayed significantly less strength when the feet were kept side by side versus one foot in front of the other. Likewise, Pheasant et al. (1982) showed that, for a given handle height, strength in the sagittal plane is strongly associated with foot placement. Daams (1993) reported that allowing participants to chose their body posture is advantageous in maximizing force output. Similarly, Hoffman (2008) determined that the position and length of the base-of-support chosen by participants increases with hand force magnitude, presumably to generate more body weight moment about the active margin of the base-of-support, and to use the mass of the under loaded lower extremities as a counter-balance mechanism.

Grieve and Pheasant (1981) hypothesized that deviation of task hand force from the nominal or required direction may be used to enhance capability. Several other researchers have observed significant vertical hand forces during nominally horizontal pushing and pulling. De Looze et al. (2000) showed that as handle height and force exertion increase, the deviation of the push forward direction increased with respect to the nominal horizontal direction, while the pull force direction transitioned from pulling upward with a substantial vertical component to the desired nominal horizontal force. Likewise, Granata and Bennett (2005) found a consistent and significant trend of greater upward pushing force for greater exertion levels and handle heights in nominally horizontal pushes. Okunribido and Haslegrave (2008) quantified significant off-axis forces, with the resulting force in the requested direction averaging between 77% and 95% of the total force exerted under various conditions. Hoffman et al. (2011) reported both substantial off-axis forces and compensatory postural strategies that directed the task force vector close to the shoulder, reducing the net joint moment at the shoulder for both pushing and pulling tasks.

A smaller number of studies have examined force exertions under kinematically constrained conditions. Kroemer and Robinson, (1971) and Kroemer (1974) concluded that maximal push and pull exertions are dependent upon the amount of reaction force available. Their studies were performed in standing posture when the participants had either braced themselves against a vertical wall, had anchored their feet on a footrest on the floor, or stood on surfaces with a range of coefficient of friction. A 50% increase in push-pull force exertion capability was observed due to an increase in coefficient of friction from 0.3 to 0.6. Pheasant et al. (1982) required participants to generate force exertion in all directions in the sagittal plane under prescribed foot placement, hand height, and the presence of a bracing wall or ceiling. Bracing against the constraint surface was found to substantially improve push and pull exertion strength. In a study that investigated force exertion in twisted or overhead working postures, Haslegrave et al. (1997) found participants braced with their free hand, wrist, or elbow against other parts of their body, what Hoffman (2008) termed "internal bracing." A subsequent analysis of single-handed kneeling posture showed that the largest forces were exerted when subject used their free hand, wrist or elbow to push against the floor or part of their body (Haslegrave et al., 1997; Ferguson et al., 2002). Ferguson et al. (2002) also suggested that supporting the body weight on an available contact surface, such as leaning with legs against an industrial bin, yielded increased hand force exertion capability. These studies support the hypothesis that force generation capability increases with bracing opportunity. However, none provides a quantitative model of bracing force and the associated postures as function of task variables that can be used for biomechanical analysis with human figure models.

The function of bracing during quasi-static force exertions has been presented as a dichotomy within the literature. Bracing has been hypothesized to be a function of basic mechanics, in that bracing forces are generated to oppose the task hand force in an effort to increase force-exertion capability (Gaughran and Dempster, 1956; Dempster, 1958). Alternatively, it has been hypothesize that the function of bracing is primarily balance and stability, wherein bracing may be expressed as percentage of body weight (Godin et al., 2008).

Subtle interactions have been shown between strength capability and the deployment of body weight as a counterbalance during push and pull tasks (Gaughran and Dempster (1956); Dempster, 1958; Grieve 1979a and 1979b; Grieve and Pheasant, 1981). Early work by Gaughran and Dempster (1956) elucidated the mechanical factors that are operative during sub-maximal seated push and pull exertions. This work highlighted two mechanisms of force production: (1) force generation capability is correlated with the generation of direct compressive and tensile forces at the braced surface, and (2) task hand exertion forces involve rotational mechanics wherein force couples are created at body weight's point of application acting at the available support surfaces. Mechanical analyses of push and pull exertions from a seated posture revealed the two opposing horizontal forces at the hand and at the seat level form a force couple which tends to apply a moment. A vertical force couple was also formed in that the effective reactive force at the seat was directed rearward of the centre-of-gravity (CoG) during maximal push exertions and forward of the CoG for maximal pull exertions. Dempster (1958) conducted a similar analysis of maximal, two-handed standing pulls that were braced at the feet using free body diagrams. This study also asserts that the magnitude of the pull force one can exert is related to trade-off between: (1) the overall joint moment distribution, (2) increasing the moment-arm to the point of force application, and (3) decreasing the moment-arm for the force couple in the requested task hand force direction acting on the system. The key mechanical principle is that the magnitude of the hand forces is proportional to the moments generated by body weight and the moment arm to the point of application of the force, irrespective of the body posture or specified task hand force direction. Note that this applies only in the case where no moment is applied at the feet, and no other contacts with the environment other than the feet and task hand(s) are permitted.

Later studies addressed this gap in the force-exertion (strength) literature and afforded subjects the opportunity to brace during standing isometric force capability studies. Kroemer (1974) for example, illustrated that strength capability at the task hand is a function of force exerted on available contact surfaces and the subsequent chain of force vectors from a supported surface through the body to the point of force application, in combination with posture that is optimized for position of body weight and muscle activation. Pheasant et al. (1982) also required subjects to generate force exertion in all directions in the sagittal plane under prescribed foot placement, force hand height and the presence of bracing wall or ceiling. Bracing against the constraint surface substantially improved the push and pull exertions for it enabled subjects to adopt a coplanar force couple, subsequently generating compressive or tensile forces. The significant effect of bracing or body support and whole-body posture on force-exertion capability is therefore apparent.

Quantification of bracing forces and support of body weight on environmental constraints is largely unaccounted for in the literature. A limited number of studies have expressed forces exerted at the contralateral support hand as a percentage of body weight. Lardi and Frazer (2003) determined that the magnitude of force exerted at the support hand, which ranged from 10% to 15% of body weight, was dependent upon magnitude of torso inclination relative to vertical. For the purpose of providing guidance on how to account for forces at the contralateral support hand when performing a biomechanical/ergonomic analysis, Godin et al. (2008) evaluated forces exerted at a prescribed location, as a percentage of body mass for a small subset of one-handed automotive assembly tasks. These tasks, which are common to those seen in industry, were physically re-created in a laboratory environment. Forces were recorded in all three directions, however only forces in the direction perpendicular to the plate surface were evaluated given that the forces in the remaining axes were observed to be negligible. Supporting hand load forces were observed to range from 5.5% to 12.1% of body mass across four individual working postures and task conditions (Godin et al., 2008). It is noteworthy that for both of these studies, subjects were instructed to reach to the task hand location, however the task hand exerted no force or load.

1.4. Research Goals

Review of the literature and observations made in the laboratory and automotive plant suggest that force exertion capability and the associated posture behaviors during one-handed force exertions performed in the presence of an environmental obstruction that afford bracing availability are affected by:

1. standing balance requirements,
2. required force magnitude and direction at the task hand,
3. joint range of motion and strength, and
4. kinematic restrictions and spatial constraints.

This dissertation seeks to understand the effects of kinematic obstructions on a person's force-exertion capabilities and posture behaviors to perform one-handed exertions, both when the obstructions can be used for bracing and when bracing is not permitted. Among the kinematically feasible force-generation strategies, people will use bracing force-generation strategies that enhance task hand force exertion capability, adopt postural behaviors that accommodate the kinematic requirements of the task, reduce task and contralateral shoulder moments and improve alignment between task hand force and requested task force direction.

The following general hypothesis guided this research:

Bracing with the contralateral hand or thigh

- extends reach capability by expanding the range of postures that are in static equilibrium,
- reduces moments at some joints by providing compensatory forces and moments, and
- allows postural strategies that reduce joint loading or increase force-exertion capability.

These general hypotheses led to some specific hypotheses concerning kinematically constrained isometric exertions with bracing availability:

1. Force exertion capability will be increased by access to bracing opportunities.
2. The availability of bracing and task requirement will alter the task hand force direction.
3. Bracing force generation strategies will fall into a small number of categories defined by specific, discrete behaviors.
4. Bracing force generation strategies will be associated with specific postural behaviors.
5. Both force generation strategies and the associated postural behaviors can be accounted for by a biomechanics-based conceptual model that maximizes task-hand force in the nominal direction while maintaining moments at the shoulders and lower back within acceptable ranges.

1.5. Research Objectives

The research was organized to achieve 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 and 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.

1.6. Dissertation Organization

The body of this dissertation is presented in six chapters. Chapter Two outlines the experimental study related to the objectives of this dissertation. Chapters Three through Seven address the specific research objectives.

Chapter Two examines the effects of task configuration variables on one-handed, isometric force exertions performed within the context of an environmental obstruction that imposes a kinematic constraint and affords bracing opportunities. The experimental conditions were selected to be typical of common industrial tasks, such as reaching into a bin to pick up a part or reaching into a vehicle engine compartment to install a part.

Chapter Three examines the effects of kinematic constraints and bracing on force exertion capability (task strength). Measured force data were analyzed to determine the effects of bracing availability on task hand force magnitude and direction for maximal, one-handed forward, backward, and upward exertions.

Chapter Four defines a theoretical framework to evaluate and classify bracing forces as effective (oppositional) or non-contributory (non-opposing) with respect to task hand force exertion. The task hand coordinate reference frame provides an effective method for classifying force-generations strategies adopted during one-hand, isometric exertions tasks with bracing availability. A force-generation strategy is a qualitatively distinct pattern of force generation at the task hand and available bracing surfaces. Quantitative criteria were developed to identify five distinct force-generation strategies. The influences of task handle location and nominal task hand force direction on the force-generation strategies is also discussed.

Chapter Five presents the development and evaluation of a strategy selection model to predict force-generation strategies during one-handed isometric tasks. It is shown that the resulting force-generation strategies can be used in static biomechanical analyses or digital human model (DHM) simulations. This force-generation strategy selection model relates task configuration variables and subject characteristics to predict the likelihood of adopting each of the identified force-generation strategies.

Chapter Six develops empirical models to predict task hand and bracing force magnitude and direction for tasks that are kinematically constrained. Force data are stratified on the nominal task hand force direction, requested exertion level and within force-generation strategy.

Chapter Seven presents statistical analysis of the influence of task configuration and subject characteristics on posture behaviors. Biomechanically critical aspects of posture are identified and quantified within nominal task hand force and force-generation strategy stratification. The efficacy of bracing and its association with postural behaviors are assessed.

Chapter Eight is an integration and discussion of the findings from the five previous chapters and presents overall conclusions and recommendations for future work. Force-generation and the associated posture selection for these tasks are hypothesized to be driven primarily by a small number of biomechanical criteria and constraints.

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CHAPTER 2

EXPERIMENT DESIGN AND METHODS

2.1. General Objectives

The objective of this experimental research is to examine the effects of task and subject variables on one-hand isometric force exertions and associated postural behaviors adopted within the context of an environmental obstruction that imposes both a kinematic constraint and affords bracing opportunities. More specifically, the goal is to understand where, when and how workers brace and the subsequent effects of biomechanical, kinematic, physical, anthropometric and physical constraints on such bracing.

Behaviors observed during a pilot study and industry suggest that the physical constraints imposed by task requirement, biomechanical constraints and individual worker factors affect force-generation strategy and associated postural modifications. The experimental research was designed to replicate common industrial tasks, such as reaching into a bin to pick up a part or reaching into a vehicle engine compartment to install a part. This chapter describes experiment methods developed and a laboratory study conducted to obtain data required for detailed biomechanical analysis of kinematically constrained one-hand isometric force exertions with bracing availability and to test the working hypotheses that govern this dissertation.

2.2. Subjects

Twenty-two paid subjects, ten females and twelve males, were recruited from a student population to participate in this study. Subjects were required to be right-hand dominant and have no history of musculoskeletal disorders or functional mobility impairments. All subjects signed informed consent forms approved by the Health

Sciences and Behavioral Sciences Institutional Review Board of the University of Michigan.

An effort was made to recruit male and female subjects with varying stature to ensure adequate representation of the upper and lower tails of the stature distribution (Table 2.2.1). An attempt to produce adequate variance on other anthropometric measures of interest, such as body mass and body mass index (BMI) also was made. Male subjects ranged from 18th %tile to 96th %tile by stature and females subjects ranged from 12th %tile to 88th %tile by stature for US adults (Roebuck, 1995). All subjects were young (median age 21 years) and relatively thin (median body mass index 23.6 kg/m^2). Subject whole-body strength capabilities were characterized by standardized arm; torso and leg lift strength tests (Chaffin, 1975). The latter values were expressed as population strength percentiles using data from Chaffin et al. (2006).

Table 2.2.1 Subject pool and summary statistics.

							Percentile Strength		
Subject Number	**Experimental Design**	**Gender**	**Age**	**Stature [cm]**	**Body Mass [kg]**	**BMI [kg/m^2]**	**Arm Lift**	**Torso Lift**	**Leg Lift**
004	II	M	22	178.5	84.8	26.6	74.0	42.5	50.7
005	I	M	23	174.4	77.8	25.6	42.3	51.5	13.3
006	I	F	20	157.0	55.6	22.5	24.9	41.9	51.0
007	II	M	23	180.0	113.4	35.0	46.1	44.2	66.9
008	I	M	22	168.0	65.8	23.3	17.6	40.9	14.7
009	I	F	21	174.5	68.0	22.3	65.5	48.4	85.1
010	II	M	23	174.0	64.6	21.3	22.4	49.5	30.5
011	I	M	21	185.9	74.8	21.7	37.5	43.3	28.3
012	II	F	21	163.0	62.1	23.4	24.8	41.8	49.5
013	II	F	19	167.2	65.8	23.5	55.7	47.3	76.1
014	II	F	21	155.8	57.6	23.7	39.9	49.5	82.9
015	I	M	19	181.5	73.7	22.4	29.2	43.9	35.6
016	II	M	22	177.6	74.6	23.7	29.0	41.4	14.2
017	I	M	21	193.5	80.5	21.5	10.5	41.1	33.2
018	I	F	21	162.6	64.0	24.2	41.4	47.2	46.6
019	II	M	20	172.6	77.1	25.9	42.3	40.2	76.7
020	II	F	19	172.0	74.8	25.3	92.1	44.5	84.2
021	II	F	19	158.3	68.0	27.2	42.3	43.9	59.7
022	II	M	24	195.6	77.1	20.2	16.1	37.2	11.7
023	I	F	21	166.0	77.1	28.0	59.7	48.7	92.9
024	I	M	21	172.0	68.0	23.0	36.4	39.9	67.3
025	I	F	20	165.6	70.3	25.6	29.1	41.8	29.1

2.3. Facilities

Testing was conducted with a reconfigurable fixture that enabled the fore-aft task handle location, contralateral hand bracing handrail height and orientation, and body-bracing surface to be varied over a wide range (Figure 2.4.1). The structure imposed a kinematic constraint or obstruction between the subject and the task handle to replicate common situations posed by a table, conveyer, car fender, workbench, parts bin, or other features of workplaces. The adjustable structure included a vertical planar surface, defined as the thigh-bracing surface, and a handrail that provided a bracing support for the contralateral hand (Figure 2.3.2). All aspects of the bracing structure were adjustable to subject body dimensions by means of linear actuators and adaptable aluminum structure (80/20 Inc., Columbia City, IN). The body bracing surface and the contralateral hand-bracing (handrail) surface were each instrumented with a six-axis load cell (AMTI, Watertown, MA) to measure the forces and moments at both the thigh and bracing hand respectively (Figure 2.4.2).

As depicted in Figure 2.3.2, the subject exerted force on a cylindrical, rigid, horizontal bar, 47 cm long and 3.5 cm in diameter, which was attached to a six-axis load cell (JR3, Woodland, CA). The handle was covered with 5-mm-thick foam rubber that provided a high-friction grip. The vertical height of the task force handle was also adjustable. Two moveable force platforms captured ground reaction forces for each trial condition (AMTI, Waterdown, MA) since it has been shown that preferred foot placements and postural strategies vary with changes in task parameters (Hoffman, 2008).

A force feedback display was positioned at eye height, allowing subjects to achieve and maintain a requested hand force. Custom software was developed in LabVIEW® (National Instruments, Austin, TX) to provide visual feedback to the subject (Figure 2.3.1). In sub-maximal trials, the display provided a graphical depiction of the subject's current force magnitude along the requested axis (Hoffman, 2008). Force data were averaged over a three-second hold-phase of each exertion in which the maximum magnitude variability was within +/-10% of the peak maximal force level (Caldwell et al. 1974). Trials in which the maximum force during the three-second window varied by more than 10% were discarded and repeated. Force and moment signals from each of the instrumented reaction surfaces were sampled at 600 Hz and synchronized with motion capture data, video and static photos of the terminal postures for each trial.

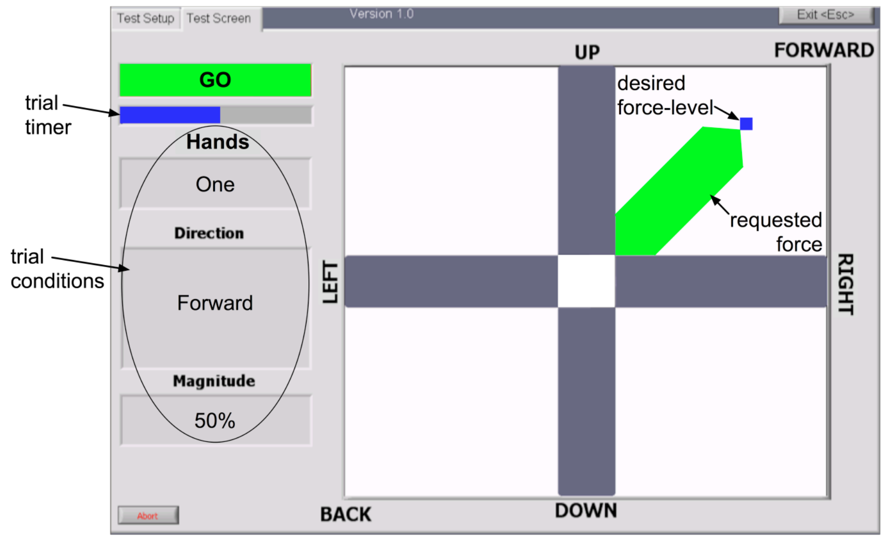

Figure 2.3.1 Visual force-feedback display with goal (blue diamond) shown for required level of force in nominal task hand force direction (Hoffman, 2008).

Figure 2.3.2 illustrates the laboratory set-up in side view. The X-axis global coordinate system runs positive rearward, the Y-axis is positive to the subject's right and Z-axis positive vertically. The origin X coordinate is defined by the thigh-bracing surface; the origin Y coordinate is defined by the centerline of the task handle location, while the origin Z coordinate is defined by point on the floor below the task handle. In general terms, vertical dimensions are measured from the floor (force plates) and fore-aft dimensions are measured from the body-bracing surface on the bracing structure.

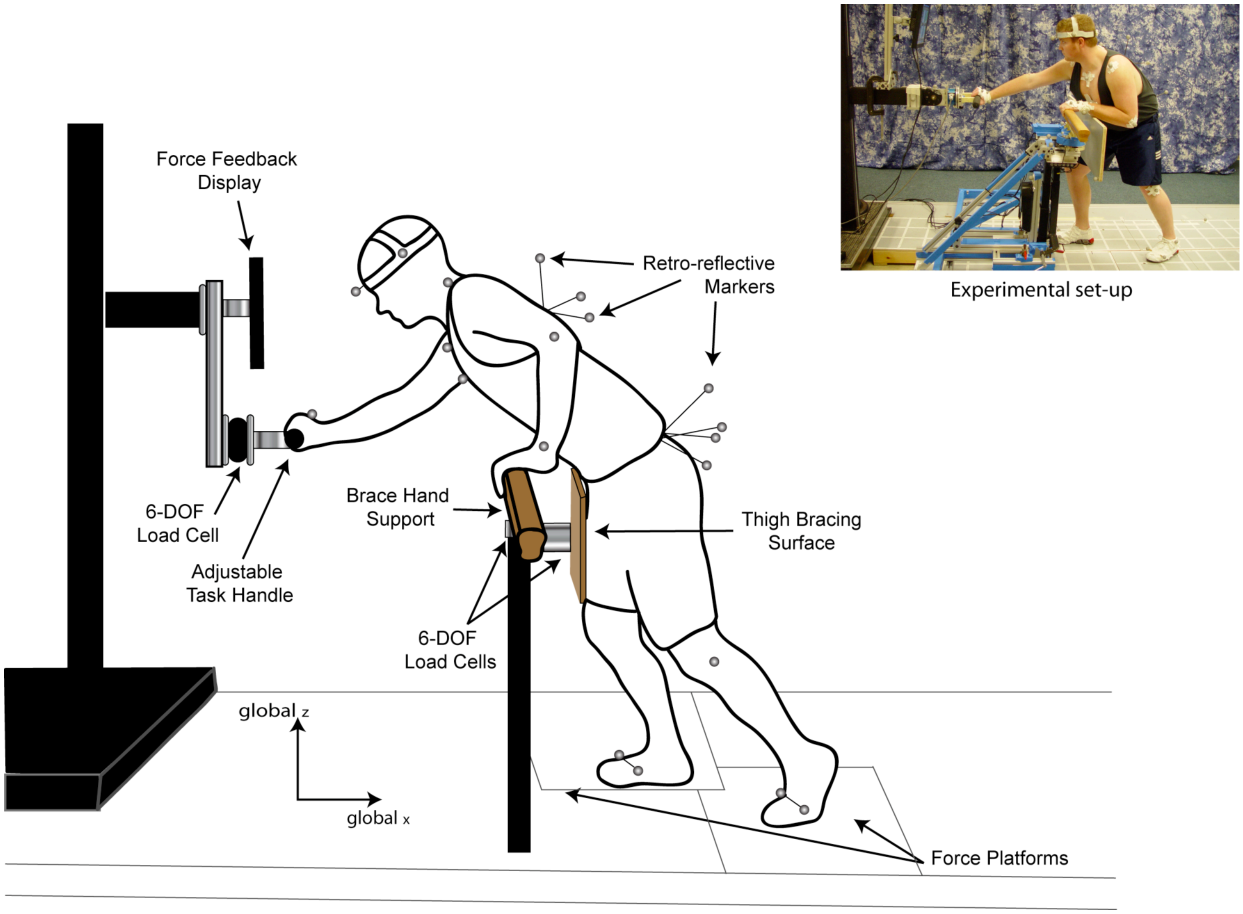

Figure 2.3.2. Laboratory configuration with visual force feedback display, 6-DOF load cells at task handle and bracing obstructions, and reconfigurable force platforms for measuring forces and moments at the hand and feet respectively.

Whole-body postures and motions were captured using an eight-camera Qualysis Proreflex 240-MCU passive optical motion tracking system. Twenty-nine 25-mm-diameter retro-reflective markers were affixed to each subject (Figure 2.3.3) and the kinematic data was sampled at 60 Hz. Optical marker locations are used in conjunction with 25 body landmarks to capture whole-body postures. Digitization was used to define locally fixed points in associated local coordinate frame defined by 3 or more reflective markers (Figure 2.3.4). Additional body landmarks on the head, torso, pelvis and feet with respect to the optical markers were subsequently identified. The set of optical markers and digitized landmark locations are summarized in Table 2.3.1 and the locations are visualized in Figure 2.3.4. Manually digitized body landmark data were combined with three-dimensional marker data from each trial and anthropometric measures obtained from each subject to calculate joint centre locations and create a linkage representation using a method similar to that described by Reed et al. (1999). The calculated whole body linkage was used to define key postural metrics characterizing the terminal postures adopted during kinematically constrained isometric one-hand force exertions with bracing availability.

Figure 2.3.3. Retro-reflective marker set used to track whole-body postures and motion.

Table 2.3.1 Summary of optical marker and digitized landmark locations (L = left, R = right).

Optical Marker Locations		**Digitized Landmark Locations**	
L & R side of head	L & R foot – lateral	L & R Tragion	T10
Front of head	Sternum top	L & R Infraorbtial	T12
L & R Acromion	Sternum bottom	L & R Acromion	L3 (approximate)
L & R Lateral Epicondyle of Humerus	T8 – top	Vertex	L5
L & R hand – thumb side	T8 –left	Suprasternale	Sacrum
L & R	T8 –right	Substernale	L & R ASIS
L & R Lateral Epicondyle of Femur	T1	C7	L & R PSIS
L & R Lateral Malleolus	L & R hip	T4	L & R foot – big toe
L & R foot - medial	L & R PSIS	T8	L & R foot – 5th Metatarsalphalangeal

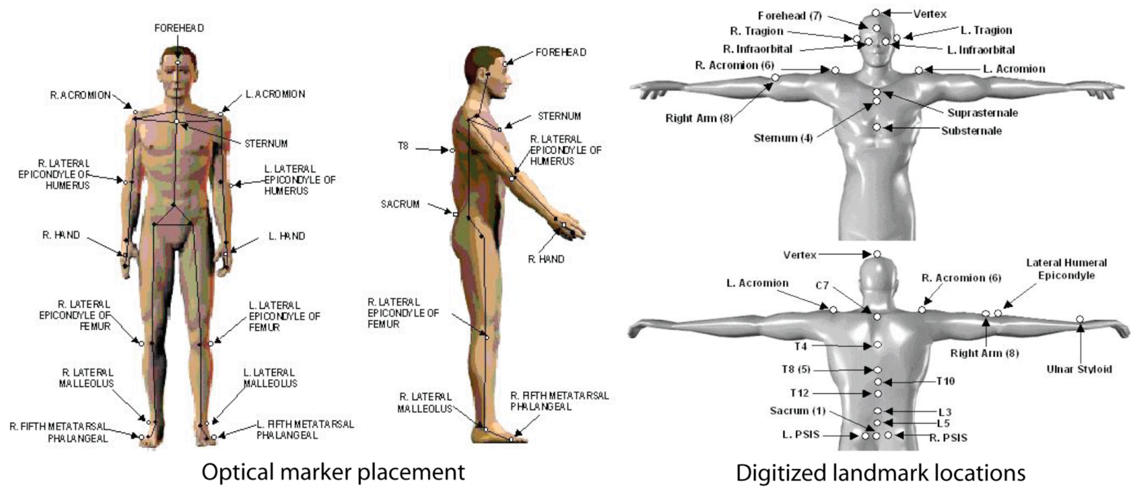

Figure 2.3.4. Retro-reflective marker placement and digitized landmark locations.

2.4. Test Conditions

Six task configuration variables were manipulated independently. Task configuration variables included: vertical task hand height, fore-aft task handle location, contralateral hand support position and orientation, levels of bracing availability, and task hand force magnitude and direction (Figure 2.5.1).

Three task handle heights were chosen to span a range typical of working heights in industry and observed in the automotive assembly plant study. The task handle locations were scaled to subject stature so that each subject would experience a similar range of posture constraint. Task handle location was scaled to a percentage of stature: low (43% of stature), medium (59% of stature) and high (76% of stature). The task handle was placed at two fore-aft locations, which were also scaled to stature: close (26% of stature) and far (44% of stature).

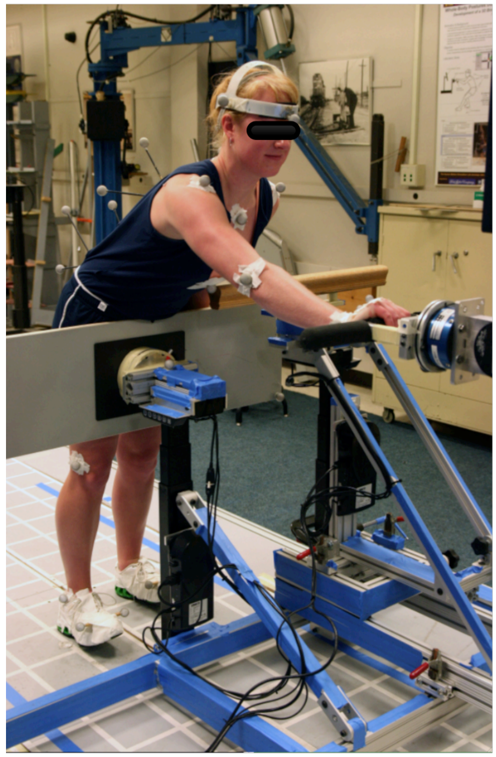

Figure 2.4.1. Subject performing an isometric exertion on the fixed task hand force handle while engaging the pelvis at the body-bracing support surface and receiving feedback on task hand force via an LCD screen.

The bracing structure limited the postures that could be achieved while also providing an opportunity for an opportunity for bracing with the thighs or left hand (Figure 2.4.2). The bracing handrail was set to hip height (55% of stature) and the top edge of the thigh-bracing surface was located at upper leg height (52% of stature). The position and orientation of the contralateral hand-bracing surface was also manipulated independently: close (5% of stature), far (22% of stature) and an orthogonal (perpendicular) orientation of the contralateral handrail.

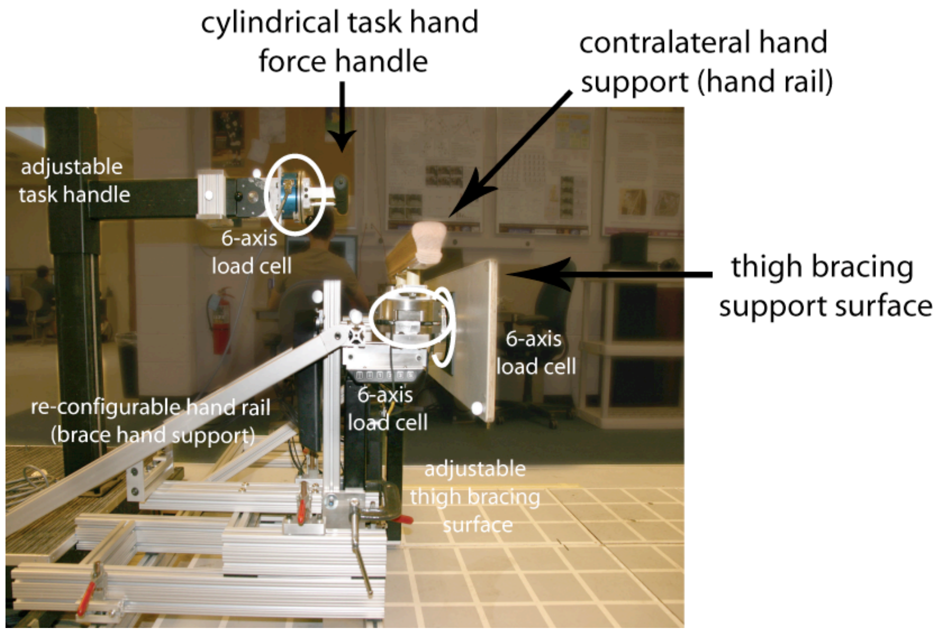

Figure 2.4.2. Bracing structure adjustability and configuration with respect to the task handle location

Levels of bracing availability were presented in a randomized order within each task handle location test configuration. Subjects were instructed as to which bracing surfaces were available, and subsequently, which bracing surfaces were not permitted to brace externally off of for each trial. Levels of bracing availability included:

1. No contact with the structure permitted other than at the task hand.
2. Hand bracing permitted, no contact with thigh structure (hand only).
3. Thigh bracing permitted, no hand bracing (thigh only).
4. Both thigh and hand bracing permitted (hand and thigh).

Five nominal task hand force directions were investigated: forward, backward, upward, and lateral forces to the right and left. All force exertions were performed at 50% and 100% of each subject's maximal exertion capability to establish the latter values. For each task handle test configuration subjects were first required to perform a maximal exertion, across all randomized combinations of task hand force directions and levels of bracing availability. Blocking trials on requested task hand force exertion level ensured that the sub-maximal tasks were normalized to the each subject's individual maximum for a specified test condition.

Exertions were performed on a raised platform with the requirement that subjects remained behind the bracing structure and within the gridded region of the platform during all exertions (Figure 2.4.1). The constraint on foot placement was imposed in an effort to prevent subjects from aligning themselves with the direction of force and thus converting all asymmetric (i.e. cross-body exertions to the right and left) task hand force directions into sagittal plane exertions. The painted wood platform had a static coefficient of friction (CoF) of approximately 0.75. All subjects wore their own athletic shoes, and thus the available friction for individual shoe-floor interfaces may have been different across subjects. At no time, however, did the subjects slip or indicate that they believed their foot would slip during the exertions.

2.5. Experiment Design

To summarize, task configuration variables and corresponding treatment levels included: vertical task hand height (3), fore-aft task handle location (2), contralateral hand support position and orientation (3), levels of bracing availability (4), task hand force magnitude (2) and direction (5). Given the large number of conditions to be tested a split-plot design was employed (Figure 2.5.1). The split-plot design afforded the opportunity to evaluate task hand force exertion capability, force-generation patterns and associated postural behaviors across a greater number of task configurations. Females and males were distributed amongst the experiment designs (I and II) in a manner that yielded equivalent groups based upon anthropometric (Table 2.5.1) and strength measures (Table 2.5.2). All subjects completed trials in Block I, which was composed of all of the task configurations (combinations of the fore-aft task handle location and contralateral hand support position & orientation) at the medium task handle height. In addition, subjects assigned to Design I performed exertions at the high task handle height (Block 2b) and those assigned to Design II performed trials at the low task handle height (Block 2a). For each subject two repetitions of forward and backward exertions trials with hand bracing and hand & thigh bracing availability levels within one task configuration were performed. The repeated trial condition was assigned in a randomized order across the task handle configurations.

Table 2.5.1 Summary statistics (mean (standard deviation)), for female and male subjects demonstrating anthropometric equivalency of subjects across the split-plot design.

Experimental Design	Females ($n_I = n_{II} = 5$)			Males ($n_I = n_{II} = 6$)		
	Age [years]	**Stature** [cm]	**BMI** [kg/m^2]	**Age** [years]	**Stature** [cm]	**BMI** [kg/m^2]
I	20.6 (0.6)	165.1 (6.4)	24.5 (2.3)	21.2 (1.3)	179.2 (9.5)	22.9 (1.5)
II	19.8 (1.1)	163.3 (6.6)	24.6 (1.6)	22.3 (1.4)	179.7 (8.3)	25.4 (5.3)

Table 2.5.2 Summary statistics (mean (standard deviation)), for female and male subjects demonstrating standardized strength equivalency of subjects across the split-plot design.

Experimental Design	Females ($n_I = n_{II} = 5$)			Males ($n_I = n_{II} = 6$)		
	Arm Lift [%tile]	**Torso Lift** [%tile]	**Leg Lift** [%tile]	**Arm Lift** [%tile]	**Torso Lift** [%tile]	**Leg Lift** [%tile]
I	44.1 (18.0)	45.6 (3.5)	60.9 (27.0)	28.9 (12.5)	43.4 (4.2)	32.1 (19.6)
II	50.8 (25.5)	45.5 (3.0)	70.5 (15.3)	38.3 (34.3)	42.5 (4.2)	41.8 (27.3)

Across the experiment designs, trials were randomly blocked on the high, medium-close, medium-far and low task handle locations. Within each task configuration, trials were blocked on the requested task hand exertion level. Maximal level task hand force exertions were performed and recorded first, and used to define sub-maximal force levels. Within each block of task handle configuration and requested exertion level, trials were randomized across all levels of bracing availability and task hand force directions.

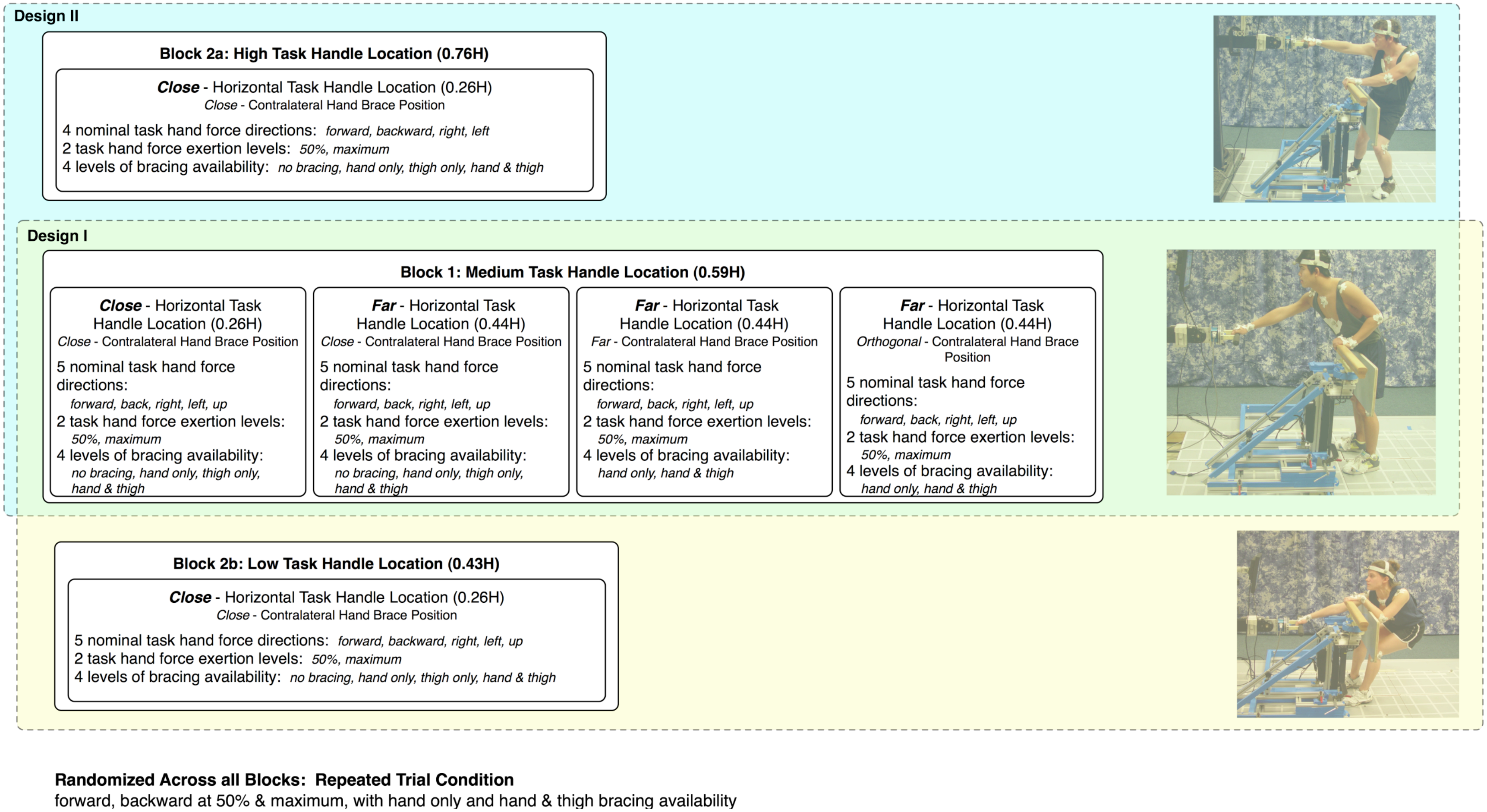

Figure 2.5.1. Split-Plot Design of Experiment: Block I performed by all subjects, Blocks 2a and 2b performed by subjects assigned to Design II and Design I respectively.

2.6. Procedure

Subjects were recruited by email advertisement and by word-of-mouth. All were undergraduate and graduate students of the University of Michigan. The Health Sciences and Behavioral Sciences Institutional Review Board of the University of Michigan approved the protocol and upon explaining the study objectives to each subject, written consent was obtained. The subjects changed from street clothes into test garb, consisting of loose fitting shorts and a short-sleeve shirt with a slit in the back to allow access to posterior spine landmarks. All subjects wore their own athletic shoes.

Subject anthropometry was quantified following the HUMOSIM anthropometric protocol (Woolley et al., 2000). Each subject's posture and anthropometry were characterized in a standardized preliminary condition, using calipers and anthropometers to record the location of palpated body landmarks (Table 2.6.1). These data were used to quantify kinematic segment geometry for calculation of joint center locations.

Table 2.6.1 HUMOSIM Anthropometric Protocol - subject anthropometric measures

Body weight	Hand length & width
Stature (with & w/o shoes)	Wrist depth & width
Seated height	Elbow width
Head width & depth	Floor to L5 standing
Nasion to top of head	C7 to L5
Nasion height from floor	Pelvis depth (ASIS to PSIS)
C1 to C7	Hip center-to-knee length
Floor to C7 standing	Femoral epicondyle width
Floor to suprasternale notch	Knee height
C7 to suprasternale notch (vertical & horizontal)	Knee-to-ankle length
Suprasternale notch to accordion process	Lateral malleolus to 1st metatarsalphalangeal (horizontal)
Inter-accordion processes	Malleolus height & width
Shoulder-to-elbow length	Ankle-to-heel distance
Elbow-to-wrist length	Foot length

Three standardized strength tests were performed to quantify subject strength capability. These strength measurements provided measures of whole-body strengths and allowed for comparison with strength values published for large population strength distributions (Figure 2.6.1). Static strength tests assumed three unique test postures to quantify composite measures of arm, leg and torso lifting strengths as described by Chaffin (1975). Whole-body strengths were measured by having the subject exert their maximum capable force against a fixed handle. The exerted force was measured a tension load cell.

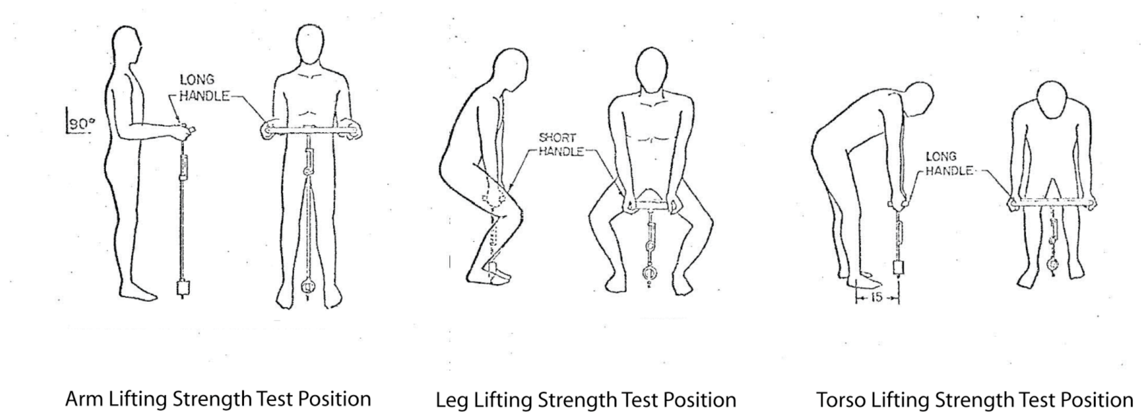

Figure 2.6.1. Illustrations of static strength test postures for standardized strength tests (Chaffin, 1975).

All strength tests were performed a minimum of two times and additional tests were conducted when the difference in strength measures between two consecutive tests exceeded 15%. Subjects were given 1 to 2 minutes of rest between tests. Strength measurements were also taken pre- and post- test conditions to assess subject fatigue. Analysis of the strength data measures did not reveal any significant fatigue, nor did the subjects report feelings of fatigue at anytime during the test sessions. To minimize the effects of fatigue, rest breaks were also provided to subjects between trials.

Following the strength testing, subjects performed a series of practice trials before 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.

In each trial, subjects were instructed to exert their maximal capability or satisfy the sub-maximal exertion requirement. Maximal trials were 6 seconds in duration, in which a three-second ramp-up was allowed before the three-second maintenance of a +/- 10% of the peak maximal force level was achieved (Caldwell et al. 1974). Sub-maximal trial durations ranged from 6 to 12 seconds depending on the time required for a subject to achieve the hand force criteria and maintain the criteria for 3 seconds. All statistical analyses were performed on the mean force during 3-s static phase of each trial. The only constraint with respect to the hand/task handle coupling was the subjects were required to adopt a power grip about the cylindrical handle. The subject determined the orientation of the task handgrip, either pronation or supination of the power grip on the horizontal handle, for each trial.

Prior to the start of each trial, the subject was instructed as to the requested direction of the task hand force and which, if any, bracing surface was available. The goal of each trial was to satisfy the task hand force exertion requirement. Subjects were allowed to support their body weight or use the permitted available surfaces to generate reactive forces with the contralateral hand and thigh if they chose to do so. Each trial began with the subject at the end of a raised platform requiring them to walk towards the bracing structure and task handle. This procedure was an effort to reduce trial sequence effects on posture. Testing with each subject lasted approximately five hours.

2.7. References

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CHAPTER 3

THE EFFECT OF BRACING AVAILABILITY ON TASK HAND FORCE EXERTION CAPABILITY

3.1. Abstract

In activities of daily living and industrial tasks people encounter many obstructions in their environment that kinematically limit the postures that they can achieve. These obstructions can also provide an opportunity for additional support by bracing with the hand, thigh or other body part. The reaction forces on bracing surfaces, which are in addition to those acting at the feet and task hand, may improve task performance capability. The effects of kinematic constraints and associated bracing opportunities on isometric hand force were quantified in a laboratory study of 22 females and males subjects from the student population with a range of body size. 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 more force at the task hand by 40.4% on average. The benefit of bracing was affected by the task hand location and requested task hand force direction.

3.2. Introduction

Tasks involving forceful exertions, specifically pushing and pulling while standing in a restricted environment are prevalent (Jones et al., 2010). During labor intensive tasks and many common activities of daily living, people often lean on an available surface with a "free" hand or body part to stabilize their body while exerting a force. In an effort to classify and quantify the distribution of such bracing, Jones et al. (2008) found that of the one-hand exertion tasks sampled in an industrial environment, 53% were performed with additional support by the contralateral hand.

A limited number of studies have examined force exertions under kinematically constrained conditions. Kroemer and Robinson (1971) and Kroemer (1974) concluded that maximal push and pull exertions are dependent upon the amount of reaction force available. Their studies were performed in standing posture when the participants had either braced themselves against a vertical wall, had anchored their feet on a footrest on the floor, or stood on surfaces with a range of coefficient of friction. A 50% increase in push-pull force exertion capability was observed due to an increase in coefficient of friction from 0.3 to 0.6. Pheasant et al. (1982) required participants to generate force exertion in all directions in the sagittal plane under prescribed foot placement, hand height, and the presence of a bracing wall or ceiling. Bracing against the constraint surface was found to substantially improve push and pull exertion strength. In a study that investigated force exertion in twisted or overhead working postures, Haslegrave et al. (1997) found participants braced with their free hand, wrist, or elbow against other parts of their body, what Hoffman (2008) termed "internal bracing." A subsequent analysis of single-handed kneeling posture also showed that the largest forces were exerted when subject used their free hand, wrist or elbow to push against the floor or part of their body (Haslegrave et al. 1997; Ferguson et al. 2002). These studies substantiate the hypothesis that force generation capability effectively increases with bracing opportunity.

Grieve and Pheasant (1981) hypothesized that deviation of task hand force from the nominal or required direction may be used to enhance capability during unconstrained force exertions. Several other researchers have observed significant vertical hand forces during kinematically unconstrained, nominal horizontal pushing and pulling. De Looze et al. (2000) showed that as handle height and force exertion increase, the deviation of the push forward direction increased with respect to the nominal horizontal direction, while the pull force direction transitioned from pulling upward with a substantial vertical component to the desired nominal horizontal force. Likewise, Granata and Bennett (2005) found a consistent and significant trend of greater upward pushing force for greater exertion levels and handle heights in nominally horizontal pushes. Okunribido and Haslegrave (2008) quantified significant off-axis forces, with the resulting force in the requested direction averaging between 77% and 95% of the total force exerted under various conditions. Hoffman et al. (2011) reported both substantial off-axis forces and compensatory postural strategies for both pushing and pulling tasks. The effect of generating task hand forces that deviate from nominal direction in an effort to increase force exertion capability during kinematically constrained task conditions have not been considered in the literature.

This chapter presents an investigation of one-hand, isometric force-exertion capability (task strength), performed in the presence of a rigid obstruction located between the subject and a force measurement handle. This experiment setup was designed to provide a range of bracing opportunities. The objective was to determine if various types of bracing availability affect one handed force-exertion capability. The following hypotheses were formulated through review of the literature and were used to develop the design of the experiment:

1. The maximum force capability of the hand performing the required forceful exertion will be affected by:

   a. the direction of the force application,
   b. the location of the exertion handle, and
   c. the availability of bracing with the contra-lateral hand or thigh.

2. Nominally horizontal push/pull forces will have a significant vertical component. More specifically:

   a. the vertical force will be directed downward when pushing on a fixed handle below shoulder height and upward when pushing on a fixed handle overhead,

   b. when pulling, the force will be directed upward for handles below shoulder height and downward for handles overhead,

   c. when lifting, the required vertical upward forces also will have a significant rearward horizontal off-axis component, and

   d. deviations in the resultant force direction from that requested will increase with bracing availability.

3.3. Methods: Data Analysis

The current analysis compares one-hand isometric horizontal push and pull exertions as well as vertical lifting exertions when performed with four different exertion handle locations, and while being presented with varying levels of bracing opportunities. For all trials, subjects were required to exert 100% of their *maximal* volitional capability. Adjustability of the task handle and bracing structure ensured that all test conditions were normalized to an individual participant's anthropometry. Exertions were performed at three vertical task exertion handle locations which were defined as a percentage of the subject's stature: low (43% of stature), medium (59% of stature), and high (76% of stature) task handle locations. The medium task handle location was differentiated further by two horizontal positions, classified as close and far locations, scaled at 26% and 44% of stature respectively. Scaling the test conditions for anthropometry ensures that all subjects experience a similar range of postural requirements.

Levels of bracing availability were presented in a randomized order within each task handle location test configuration. Subjects were instructed as to which bracing surfaces were available and subsequently which bracing surfaces were not permitted to brace externally off of for each trial. Levels of bracing availability included:

1. *No Brace*: no contact with the structure permitted other than at the task hand.

2. *Hand Only*: hand bracing permitted, no contact with thigh structure.

3. *Thigh Only*: thigh bracing permitted, no hand bracing.

4. *Hand & Thigh*: Both thigh and hand bracing permitted.

Forces on the exertion handle are positive upward (Z-axis) and rearward (X-axis). The angle of the resultant task hand force direction is relative to horizontal, and is defined positive upward for horizontal forward and backward exertions. This angle is used to quantify the force direction in the XZ (sagittal) plane, with an angle of zero degrees corresponding to the requested backward pull exertion, and an angle of 180 degrees to a requested forward push exertion. The direction of upward lifting exertions was defined positive rearward (along the x-axis), with an angle of 90 degrees.

Means for task hand force components, the magnitude of the resultant task hand force vector, and task hand direction with respect to the nominal requested hand force direction were computed in global coordinates for each trial condition. Measures were presented as both resultant force magnitude [Newton] and direction [degrees]. For each test condition, mean force values were computed as the average of the measured force components in the x, y, and z-direction, i.e., the mean magnitude of the resultant vector across all participants. Similarly a standard deviation was determined for each force component, and the magnitude of the resultant vector was then used to quantify the variation in hand forces within a given trial condition.

Off-axis forces measured in the lateral and vertical (forward/backward exertions) or fore-aft (upward exertions) directions were used to quantify differences between actual and requested task hand force. The relative magnitude of off-axis force was quantified by expressing off-axis forces as a percentage of the mean on-axis task hand force component.

A 3 x 4 x 4 analysis of variance (ANOVA) was used to test each of the hypotheses, as well as to test the effects of direction of the requested hand force, location of the exertion handle, and levels of bracing availability on the strength and direction of the task hand exertions. Given the large number of hypotheses tests, a conservative p-value of 0.0001 was used to determine the statistical significance of the effects in the analysis of variance. Post-hoc Tukey tests were then performed on significant main effects to compare task strength and direction between task handle location; force direction and bracing availability for which an alpha level of 0.05 was adopted for all mean pair-wise comparisons. All statistical analyses were conducted using JMP software version 5.0 (SAS, Cary, NC).

3.4. Results

Mean maximal one-hand force exertion magnitudes were significantly affected by bracing availability (Table 3.4.1). Further, task hand force capability was significantly affected by the location of the exertion handle and the direction of the requested task hand force (Figure 3.4.2).

Resultant Task Hand Force

A three-way ANOVA was performed on the magnitude of the mean resultant hand force data collected from the four exertion handle locations, three force application directions, and four conditions of bracing availability, for both female and male subjects. Each of the independent measures significantly affected resultant task hand force magnitude. Post-hoc analysis of the means revealed significant differences in task hand strength for no brace vs. bracing availability in 64% (21/33) of test conditions (Figure 3.4.1 and Figure 3.4.2). Means and standard deviations for mean resultant task hand forces across trial conditions are summarized in (Table 3.4.1).

Table 3.4.1 Mean (standard deviation) resultant task hand force magnitude [Newton] and task hand force direction expressed as angle relative to the nominal requested force direction [Degrees] across task handle locations (normalized to stature) and bracing availability conditions.

Task Handle Location	Nominal Task Hand Force Direction	Resultant Task Hand Force [N]				Task Hand Force Direction [Degrees]			
		No Bracing	Hand Only	Thigh Only	Hand & Thigh	No Bracing	Hand Only	Thigh Only	Hand & Thigh
High (0.76H)	**Backward**	248 (58)	356 (101)	349 (96)	376 (134)	-21.9 (7.8)	-10.7 (5.6)	0.1 (4.8)	-2.6 (6.1)
	Forward	291 (61)	367 (112)	289 (112)	330 (124)	12.4 (5.7)	8.8 (3.6)	15.3 (6.7)	7.9 (6.1)
Medium (0.59H) Close (0.26H)	**Backward**	270 (43)	389.6 (91)	364.7 (94)	417.7 (88)	-8.7 (5.5)	3.1 (5.9)	15.8 (8.8)	14.0 (10.1)
	Forward	312 (74)	392 (95)	262 (88)	386 (93)	-4.7 (5.4)	-7.4 (5.6)	-1.2 (9.9)	-9.8 (5.8)
	Upward	131 (29)	225 (65)	319 (120)	328 (109)	17.7 (15.2)	31.2 (12.5)	35.2 (10.5)	35.0 (5.1)
Medium (0.59H) Far (0.44H)	**Backward**	171 (28)	322 (86.	397 (108)	421 (116)	-13.0 (8.8)	0.5 (5.6)	11.1 (4.6)	9.4 (4.0)
	Forward	222 (61)	343 (90)	234 (58)	333 (97)	-6.2 (10.5)	-9.2 (3.6)	-6.0 (5.3)	-8.4 (3.8)
	Upward	98.9 (52.	176 (73)	328 (117)	330 (120)	17.0 (22.7)	37.4 (6.2)	41.6 (2.4)	40.1 (4.2)
Low (0.43H)	**Backward**	281 (51)	388 (82)	347 (51)	401 (94)	16.4 (5.9)	20.8 (4.6)	30.7 (8.5)	24.6 (8.2)
	Forward	293 (65)	391 (117)	261 (32)	380 (100)	-27.8 (5.2)	-30.8 (4.7)	-30.2 (2.4)	-31.2 (4.9)
	Upward	160 (42)	273 (57)	364 (91)	385 (96)	21.4 (8.0)	27.0 (4.8)	29.6 (2.2)	27.7 (1.7)

Analysis of variance revealed several significant interactions between bracing availability, task handle location, force direction application, and gender. One exception was the lack of a demonstrated interaction effect of task handle location and gender. Apparently, given that the bracing structure was normalized relative to participant anthropometry, gender did not influence task strength for different exertion handle locations (p=0.95).

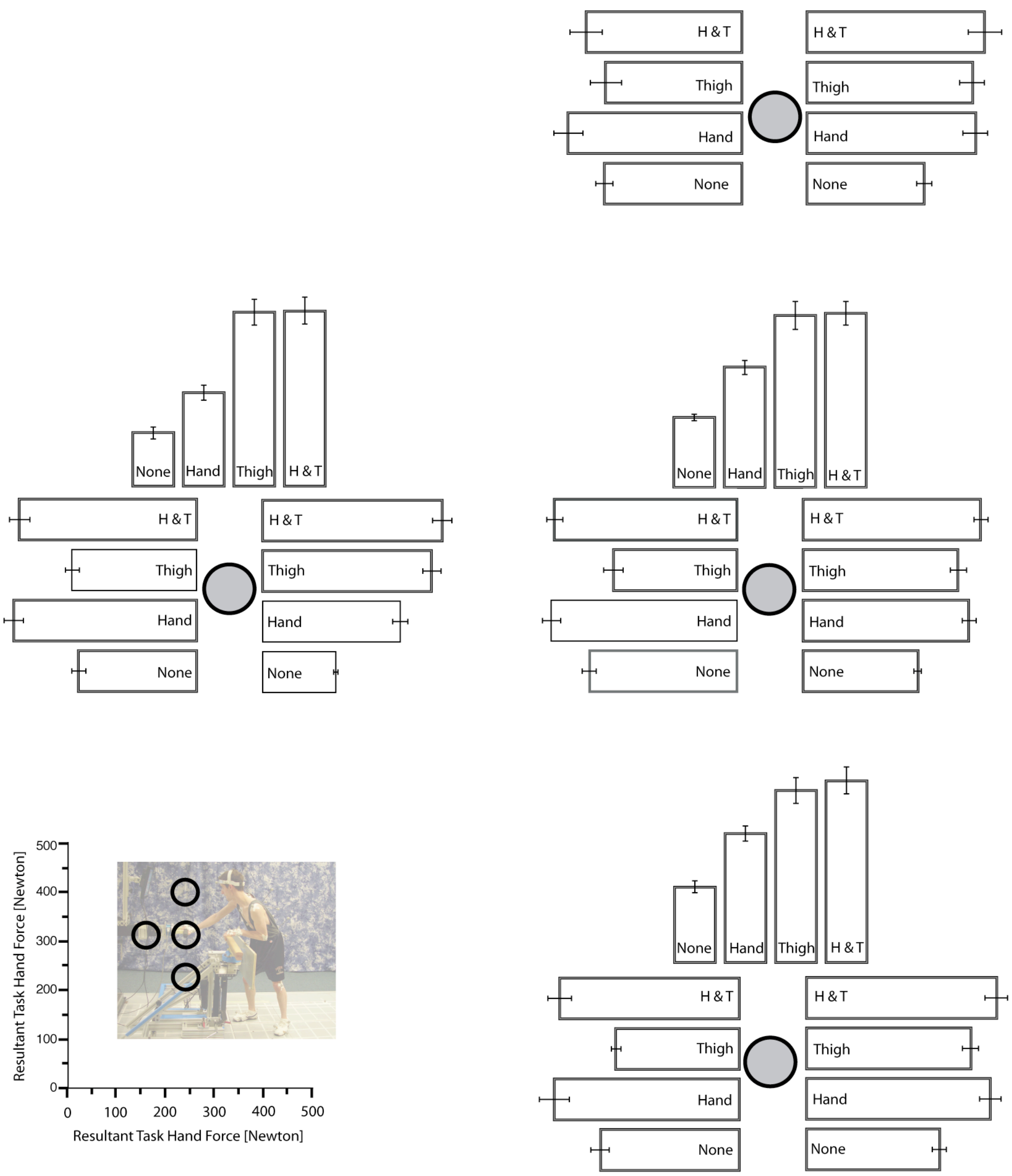

Figure 3.4.1 Mean (standard error) magnitude of mean resultant task hand force vector, expressed as an absolute force [Newton] with bars of mean forces oriented in the direction of the requested force across all levels of bracing availability. Each error bar is constructed using 1 standard error from the mean. None– denotes No Brace condition; Hand – denotes Hand Only; Thigh – denotes Thigh Only; H & T – denotes Hand & Thigh levels of bracing availability.

Backward Exertions

Backward exertions performed at the medium-close, medium-far and low task handle locations were found to have greater task hand force capability across all test conditions that afforded bracing. Resultant task hand force averaged 363 (SD = 95) N for backward trials that involved some level of bracing, as compared to 242(45) N during the No Brace condition (Figure 3.4.1). No significant differences were observed between Hand Only, Thigh Only and Hand & Thigh bracing conditions across all of the task handle locations, with the exception of trials performed at the high handle height. The high task handle location was the only test condition that did not show an interacting effect between the vertical task handle height and bracing availability on task hand force exertion capability ($p=0.118$).

Forward Exertions

Additional bracing opportunities did not affect task hand strength during forward exertions across the range of vertical tasks handle heights. Change in the fore-aft task handle location did, however, yield mean task hand force differences between No Brace and Thigh Only bracing conditions, in comparison to the Hand Only and Hand & Thigh conditions. On average, test conditions that involved hand bracing were observed to average 365(104) N, while No Brace and Thigh Only bracing availability levels averaged 270(69) N (Figure 3.4.1). No significant differences were found between levels of bracing availability for the high task handle height ($p<0.21$).

Upward Exertions

Task hand force capability differed with levels of bracing availability for upward exertions performed at the medium-close, medium-far, and low task handle locations. Specifically, bracing conditions that involved oppositional forces to be generated at the thigh (Thigh Only and Hand & Thigh) were found to have the greatest task hand force, averaging 341(109) N (Figure 3.4.1). Mean pair wise comparison determined that significant differences were also observed between the No Brace and Hand Only bracing conditions.

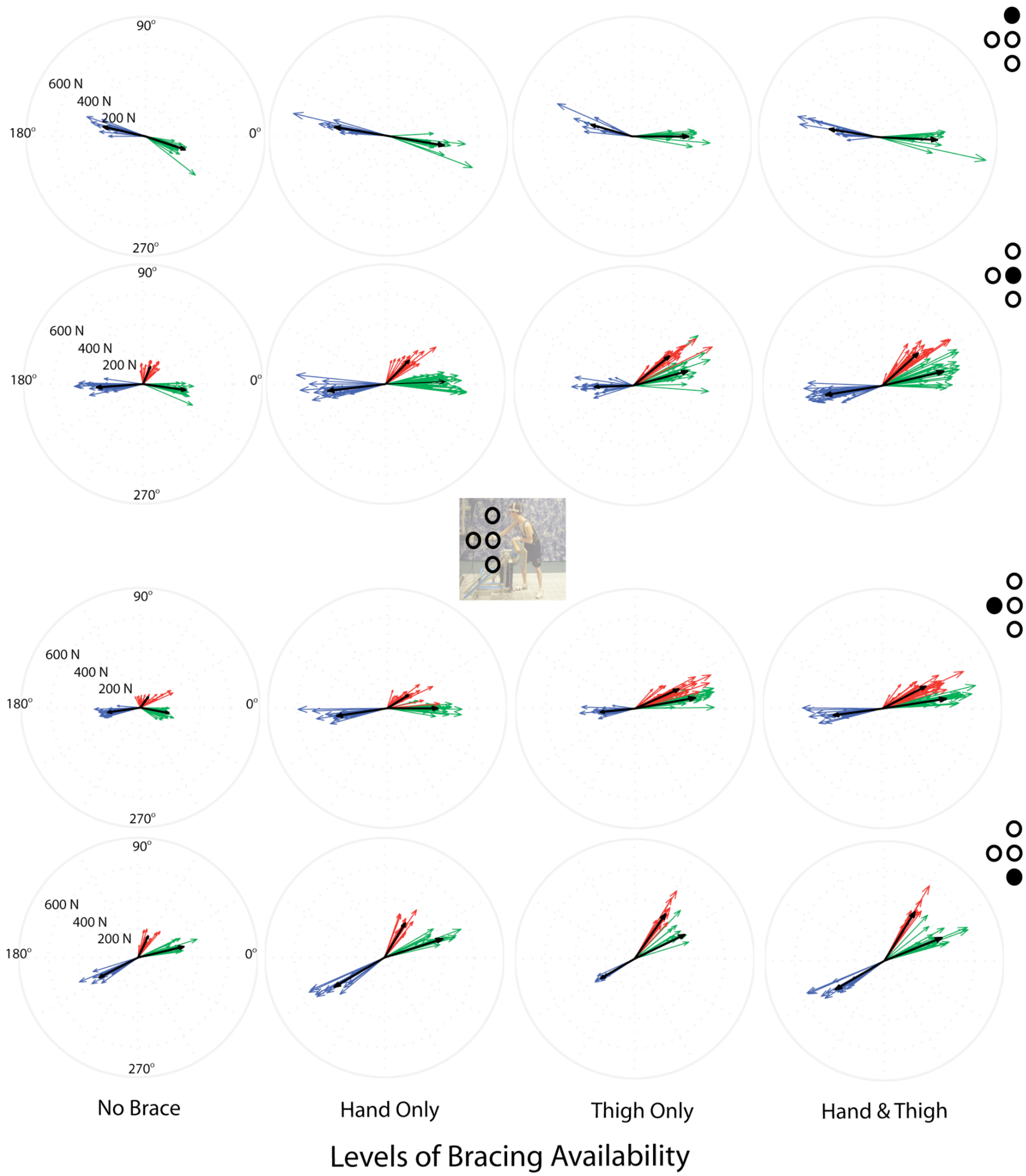

Figure 3.4.2. Task hand force magnitude [Newton] and direction with respect to nominal in the sagittal (XZ) plane [degree] across task handle locations and levels of bracing availability. Zero-degrees correspond to a nominal backward exertions (green vectors), 90-degrees correspond to nominal upward exertions (red vectors) and 180-degrees correspond to nominal forward exertions (blue vectors). Black vector denotes the mean resultant task hand force magnitude for respective nominal force direction and task handle location.

Task Hand Force Direction in the Sagittal (XZ) Plane

The distribution of task hand force vector directions across levels of bracing availability and task handle configurations are shown in Figure 3.4.2 and Figure 3.4.3. Means and standard deviations for mean task hand force direction across trial conditions are summarized in Table 3.4.1.

Backward Exertions

Backward exertions were characterized by a larger upward force at the low task handle height, followed by a transition to a downward oriented force vector at high handle height, with mean differences of 23(7) deg and -9(6) deg respectively.

Task hand force direction was observed to more closely associate with the nominal direction with increasing levels of bracing availability for backward exertions at the high task handle location. Thereby, the mean resultant vector transition from a downward oriented vector of -22(8) deg to -3(6) deg on average, for tasks performed with the No Brace and Hand & Thigh bracing condition respectively (Figure 3.4.3). For backward exertions performed at the medium task handle locations, the relative magnitude of the angular deviation of task hand force vector with respect to nominal did not change with bracing availability. However, a more downward directed task hand force vector was associated with No Bracing condition, while the task force vector transition to a more positive direction with the addition of bracing availability. For backward tasks at the low task handle, small increments of increased deviation with respect to nominal direction of the backward task hand force vector were observed between No Brace, Hand Only and Thigh Only bracing conditions, of 16(6), 21(5) and 32(9) degrees on average, respectively (Figure 3.4.3). However, there were no significant differences in the task hand direction when both hand and thigh bracing were permitted.

Forward Exertions

Forward exertions were observed to transition from a downward force vector of -30(4) deg at the low handle height to an upward task force direction of 11(6) deg for the high task handle location (Figure 3.4.3). At the medium handle height locations the task hand force direction was more closely oriented to the requested horizontal direction.

Bracing availability did effect orientation of the task hand force direction for the medium-close and high task handle locations. Hand bracing conditions, Hand Only and Hand & Thigh, were found to have greater directional deviation with respect to nominal (-9(6) deg), as compared to the No Brace and Thigh only conditions (-3(8) deg) at the medium-close task handle (Figure 3.4.3). The opposite trend was observed at the high task handle location, in that the task hand force direction was more closely associated to nominal with hand bracing (8(5) deg) versus no bracing (14(6) deg) conditions (Figure 3.4.3). No significant differences were observed between bracing conditions for the medium-far and low task handle locations (Figure 3.4.3).

Upward Exertions

Upward lifting exertions were observed to have significant differences between the No Brace and the remaining bracing conditions across all task handle locations (Figure 3.4.2). The trend was to increase the directional deviation of the task vector from nominal vertical with bracing availability. The mean direction upward force direction was observed to increase from 19(16) deg to 38(5) deg, from No Brace to bracing conditions, for tasks performed at the medium task handle locations (Figure 3.4.3). A similar trend was found at low task handle height in that the degree of directional deviation increased from 21(8) deg to 28(3) deg with respect to nominal vertical during upward exertions performed at the low handle height with additional bracing availability (Figure 3.4.3).

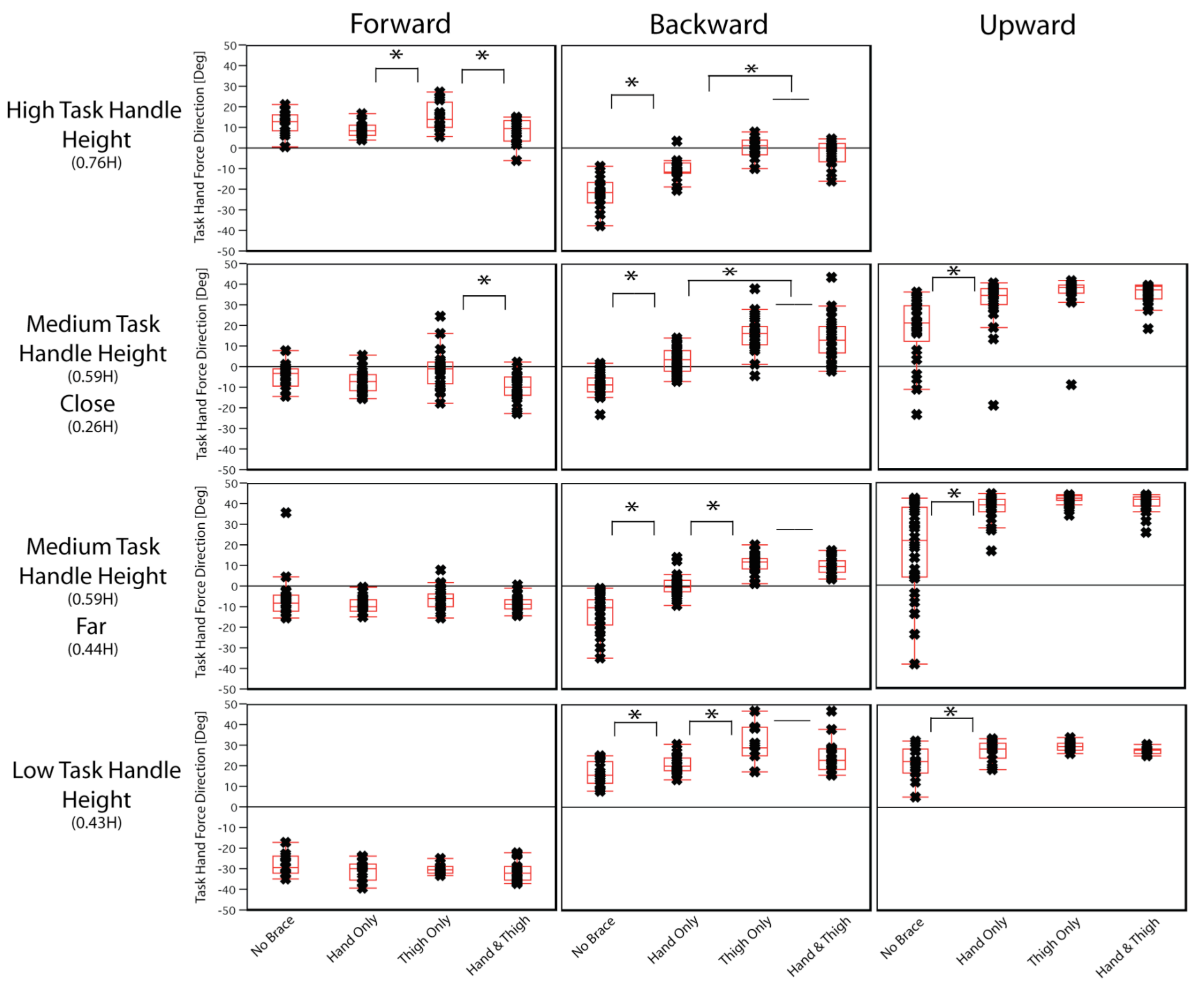

Figure 3.4.3. Mean direction [deg] of the task hand force vector with respect to the requested, nominal direction are shown as a function of bracing availability. Direction of task hand force is defined with respect to horizontal for forward and backward exertions (i.e. direction is + upward) and vertical for upward exertions (i.e. direction is + rearward, along x-axes). Asteriated brackets illustrate significant differences in pair-wise comparison of mean values.

Off-Axis Components

Mean off-axis task hand force components across trial conditions are presented in Figure 3.4.4 as a percentage of the mean requested on-axis task hand force component. Across all trial conditions the lateral force component (F_y) was found to be less than all other measured force components, 90% of lateral off-axis forces measured were less than 19% of the mean on-axis task hand force. The overall lateral off-axis force component average was equal to approximately 9(9)% of the mean on-axis task hand force component.

During both forward and backward force exertions the mean resultant task hand force was found to closely approximate the mean on-axis task hand force, averaging 105(6)% of the mean on-axis task hand force. Forward trials did not reveal significant increases in the vertical off-axis task hand force fraction of on-axis task hand force as a function of bracing availability. On average, backward trials observed a significant increase in vertical off-axis force component with increasing levels of bracing. The relative contribution of the off-axis forces varied with exertion handle locations, with the largest vertical (F_z) component found at the low task handle location, averaging 44% (percent of on-axis force) during backward trials and 58% (percent of the on-axis force) during forward exertions. The high task handle location was the only exception, in that there was a decrease in off-axis force with bracing availability (Figure 3.4.4).

In contrast, the mean resultant task hand force was found to exceed the requested vertical on-axis task hand force, averaging 166 (63)% (percent of on-axis force) across all upward exertion trial conditions (Figure 3.4.4). The horizontal oriented, fore-aft off-axis forces were observed to increase with bracing availability at the medium-close and -far task handle locations. The largest fore-aft, off-axis force components were found during the braced medium-far task handle location, averaging 209% of on-axis upward force (Figure 3.4.4). Off-axis forces during upward lifting exertions performed at low height task handle location were found to be smaller at 60(10)% (percent of on-axis), with the magnitude of the vertical direction closely approximating the magnitude of the resultant task hand force vector, despite the levels of bracing available (Figure 3.4.4).

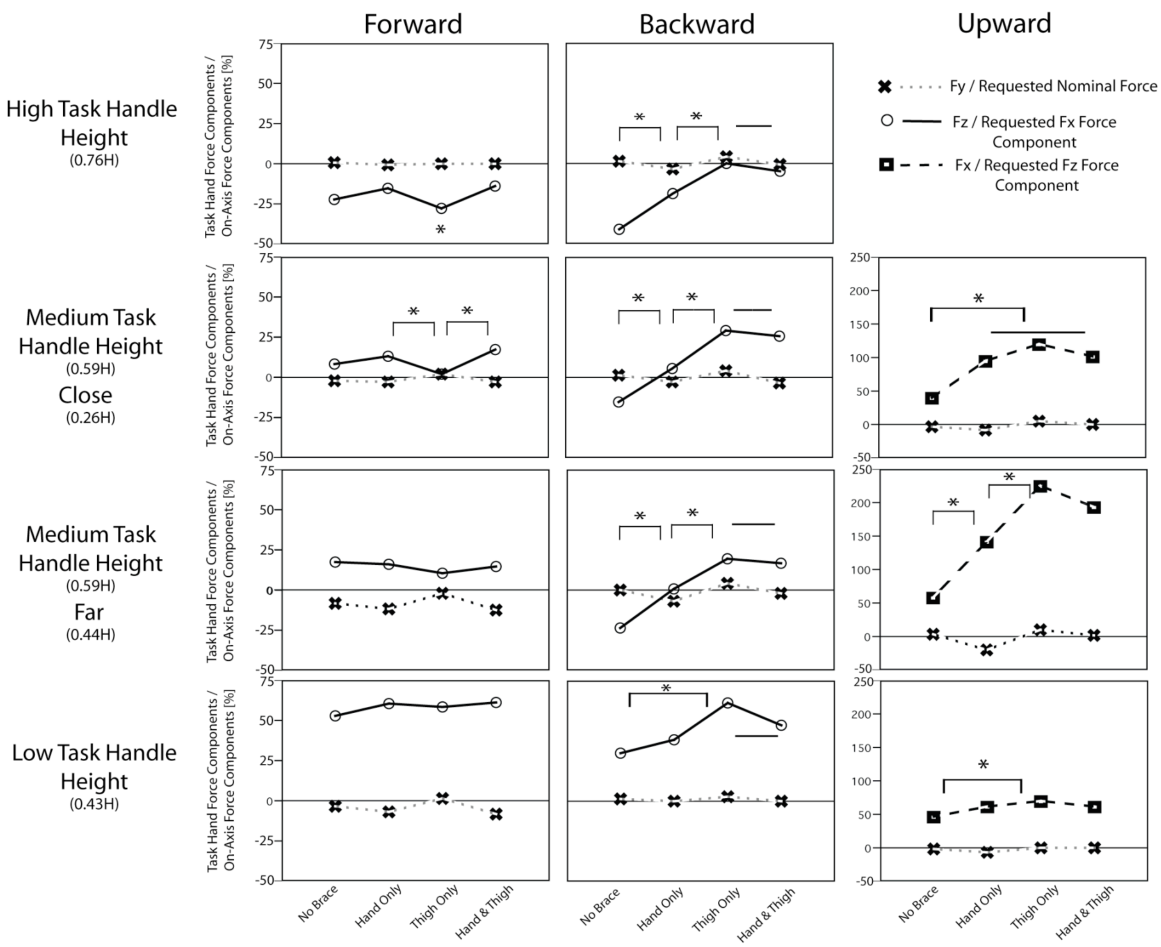

Figure 3.4.4. Mean force components along the off-axes (lateral and vertical for forward/backward exertions and fore-aft for upward exertions) with respect to the requested, nominal direction are shown as a function of bracing availability. Off-axis force components are expressed as a percentage of mean requested on-axis (nominal) task hand force component. Asteriated brackets illustrate significant differences in pair-wise comparison of mean values.

3.5. Discussion

Bracing with the contralateral hand and/or thighs significantly increased one-hand force exertion capability. Substantial off-axis forces were observed, consistent with previous studies (de Looze et al., 2000; Hoffman et al., 2011). Importantly, both the magnitude and direction of task hand forces changed with varying levels of bracing availability (Figure 3.4.2).

Backward Exertions

For backward exertions, forces exerted at both the contralateral hand support and thigh provided opportunities to generate opposing forces, which could then increase force-exertion capability. Indeed, all of the bracing conditions resulted in task hand force exertion capability that was 36% greater than task hand force generated during the No Brace condition for backward tasks at the medium and low task handle heights. Changes in the direction of the task hand force vector may also be indicative of postural behaviors adopted to increase task exertion capability.

Forward Exertions

Task hand force exertion capability was increased with contralateral hand bracing by 24%. As postulated by Dempster (1958) in these latter condition the contralateral hand provided the only oppositional force, therefore it is plausible that the upper extremities formed a closed chain which create a single joint and line of action, thus minimizing the off-axis deviations. Thereby, forward exertions did not show any significant differences in task hand force direction or vertical off-axis force contribution as a function of bracing availability for trials performed at the medium and low task handle heights. However, the transition of the direction of the task hand force vector from downward when pushing on a fixed handle at or below pelvic height to upward when pushing on the higher task handle height was akin to the effect of task handle location observed during push tasks performed in unconstrained environments (Chaffin et al, 1983; de Looze et al. 2000; Hoffman et al, 2011).

Upward Exertions

Upward exertions performed with bracing availability resulted in the most significant increase in force-exertion capability, averaging a 62% increase in task hand force production relative to No Brace condition. The bracing structure provided participants the opportunity to generate opposing, compensatory forces relative to upward exertions performed at medium and low task handle locations. A substantial rearward, horizontally oriented off-axis force of 62% on average was also observed during upward lifting with bracing availability. The low task handle location resulted in the largest for-aft off-axis forces, which can be explained in part by the kinematic difficulty of this task. This change in direction of the resultant rearward force vector with task handle height is consistent with vectors quantified by Grieve and Pheasant (1981) for maximal exertions. Bracing availability affords participants the opportunity to direct the task hand force direction in a deviated direction in order to increase force-exertion capability in the requested direction, similar to the strategies observed in unconstrained conditions (Hoffman et al., 2008).

It is noteworthy, that task hand force capability did not differ as a result of bracing availability, for backward or forward exertions performed at the high task handle height. Exertions at the high handle height were also characterized by a smaller directional deviation from nominal with addition of bracing availability. It is plausible that the height differential between the forces generated at the shoulder task handle and compensatory forces at the bracing structure reduced the number of kinematically feasible postures, and limited the extent to which the bracing structure may afford the opportunity to generate compensatory forces and moments that are aligned with the task hand. Further analysis of the postural behaviors associated with the force exertions performed at the high task handle location may provide insight into the lack of significant difference between levels of bracing availability during nominal push and pulls.

Consistent with the initial hypotheses, increase in task hand force was attributed to increasingly levels of bracing availability, resulting in statistically significant differences in task strength capability between bracing conditions. The increase in force-exertion capability observed in these data is generally consistent with other research that has shown that bracing against external structures can increase maximal force exertion (Gaughran and Dempster, 1956). Kroemer (1974), moreover, found that forces were highest when pushing with the back and feet braced against a wall, with the legs completed extended, or with the shoulders against a wall and arms held straight forward.

Unconstrained task hand force exertion capability is derived from postural strategies that make use of body balance and the available co-efficient of friction (CoF) at the feet (Grieve and Pheasant, 1981; Pheasant et al., 1982; Hoffman et al, 2008). Force-exertion capability in this study was limited by the bracing structure, which acted as an obstruction that imposed a kinematic constraint on the task postures and restricted the body mass location relative to the base of support. The existence of a bracing structure also enabled subjects to modify postural behaviors and effectively assist a person in performing maximal exertions. Bracing also provided additional compensatory forces and moments, beyond those available at the feet. On balance, the bracing forces demonstrated in this study allowed postural strategies that increased task hand force exertion, and in doing so may actually reduced the loading in certain "high risk" joints, such as the shoulder and low back.

Application

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 ergonomic and biomechanical analyses. It is obvious from the results that the constraints imposed by task configuration; particularly where access restricts reach distance to the task hand and the surfaces available for bracing, effect the force-exertion capability. However, no workplace is without constraints.

Limitations

The current analysis is limited to the effect of bracing on task hand force magnitude and direction. Further quantification and modeling of the kinematic and biomechanical variables in the subsequent chapters will assist in defining the underlying biomechanical principles that affect postural adjustments in relation to kinematic constraints during forceful exertions.

Application of the trial conditions to the industrial workplace is limited in that maximal exertions are not common. The current analysis would benefit from incorporating sub-maximal force magnitudes that are more common in industrial tasks. This experiment was also conducted with a fairly small number of subjects, but the force-exertion behaviors were reasonably similar across subjects between the conditions of bracing availability. Utilizing experienced workers, with more variable anthropometric statistics, may have produced different results.

3.6. Conclusions

This study provides a detailed and systematic quantitative analysis of how maximal isometric one-hand force exertion magnitude and direction are significantly affected by a structure that imposed a kinematic constraint upon which body bracing could achieved. When permitted to do so, subjects braced with their hands and thigh in ways that increased force-exertion capability. Task hand exertions that are performed in the absence of such bracing availability are derived from body and ground reaction force only. Oppositional forces generated at both the contralateral hand and body-bracing surface enabled an increase in resultant task hand force magnitude and off-axis forces. Such bracing also was found to significantly modify the direction of task hand forces for a wide range of force directions and task handle locations.

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CHAPTER 4

CLASSIFICATION OF FORCE-GENERATION STRATEGIES

4.1. Abstract

Obstructions and kinematic constraints within a task configuration provide an opportunity for additional support by bracing with the contralateral hand, thigh or other body part. However, given the inherent variability within human behavior, people with similar body size may adopt different bracing force strategies and postures to enhance task performance capability within a kinematically constrained space. The effect of bracing on task-exertion capability provides a template for a multinomial classification approach to evaluate and classify bracing forces. Bracing forces were decomposed into opposing and non-opposing components and normalized relative contribution to the generation of task hand force. Patterns of bracing were termed force-generation strategies (FGS). An FGS classification identifies the bracing forces (contralateral hand and/or thigh) and whether the thigh force is aligned or opposed with respect to the task hand force vector. Subjects braced with their hands and thighs in five distinct FGS that increased force-exertion capability by 44%, 14% and 60% across nominal backward, forward and upward exertions relative to the no brace (NB) FGS, respectively. FGS were associated with significant differences in both opposing and non-opposing components of normalized contralateral hand- and thigh-bracing forces during nominal backward and upward exertions across task handle locations and force exertion levels. In contrast, bracing forces generated during nominal forward exertions did not vary as a function of FGS.

4.2. Introduction

Chapter Three affirmed that bracing with the contralateral hand and/or thighs significantly increased one-hand force exertion (task strength) 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. Importantly, both the magnitude and direction of task hand forces changed with varying levels of bracing availability.

Quantification of bracing forces and support of body weight on environmental constraints is largely unaccounted for in the literature. A limited number of studies have expressed forces exerted at the contralateral support hand as a percentage of body weight. Lardi and Frazer (2003) determined that the magnitude of force exerted at the support hand, which ranged from 10% to 15% of body weight, was dependent upon magnitude of torso inclination relative to vertical. Godin et al. (2008) evaluated forces exerted at a prescribed location, as a percentage of body mass for a small subset of one-handed automotive assembly tasks. Supporting hand load forces were observed to range from 5.5% to 12.1% of body mass across four individual working postures and task conditions (Godin et al., 2008). For both of these studies, subjects were instructed to reach to the task hand location, but the task hand exerted no force or load.

Obstructions and kinematic constraints within a task configuration limit the postures that can be achieved. However, given the inherent variability within human posture and behaviors, it is plausible subjects of similar body size may adopt different bracing force strategies and postures to enhance task performance capability within a kinematically constrained space. Investigation of bracing forces, exerted at the contralateral hand and thigh, and clarification of the contribution of each bracing force with respect to task hand magnitude may bear out that there are distinct patterns of force-generation strategies. It is in this spirit that the following data analysis was conducted.

Three of main strategies of exploratory data analysis include: 1) graphical representation, 2) provision of flexibility in viewpoint, and 3) intensive search for parsimony and simplicity. Visualization of the bracing data will be used to identify patterns of bracing force generation into two or more groups based on the proximity of the patterns. The result in that each bracing strategy is internally homogenous and highly heterogeneous with other bracing force-generation strategies (Hair and Black, 2000). In contrast to discriminant analysis, it *does not* require that the number of bracing strategies be specified a priori. Therefore, it seems a more appropriate technique for the current problem of interest (i.e. to identify patterns of bracing force at the contralateral hand and thigh).

The objective of this chapter is to identify, quantify, and parameterize the force-generation strategies employed during one-hand, isometric exertions with a range of bracing opportunities. An important goal of the current analysis is to differentiate between bracing forces that directly oppose the task hand force and those that provide postural support without provide a direct reaction to the task hand force. As an example, a subject pulling rearward on the bracing handhold while pushing forward on the task handle is obtaining an opposing force at the bracing handle. In contrast, a subject pushing downward on the bracing handhold while pushing forward on the task handle (a non-opposing bracing force) is interpreted as using bracing for posture support.

To that end, this chapter presents an approach to define a task-based coordinate reference system that enables the interpretation and evaluation of the contralateral hand and body bracing reactive forces and the classification of each as either **opposing** or **non-opposing** relative to task hand force.

The specific objectives of the current work are:

1. To define a theoretical framework for the evaluation of the relative contributions of bracing forces exerted at the contralateral hand and thigh with respect to task hand force exertion capability.

2. To develop objective criteria to differentiate patterns of bracing force generation during exertions.

3. To decompose bracing force vectors into opposing and non-opposing components relative to the task hand force vector.

The following hypotheses were formulated through review of the literature and were used to guide the data analysis and interpretation:

1. Nominal task hand force directions (i.e. forward, backward, upward) result in unique patterns of compensatory bracing force generation.

2. Task hand force exertion capability will be affected by the pattern and distribution of force generation at the contralateral hand and thigh.

3. Bracing forces at the contralateral hand will employ both opposing and non-opposing components in response to task configuration variables.

4. Body brcing at the thigh support will involve both opposing and non-opposing forces and the relative contribution of reactive forces exerted at the thigh support to task hand force-generation capability will be dependent on the nominal task hand force direction.

4.3. Methods: Data Analysis

Transforming Analog Data from Global Coordinates to Task Hand-Based Force Coordinate Reference Frame

A task hand force coordinate reference frame, defined by the x-axis of the actual task hand force vector in global coordinates, was determined for each trial. In general, this direction is different from the requested nominal direction. The task hand force coordinate frame x-axis is aligned with the global task hand force vector. The y-axis of the task hand force coordinate frame is defined by a cross product of the task hand force (x-component) with the global vertical z-axis, and hence is horizontal and perpendicular to the task hand force. The z-axis of the task hand force coordinate frame is the cross product of the x and y-axes. The rotation matrix mapping the global task hand force vector and global bracing forces to the 3D space was used to map the data to the task hand–based force coordinate reference frame (Figure 4.3.1).

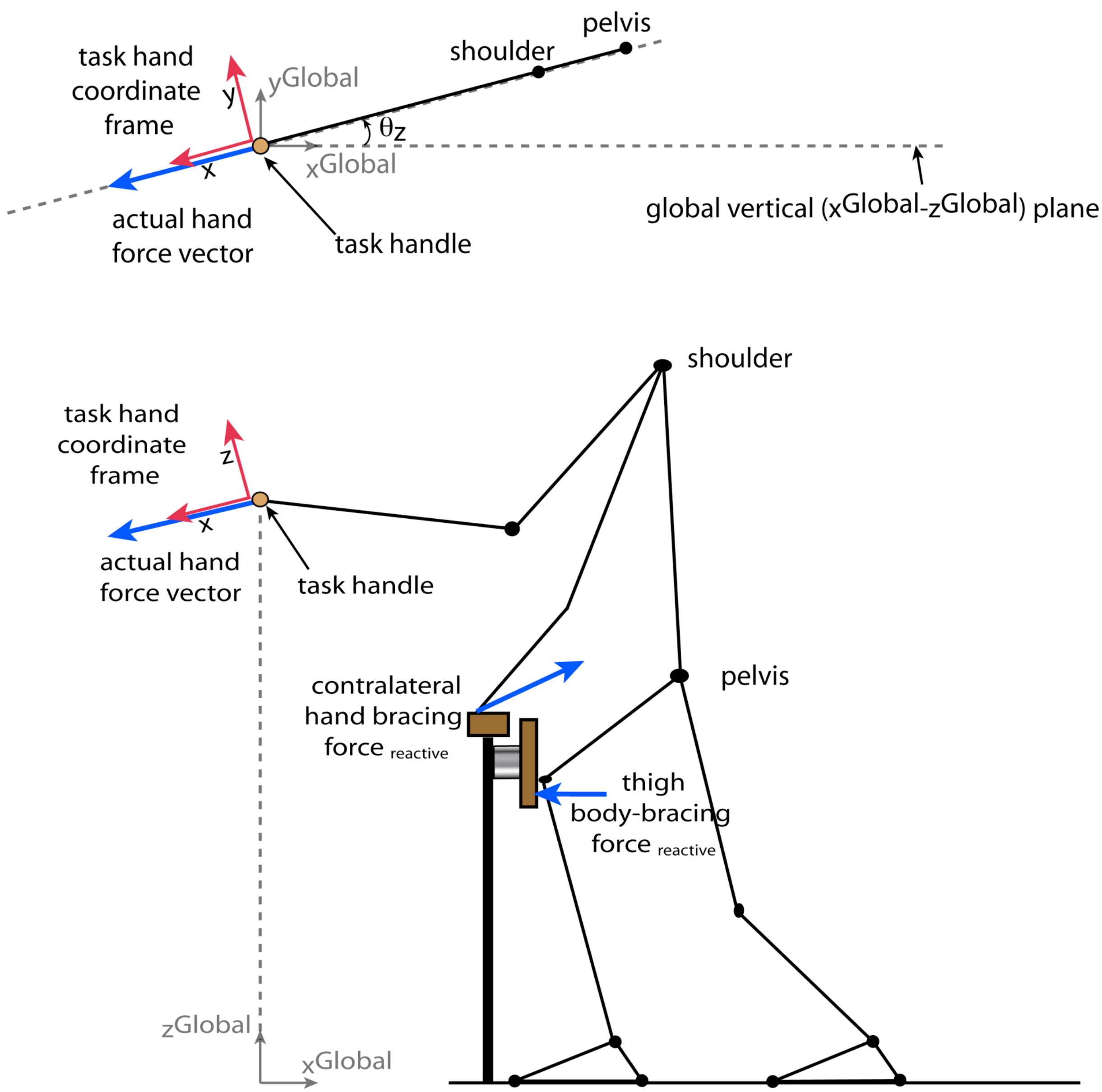

Figure 4.3.1 Visual depiction of transformation from global coordinate system to task hand coordinate frame. Top and side-view of the laboratory experiment. Transformation between the global and task hand coordinate frames in performed by the x-axis of the actual task hand force vector in global coordinates. The y-axis of the task hand force coordinate frame is defined by a cross product of the task hand force (x-component) with the global vertical z-axis, and hence is horizontal and perpendicular to the task hand force. The z-axis of the task hand force coordinate frame is the cross product of the x and y-axes.

Normalization of Bracing Forces to the Resultant Task Hand Force Vector

In an effort to develop a method for representing and classifying the force-generation strategies adopted during isometric bracing tasks all reactive forces were normalized to the task hand force. Normalization relative to the task hand force magnitude enables all compensatory forces to be parameterized and expressed as:

(i) *Opposing component*: percentage of task hand force that is opposed by the bracing force.

(ii) *Non-opposing component*: force normal to the task hand force direction as a fraction of task hand force.

This quantitative approach to force analysis illustrates unique load distribution strategies and compensatory force employment strategies across all task configuration variables. To this end, relative force contribution plots were created for each trial to categorize and visualize force-generation strategies (Figure 4.3.2).

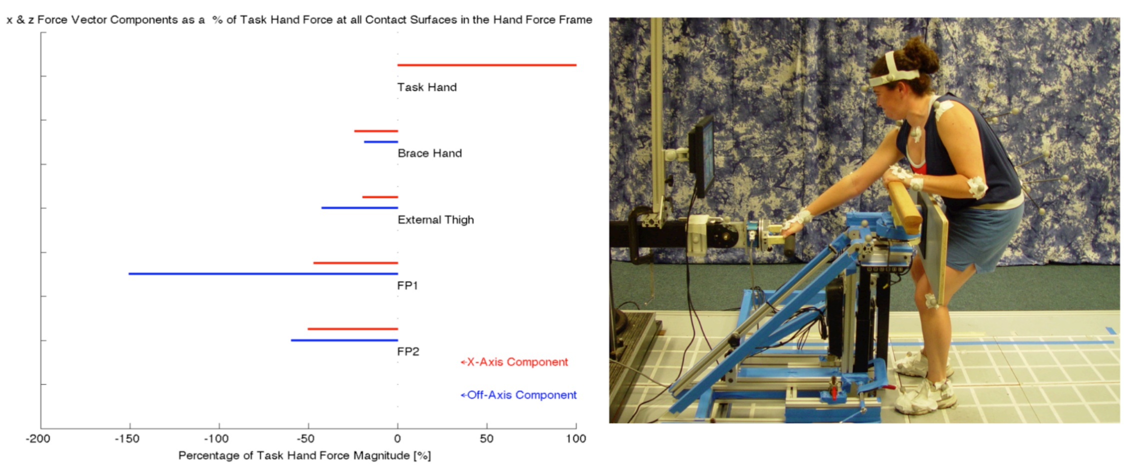

Figure 4.3.2. Representative trial illustrating the classification of reaction forces, expressed as a fraction of resultant task hand force magnitude. Red bars indicate the opposing or on-axis component and blue bars indicate the non-opposing or off-axis component of reactive forces at the contralateral hand, thigh and ground reaction forces each expressed as a fraction of the task hand force magnitude.

Multinomial Classification of Bracing Force-Generation Strategies

Bivariate plots of the opposing components of the contralateral hand and thigh bracing forces, normalized to the magnitude of the resultant task hand force within the task hand coordinate reference frame, were generated to visualize the distribution of bracing forces. Bivariate analyses conducted with JMP statistical software package version 9.0 (SAS, Cary, NC) are based upon the assumption that the data is normally distributed. Multinomial classification of the data into discrete groupings involved fitting parametric bi-ellipsoids. Given that normalized bracing forces data were not normally distributed, such parametric techniques truncate the tails of bracing force distribution. Bagplots provided an alternative method that is a 2D generalization of the box plot, which enables non-parametric fitting of the data into discrete groupings.

Bagplots, a bivariate generalization of the univariate boxplot, were used to visualize the distribution of data points from various conditions and identify force-generation strategies. The nonparametric bagplot is ideal for this purpose because the data do not follow a symmetric distribution. The key notion of a bagplot is the halfspace depth of a point relative to a bivariate dataset, which extends the univariate concept of rank. In two dimensions, the halfspace depth of a bivariate dataset is the minimum number of points (as a fraction of the total number of points) that lie on either side of a line passing through the point. The depth median is the point with the largest halfspace depth (by definition 0.5) is the deepest location that is surrounded by a bag containing the 50% of the points with the greatest halfspace depth. Observations lying outside a fence obtained by magnifying the box by a factor of 3 (analogous to the whiskers on a box plot) are flagged as outliers (marked as stars). The bagplot visualizes the location, spread, correlation, skewness, and tails of the data (Rousseeuw et al., 1999).

Analysis of variance also was used to test each of the hypotheses and to determine the significant main and interaction effects for each nominal task hand force direction and corresponding force-generation strategies. Post-hoc Tukey tests were then performed on significant main effects to compare bracing force contribution between task handle location; force direction and bracing availability for which an alpha level of 0.05 was adopted for all mean pair-wise comparisons. Analysis of variance was conducted using the JMP statistical software package version 9.0 (SAS, Cary, NC).

For the current analysis, force measures were presented as the resultant task hand force magnitude and opposing and non-opposing components of the contralateral hand and thigh bracing forces, normalized to the magnitude of the resultant task hand force within the task hand coordinate reference frame.

4.4. Results

Classification of Force-Generation Strategy

Based on an exploratory analysis using bagplots and other techniques, 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 hand or thigh except at the feet.

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

(iii) *Hand & Thigh Bracing-opposed* (HTB-o): 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).

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

(v) *Hand & Thigh Bracing-aligned* (HTB-a): 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).

A force-generation strategy (FGS) classification identifies the bracing forces (hand and/or thigh) and whether the thigh force is aligned or opposed. The classification of the force-generation strategies across the nominal task hand force directions can be visualized in Figure 4.4.2.

Multinomial classification of the force-generation strategies (FGSs) was achieved using bagplots. Bagplots provided an alternative method to visualize the distribution of the data into spaces and identify discrete, groupings of normalized bracing force data. Bagplot techniques enabled non-parametric fitting of normalized bracing force data into discrete groupings of force-generation strategies (FGSs) and within task handle locations (Figure 4.4.2). Consider the bivariate scatter plot in Figure 4.4.1. The depth median, the point with the highest halfspace depth, of trials performed at each task handle configuration lies in the center of the color-coded bag and is indicated by a cross. The bag is the polygon drawn as a full line (black), with task handle location color-coded fill interior. The observations that lie outside the bag but inside the fence are also coded-coded for each respective task handle location. The fence itself is not plotted in the bagplots presented in this chapter because it would draw the attention away from the data. Black asterisks for all trials indicate outliers that are outside the fence. Given that the bagplot is showing dataset from four discrete task configurations (high, medium-close, medium-far and low task handle locations) in one graphical representation, overlapping of the dataset resulted. For instance, for trials performed at the high task handle location the bag are plotted purple, whereas for the trials performed at the medium-close task handle location the bag are plotted red. Therefore, for trials that are within overlapping region, the bag is plotted pink.

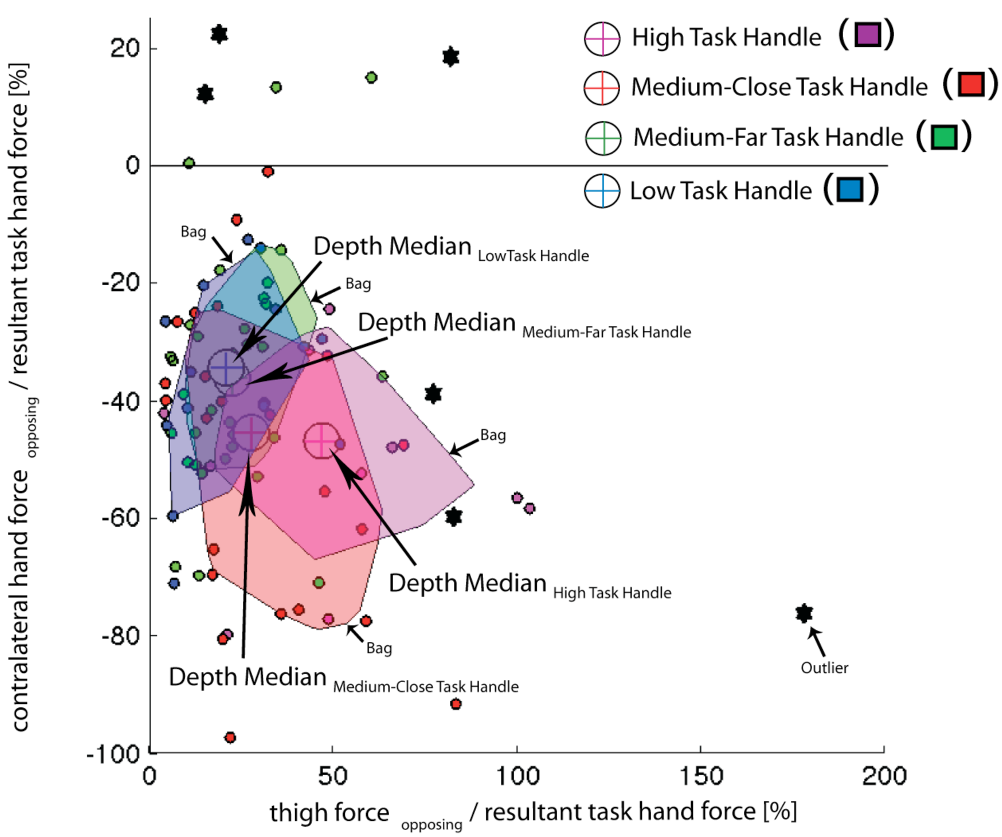

Figure 4.4.1 Bagplot depicting the opposing component of normalized contralateral hand bracing and thigh bracing (percentage of task hand force) across task handle locations during forward exertions within the HTB-a FGS.

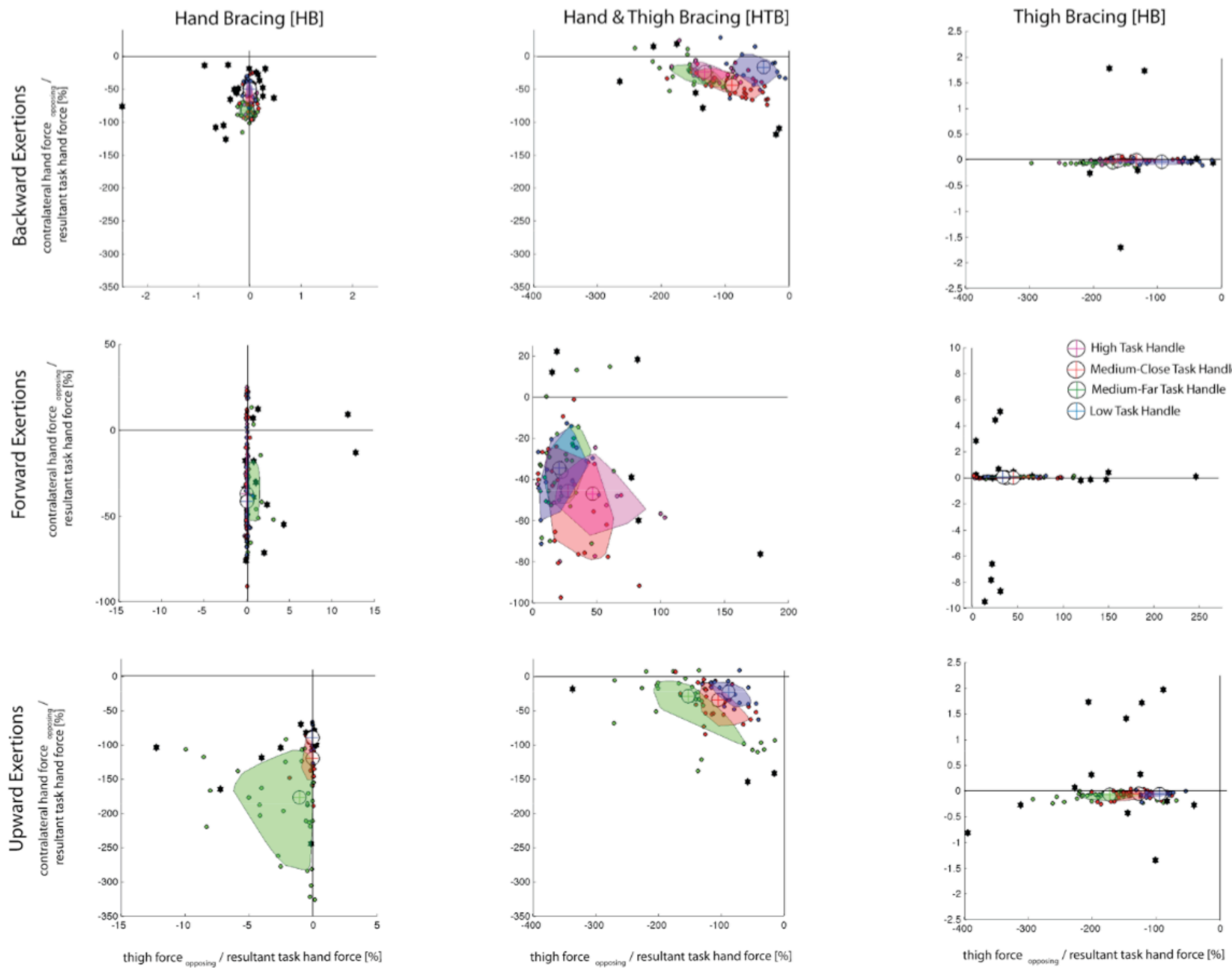

Figure 4.4.2 Bagplot visualization of the opposing component of normalized contralateral hand force with the opposing component of thigh-bracing force across nominal task hand force directions (i.e. backward, forward, upward) and within FGSs. Bagplot parameters include: the depth median defined by the circle and cross; spread of data indicated the color bag; circles denote inliers and stars denote outliers. All parameters are color coded by task handle location: purple – high; red – medium-close; green – medium-far; blue – low task handle locations.

Force-Generation Strategy Classification Criteria

Based on the qualitative analysis and graphical visualization described above (Figure 4.4.2), a set of simple quantitative criteria was developed to numerically categorize the multinomial force-generation strategy (FGS) classification observed in each trial. The 10 N threshold value was derived from the aforementioned multinomial classification of FGSs. The criteria are applied to the hand and thigh-bracing forces in the task-based coordinate frame. The criteria are:

NB Force-Generation Strategy:

$$\left| ContralateralBrace_{\text{Task Hand Coordinate Frame}}(1,3) \right| \leq 10\ \text{N} \;\; \&\& \left| ThighBrace_{\text{Task Hand Coordinate Frame}}(1,3) \right| \leq 10\ \text{N}$$

HB Force-Generation Strategy:

$$\left| ThighBrace_{\text{Task Hand Coordinate Frame}}(1,3) \right| \leq 10\ \text{N} \;\; \&\& \left| ContralateralBrace_{\text{Task Hand Coordinate Frame}}(1,3) \right| \geq 10\ \text{N}$$

TB Force-Generation Strategy:

$$\left| ContralateralBrace_{\text{Task Hand Coordinate Frame}}(1,3) \right| \leq 10\ \text{N} \;\; \&\& \left| ThighBrace_{\text{Task Hand Coordinate Frame}}(1,3) \right| \geq 10\ \text{N}$$

HTB-o Force-Generation Strategy:

$$\left| ThighBrace_{\text{Task Hand Coordinate Frame}}(1,3) \right| \leq -10\ \text{N}$$

HTB-a Force-Generation Strategy:

$$\left| ThighBrace_{\text{Task Hand Coordinate Frame}}(1,3) \right| \geq 10\ \text{N}$$

Prevalence and Distribution of Force-Generation Strategies

The bivariate mosaic plot in Figure 4.4.3 depicts the relationship between nominal task hand force direction (x-axis) and force-generation strategy (FGS) classification (y-axis) for trials with all surfaces available. The plot on the right in Figure 4.4.3 shows the observed FGS classification. The plot on the left has the distribution of FGS on the vertical axis and the nominal task hand force direction on the horizontal axis.

Across the task handle configurations and nominal task hand force directions there was a preference of the HTB-opposed FGS, as it was selected for 50% of the trials with all surfaces available. For backward exertions, the NB, TB, HB and HTB-o FGS were observed in 5%, 6%, 15% and 74% of the trials. In forward trials, the HTB-a and HB FGS were most prevalent across the task handle locations, at 62% and 29% respectively. Similar to backward trials, the most prevalent FGS was found to be HTB-o at 82% for upward task hand forces. Figure 4.4.3 shows distribution of classification of FGS across nominal task hand force directions, for trial in which contralateral hand and thigh bracing were available. The data are combined across task handle locations and task hand force exertion levels.

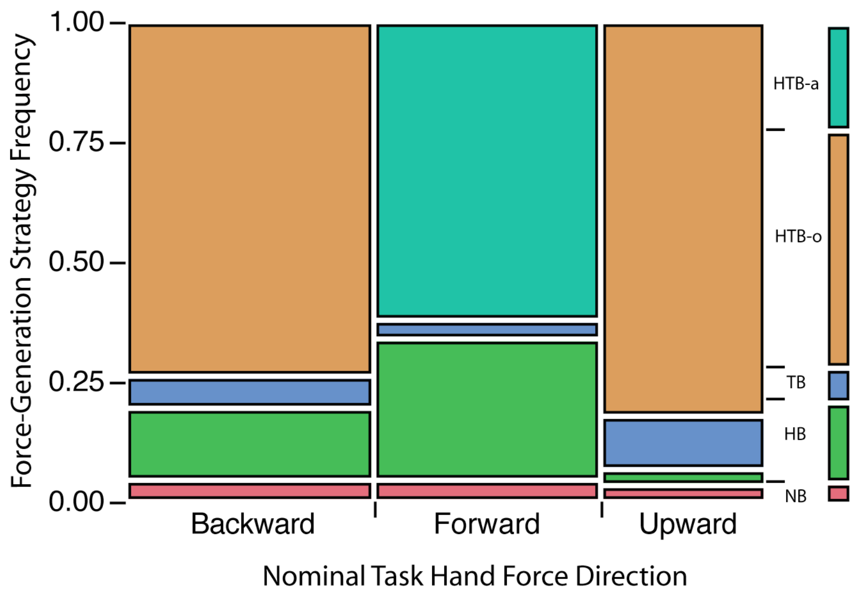

Figure 4.4.3 Mosaic plot of the distribution of the FGSs across the nominal task hand force directions for trials with both hand and thigh bracing available. The data are combined across task handle locations and force levels.

Task Hand Force Exertion Capability as a Function of Force-Generation Strategy

The effect of bracing availability on task hand force exertion capability was presented in Chapter Three. Consistent with this observation, FGSs that provide opposing forces were associated with higher task-hand forces. Figure 4.4.4 graphically depicts task hand force generation associated with each of the FGSs for the three nominal task hand force direction, across the entire data set. Task hand force exertion capability was observed to differ with FGS selection across the four task handle locations (color-coded), consistent with the level of bracing availability segmentation. As an example, subjects generated an average of 86 N in upward trials in which the NB FGS was observed. In trials with the HB FBS, the mean task hand force was 159 N. The addition of thigh bracing yielded significantly higher force-exertion capability of 238 N and 260 N on average, for TB and HTB-opposed FGSs respectively.

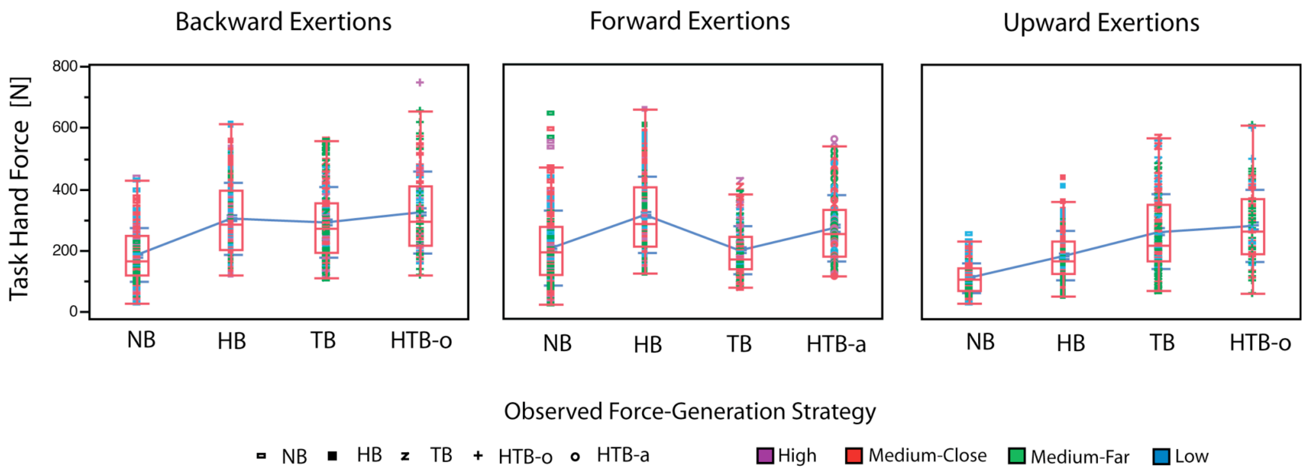

Figure 4.4.4 Variation of task hand force exertion capability [Newton] across nominal task hand force directions and between FGSs.

Quantitative Comparisons of Force-Generation Strategies

Backward Exertions

In backward trials with the HB FGS, the opposing component of contralateral hand bracing force averaged -63% (expressed as percentage of task hand force magnitude) compared with -33% for trials with the HTB-o FGS. The same trend was observed for the opposing component of thigh bracing, which was significantly greater for the TB trials, on average -147% versus -109% for HTB-o trials. Non-opposing bracing hand forces (that is, perpendicular to the task hand force direction) also differed between the two FGSs that employed hand bracing. Non-opposing bracing hand forces were generated at 42% and 23% of task hand force magnitude on average within the HB and HTB-a FGSs, respectively.

Hand-Bracing (HB) Force Generation Strategy

In HB trials, the magnitude of the opposing hand-bracing component averaged -60% at the medium-close handle position and -82% at the medium-far location (Figure 4.4.5).

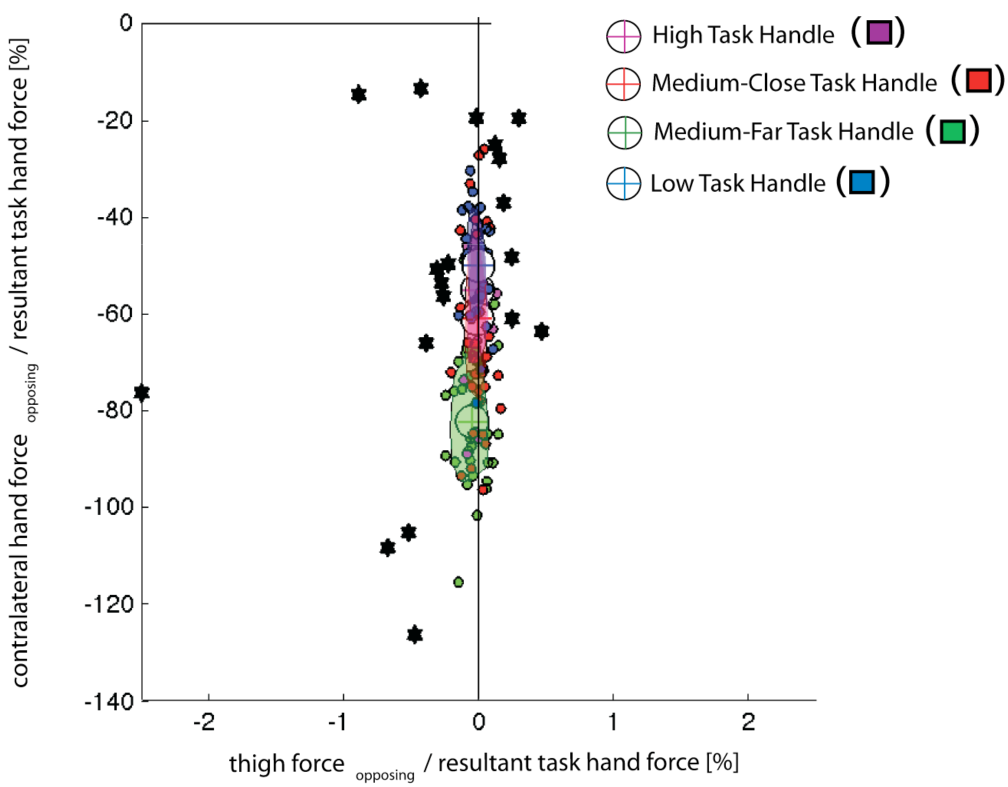

Figure 4.4.5 Change in the opposing component of normalized contralateral hand bracing (percentage of task hand force) across task handle locations within the HB FGS.

The relative contribution (magnitude) of the non-opposing component of hand bracing force was observed to increase with vertical task handle height (Figure 4.4.6). A positive correlation was observed between the non-opposing component of the contralateral hand force and handle height at the high, medium-close and low task handle locations.

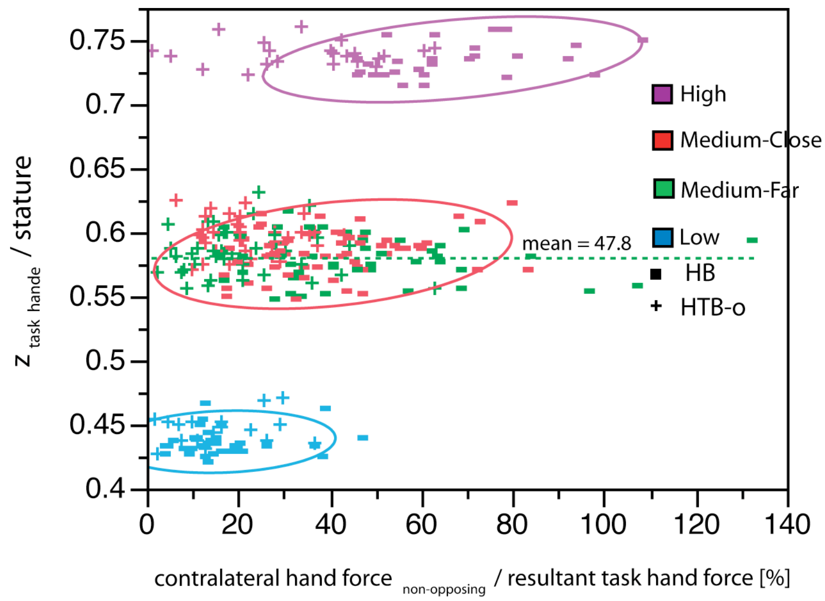

Figure 4.4.6 Variation in the non-opposing component of contralateral hand bracing force across task handle locations during backward exertions within the HB FGS. The ellipses denote the non-opposing component of hand bracing generated with the HB FGS at the individual task handle location.

Thigh-Bracing (TB) Force-Generation Strategy

In TB trials, change in the fore-aft horizontal task handle location resulted in significant differences in the magnitude of the opposing component of the normalized thigh bracing force, which averaged -130% at the medium-close handle position and -173% at the medium-far location (Figure 4.4.7). The vertical height of the task handle location also affected the thigh bracing force, as the opposing thigh bracing component averaged -90% at the low handle position and -152% at the medium height (Figure 4.4.7).

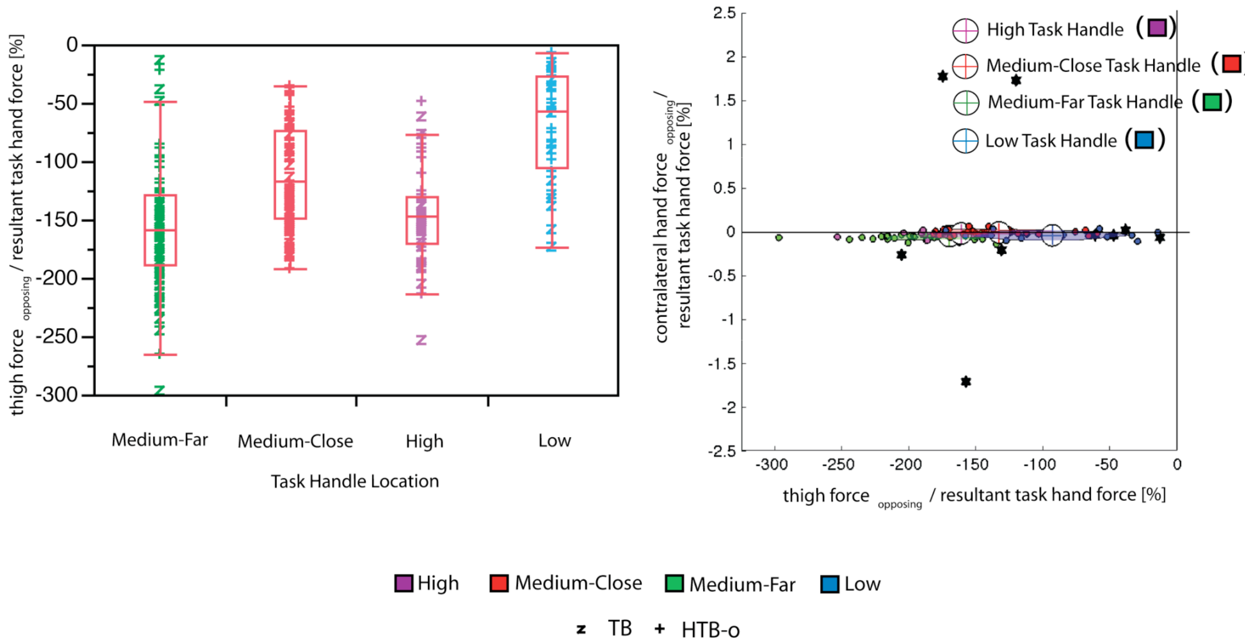

Figure 4.4.7 Change in the opposing component of normalized thigh bracing (percentage of task hand force) across task handle locations during backward exertions within the TB FGS.

The magnitude of the non-opposing component of the normalized thigh bracing force was substantially less than the opposing component, averaging 46% versus 147%. In TB trials, the degree of kinematic constraint significantly affected the magnitude of non-opposing component of thigh bracing which averaged 69% at the medium-close and low handle positions and 29% at the medium-far and high locations.

Hand Bracing & Thigh Bracing-Opposed (HTB-o) Force-Generation Strategy

In HTB-o FGS trials, the opposing component of the hand-bracing force averaged 50% less than the opposing component of the hand-bracing forces exerted during HB trials. The task configuration the imposed the least degree of kinematic constraint, the medium-close task handle position, was observed to have the highest magnitude of opposing component of hand-bracing force, at 44% of task hand force (Figure 4.4.8).

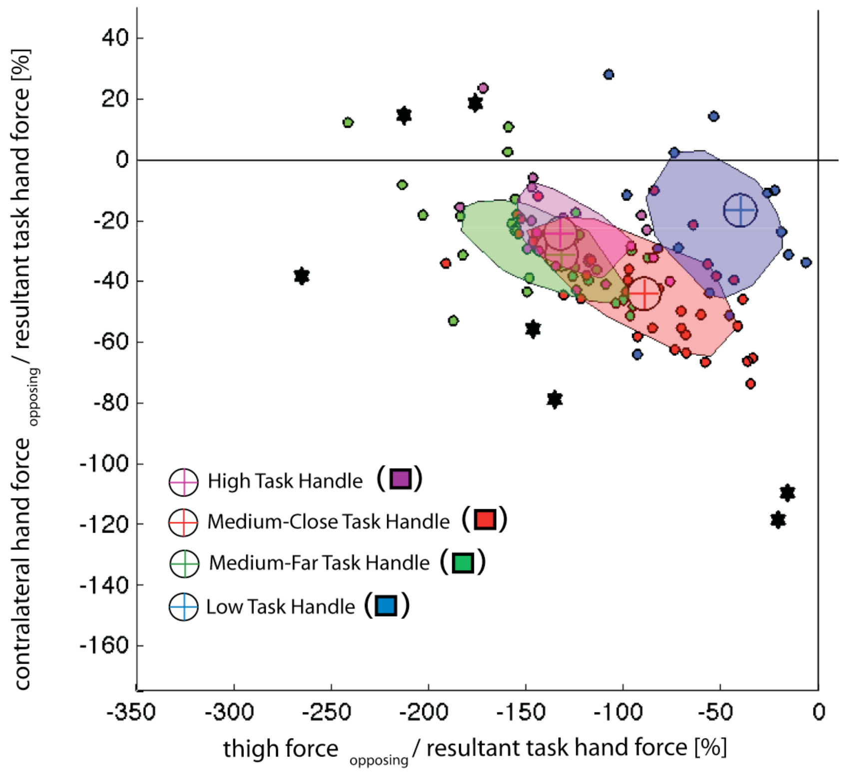

Figure 4.4.8 Bagplot depicting the opposing component of normalized contralateral hand bracing and thigh bracing (percentage of task hand force) across task handle locations during backward exertions within the HTB-o FGS.

The magnitude of the non-opposing component of the contralateral hand forces for HTB-o trials averaged 45% less than HB trials. Consistent with HB trials, the vertical task handle position was associated with an increase in the relative contribution of the non-opposing hand bracing force as the handle position transitioned from low to high. With an increase in task hand force level, a lower magnitude of the non-opposing contralateral hand force was found for HTB-o trials at the kinematically constrained medium-far task handle position.

The magnitude of the thigh-bracing force was substantially less as compared to TB trials. Consistent with TB trials, the degree of kinematic constraint affected the magnitude of the opposing component of thigh-bracing force, which averaged -137% and -129% at the medium-far and high task handle positions respectively and 40% and 74% at the medium-close and low handle positions.

Forward Exertions

In forward trials, there were no significant differences found in the magnitude of the opposing and non-opposing components of the normalized hand and thigh-bracing forces between HB, TB or HTB-a trials.

Hand-Bracing (HB) Force Generation Strategy

In HB, the magnitude of the opposing hand-bracing component averaged -35% across all task handle locations. Task hand configuration variables did not reveal any significant effect on the relative contribution of bracing forces at the contralateral hand. Increase in force level was associated with lower magnitudes of the opposing hand bracing across the task handle conditions (Figure 4.4.9).

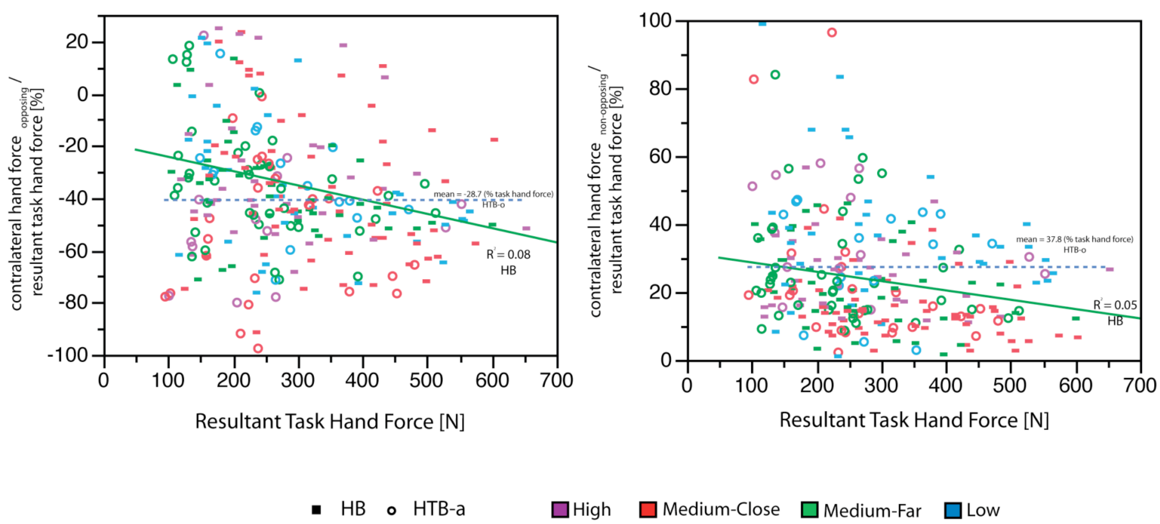

Figure 4.4.9 Relationship between contributory ($R^2 = 0.08$) and non-opposing ($R^2 = 0.05$) component of the normalized contralateral hand force with resultant task hand force during forward exertions performed with HB and HTB-a FGS.

Thigh-Bracing (TB) Force-Generation Strategy

In TB trials, there was no associated between task configuration variables and thigh-bracing forces, neither opposing nor non-opposing components. Increase force levels were associated with lower opposing thigh-bracing forces at the medium-far handle position, which imposed a kinematically constrained reach to the task handle for both TB and HTB-a trials (Figure 4.4.10).

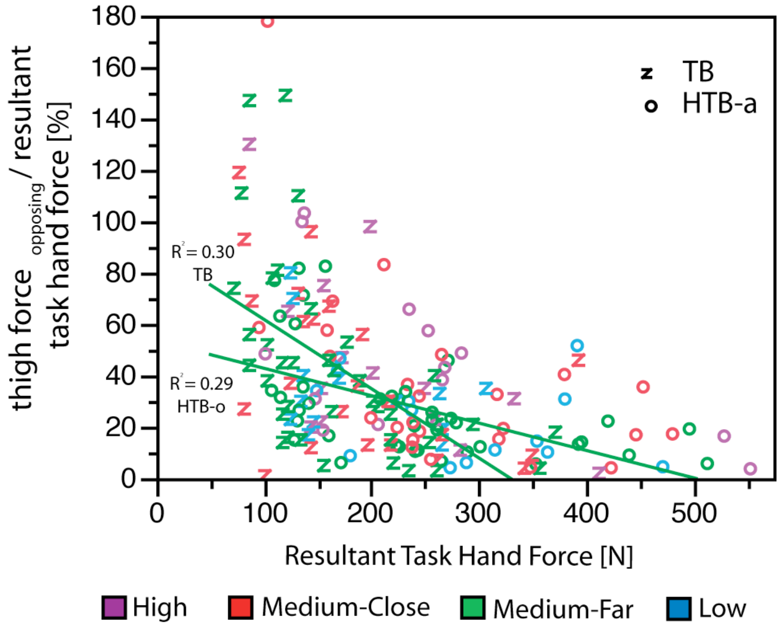

Figure 4.4.10 Change in the opposing component of normalized thigh force with resultant task hand force for forward exertions within TB (R^2 = 0.30) and HTB-a (R^2 = 0.29) FGS at medium-far task handle location.

Hand Bracing & Thigh Bracing-Aligned (HTB-a) Force-Generation Strategy

On average, the opposing component of hand-bracing force averaged -41% for the HTB-a FGS. Change in the fore-aft horizontal task handle location resulted in significant differences in the magnitude of the opposing component of the normalized hand-bracing force, which averaged -34 % at the medium-far handle position and -52% at the medium-close location (Figure 4.4.11).

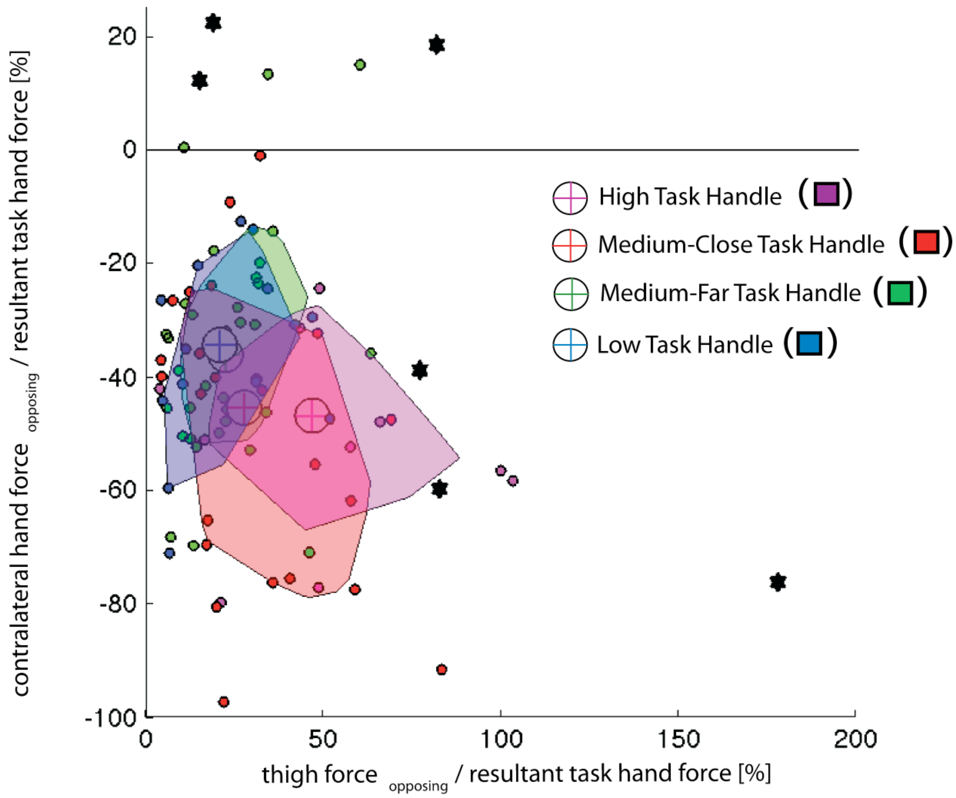

Figure 4.4.11 Bagplot depicting the opposing component of normalized contralateral hand bracing and thigh bracing (percentage of task hand force) across task handle locations during forward exertions within the HTB-a FGS.

The opposing component of thigh-bracing force averaged +32% for the HTB-a FGS. Task configuration variables were not associated with any significant differences in thigh bracing. Consistent with TB trials, increased force levels were associated with a lower opposing (+% of task hand force) thigh bracing at the medium-far handle position (Figure 4.4.11).

Upward Exertions

In upward trials with HB FGS, the opposing component of contralateral hand bracing force averaged -138% (expressed as percentage of task hand force magnitude), compared with -37% for HTB-o trials. The same trend was observed for the opposing component of thigh bracing which was significantly greater for the TB trials, on average -149% versus -123% for HTB-o trials.

Hand-Bracing (HB) Force Generation Strategy

In HB trials, the magnitude of the opposing hand-bracing component averaged -122% at the medium-close handle position and -182% at the medium-far location (Figure 4.4.12).

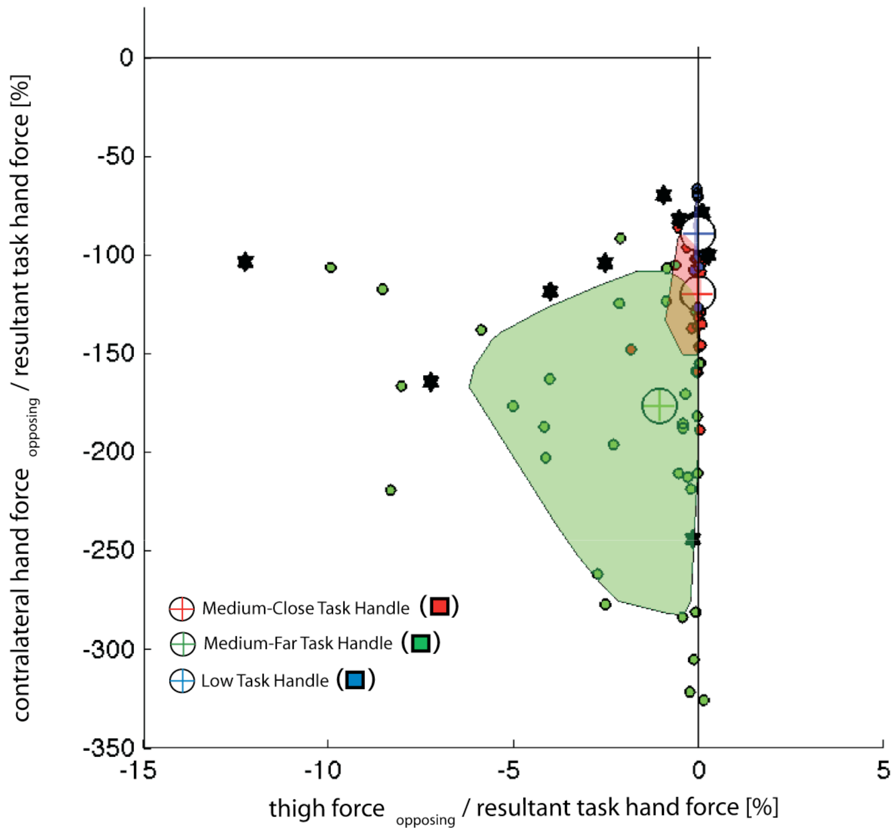

Figure 4.4.12 Bagplot depicting the opposing component of normalized contralateral hand bracing (percentage of task hand force) across task handle locations during upward exertions within the HB FGS.

Thigh-Bracing (TB) Force-Generation Strategy

In TB, the magnitude of the opposing thigh-bracing component averaged -149% across all task handle locations. Change in the fore-aft horizontal task handle location resulted in significant differences in the magnitude of the opposing component of the normalized thigh bracing force, which averaged -128% at the medium-close handle position and -182% at the medium-far location (Figure 4.4.13). The vertical height of the task handle location also affected the thigh bracing force, as the opposing thigh bracing component averaged -98% at the low handle position and -128% at the medium height (Figure 4.4.13).

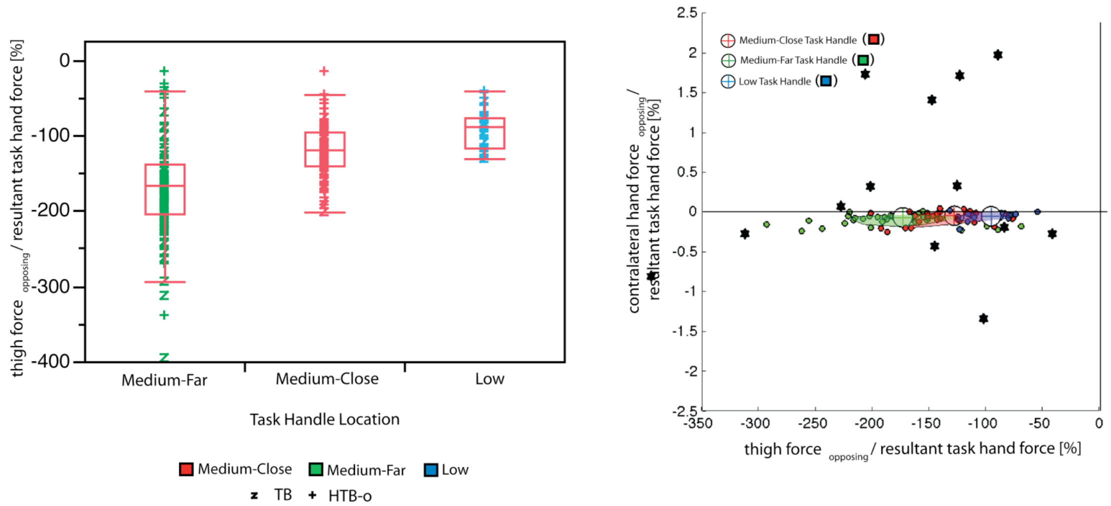

Figure 4.4.13 Change in the opposing component of normalized thigh bracing (percentage of task hand force) across task handle locations during upward exertions within the TB FGS.

Hand Bracing & Thigh Bracing-Opposed (HTB-o) Force-Generation Strategy

In HTB-o FGS trials, the opposing component of the hand-bracing force averaged 73% less than the opposing component of the hand-bracing forces exerted during HB trials. The only task configuration effect observed was an interacting effect with an increase in task hand force level that was associated with higher opposing bracing hand forces at the low task handle position.

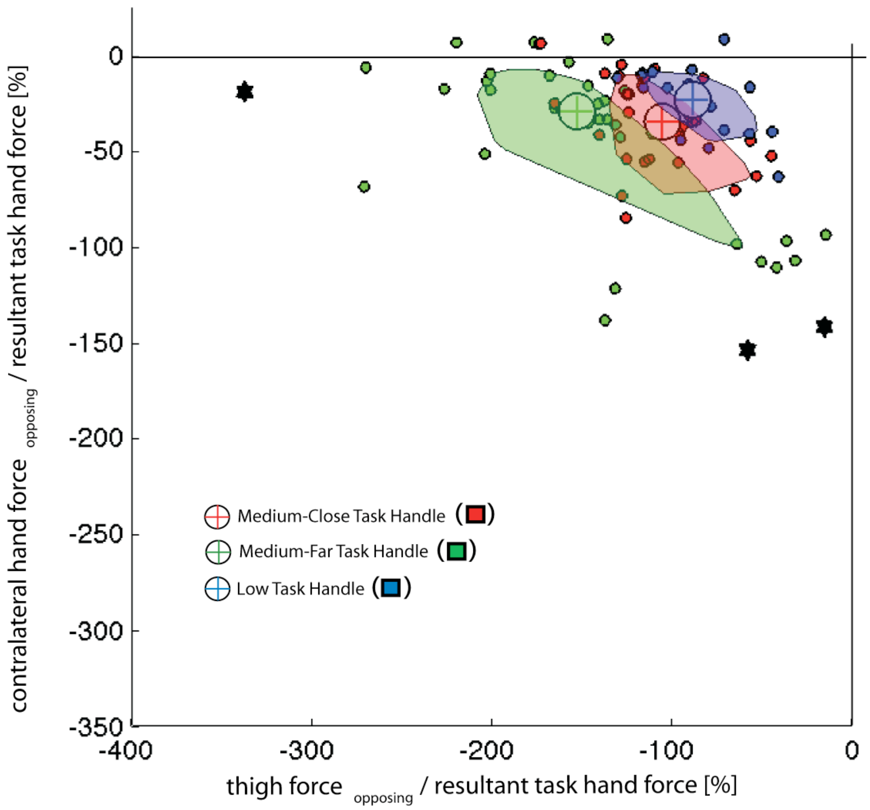

Figure 4.4.14 Bagplot depicting the opposing component of normalized contralateral hand bracing and thigh bracing (percentage of task hand force) across task handle locations during upward exertions within the HTB-o FGS.

The magnitude of the non-opposing component of the contralateral hand forces for HTB-o trials averaged 32% of the task hand force across task handle locations, while the HB trials averaged 55%. The low task handle height was associated with the least contribution of non-opposing bracing force for both HTB-o trials (16%) and HB trials (28%).

The magnitude of the thigh-bracing force was less for HTB-o trials, at an average of -123%, as compared to TB trials at an average of -149%. Consistent with TB trials, the degree of kinematic constraint affected the magnitude of the opposing component of thigh-bracing force, which averaged -154% at the medium-far task handle position. To the contrary, the magnitude of the non-opposing component of thigh bracing was observed to be greatest at the medium-close (119%) and low (118%) task handle locations (Figure 4.4.14).

4.5. Discussion

This chapter has presented a method to categorize bracing forces with respect to their contribution to task hand force generation. Expressing bracing forces in the task hand coordinate reference frame and normalizing relative to task hand force magnitude further clarified the relative contribution of each reactive force. Subjects braced with their hands and thighs in five distinct force-generation strategies that each increased force-exertion capability.

Transformation to the local task hand-based coordinate reference frame 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 contributory and non-contributory aspects of the compensatory forces with respect to task force-exertion. Opposing force component is considered an effective force that contributes to task hand force exertion capability. The non-opposing force component constitutes the magnitude portion that does not oppose the task hand force vector and is therefore considered as not contributing directly to the generation of task hand force.

The principal findings from this analysis are:

- Force-generation strategy (FGS) was associated with significant differences in both opposing and non-opposing components of contralateral hand bracing and body-bracing forces during nominal backward and upward exertions.

- Task hand force exertion capability was increased by the selection of a FGS with bracing availability relative to the NB FGS across the nominal task hand force exertions. Task hand force exertion capability increased by 44%, 14% and 60% during backward, forward and upward exertions.

- Higher task hand forces are associated with increased bracing forces, both opposing and non-opposing components, across all task hand force directions. On average, the opposing and non-opposing components of both contralateral hand and thigh bracing forces, increased 46%, 27% and 48% during nominal backward, forward and upward exertions, respectively, for sub-maximal to maximal task hand force exertions.

- Opposing, normalized contralateral hand bracing forces, adopted during the HTB-o FGS were significantly less, on average 48% and 73% less than opposing bracing forces exerted adopted the HB strategy during nominal backward and upward trials, respectively.

- On average, the non-opposing component of the normalized thigh bracing force was 73% and 35% less than the opposing component for nominal backward and upward exertions across both TB and HTB-o FGSs.
- The fore-aft horizontal location of the task handle increased the opposing component of the normalized contralateral hand bracing for nominal backward (27%) and upward (33%) exertions within the HB FGS.
- The opposing component of the normalized thigh bracing increased during the extended reach to the furthest fore-aft task handle location for backward and upward exertions performed with TB (27%) and HTB-o (34%) FGSs.
- The effects of task configuration (fore-aft horizontal task handle location or vertical task handle height) *did not affect* bracing forces at the contralateral hand or thigh during *forward* exertions, within or between FGSs.

Across all of the nominal task hand force directions and FGS increased task hand force levels were associated with increased bracing forces. Both opposing and non-opposing force components of the contralateral hand and body-bracing forces of bracing forces were increased by 46%, 27% and 48% at higher task hand force during backward, forward, and upward tasks, respectively.

The most important observation from the quantitative comparison of the opposing and non-opposing components of the normalized contralateral hand and thigh bracing forces is that there is a significant distinction in the pattern of bracing forces between FGSs for nominal backward and upward task exertions. Therefore, the contribution of both opposing and non-opposing components of the normalized bracing forces differed significantly between HB, TB and HTB-o FGSs. The opposing component of the contralateral hand bracing force adopted during the HB FGS were on average 61% greater than those exerted during nominal backward and upward trials with the HTB-o strategy. In a consistent trend, the magnitude of the opposing component of the normalized thigh bracing force was 73% and 35% greater than the non-opposing component for nominal backward and upward exertions across both TB and HTB-o FGSs.

Of the task configuration variables studied, the fore-aft horizontal location has the largest effect on both hand and thigh bracing forces, but only for backward and upward exertion tasks. The effect of the fore-aft horizontal task handle location on the contralateral hand bracing forces was found to be significant within the HB FGS, while the change in normalized body bracing forces were observed within both TB and HTB-o FGSs. The extended reach to the medium-far task handle position, as compared to the medium-close location, was associated with an average increase of 27% and 33% in the opposing contribution of normalized contralateral hand bracing for backward and upward exertions respectively. Similarly, the aft task handle position resulted in opposing thigh forces that were increased by an average of 27% and 34% during nominal backward and upward tasks. In contrast to the relatively large changes in contributory bracing exerted during backward and upward tasks, there were no significant changes to bracing forces for push tasks.

The analysis shows that substantial components of bracing forces that are non-opposing, meaning they do not contribute directly to the task hand force. To put it another way, bracing force directions are often not well aligned with the task hand force. Further analysis of these forces is required to gain a more comprehensive understanding of the efficacy of bracing.

Application

Knowledge that five distinct force-generation strategies exist across nominal task hand direction, task handle location and bracing availability provides a framework to model bracing forces with existing biomechanical models (i.e. 3DSSPP). 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. Within the context of this analysis, guidelines for practitioners to account for bracing forces are as follows:

- Opposing component of normalized contralateral hand bracing is 33% and 37 % for HB FGS and 63% and 138% for HTB-o FGS during nominal backward and upward exertions, respectively.

- During nominal forward tasks, the opposing component of normalized contralateral hand bracing is 38% of task hand force across FGSs with contralateral hand bracing.
- Opposing component of normalized thigh bracing is 397% and 334% for HB FGS and 317% and 301% for HTB-o FGS during nominal backward and upward exertions, respectively.
- The normalized thigh force generated during nominal forward tasks are aligned with the task hand force direction and average 66% of task hand force across all FGSs with body-bracing.

4.6. Conclusions

This study presents an analysis and method that divided an initially diverse bracing force data set into several homogenous groups using multinomial classification methods (i.e. bivariate scatter plots and bagplots) identified distinct force-generation strategies. Five consistent strategies were identified and determined to be prevalent across the nominal task hand force direction and task configuration variables. The specific strategies were, NB, HB, TB, HTB-o, and HTB-a, with each representing a distinct force-generation strategy. The main application of the FGS identified in this study is for ergonomic analysis. The ability to cluster or partition the data into individual, discrete FGSs increases the accuracy of predictive models, as each FGS is more homogenous than the entire data set.

4.7. References

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CHAPTER 5

PREDICT FORCE-GENERATION STRATEGY SELECTION FROM TASK AND SUBJECT PARAMETERS

5.1. Abstract

Quantitative criteria were developed to differentiate five force-generation strategies (FGS) across the nominal task hand force directions, task handle locations and bracing availability. The ability to partition the data into discrete FGS increases the accuracy of predictive models, as each FGS is more homogenous than the entire data set. The models presented provide, for the first time, a quantitative method to predict the FGS that a person will choose to perform a range of kinematically constrained, one-hand, isometric force exertions. Level of bracing availability, increase in task hand force and the subsequent interaction between bracing availability and force exertion are the most influential classifiers associated with FGS selection or exclusion. Fore-aft task handle location was also a predictor of FGS selection across all of the nominal task hand force directions. In general, the task configuration conditions were the most effective parameters for predicting force-generation patterns. Model validation demonstrated strong alignment between the actual classified dataset for kinematically constrained, nominal task hand exertions and predicted FGS selection. On average, the models accurately predicted the FGS for 83% of nominal backward and upward exertions and 65% of nominal forward exertions. By design, the models use inputs that are readily available in industrial ergonomics applications, and hence these results are applicable for predicting worker behavior.

5.2. Introduction

Biomechanical models and digital human models (DHMs) have been used extensively in industrial ergonomics to achieve diverse benefits such as reductions in worker injuries, reduced design/engineering costs and time, and ergonomic quality improvement (Chaffin, 2005, 2007). Ergonomists typically perform static analysis of the most extreme posture and/or hand force that is anticipated or predicted for a specified task allocation (Stephens et al., 2006). A variety of methods, including multiple regression (Snyder et al., 1972); optimization-based inverse kinematics (Marler et al., 2005; Wang et al., 2005); scaling of motion capture data (Park et al., 2002; 2005; Faraway, 2004), neural networks (Perez and Nussbaum, 2008) have been used to model and predict force-exertions and postures (Faraway and Reed, 2007; Chaffin, 2007). DHM tools coupled with these methods, however, are acknowledged as requiring additional refinement and/or accuracy to achieve a sufficient level of fidelity for ergonomic analysis of human force-exertions and postures (Chaffin et al, 1999; Chaffin, 2005, 2007). To increase the validity and accuracy of ergonomic applications, human simulations must be quantitatively accurate, thereby quantitatively represent characteristics of human behaviors and/or strategies identified for force-exertions and postures (Chaffin, 2005). This need for quantitative accuracy means that the prediction models used to simulate force-exertions and associated postural behaviors must be developed and validated with reference to data from task performance.

Chapter Four defined a theoretical framework to evaluate and classify bracing forces that provided an effective method for identifying force-generation strategies adopted during one-hand, isometric exertions tasks with bracing availability. As defined in Chapter Four, a force-generation strategy (FGS) is a qualitatively distinct pattern of force generation at the task hand and available bracing surfaces. Quantitative criteria were developed to identify five distinct FGSs. The ability to cluster or partition the data into individual, discrete FGSs increases the accuracy of predictive models, as each FGS is more homogenous than the entire data set.

The objective of this chapter is to develop logistic regression models that relate task configuration variables and subject characteristics to the likelihood of adopting each of the identified FGSs. The selection of a FGS is based on task parameters, such as the fore-aft and vertical location of the task handle, levels of bracing available, requested task hand force exertion level and nominal direction, in addition to subject anthropometric and strength characteristics.

This chapter is organized as follows. First, logistic regression models are developed to predict FGSs adopted during kinematically constrained one-hand isometric force exertions across the nominal task hand force directions. Second, the performance of the classification-based FGS selection model is evaluated over a representative set of task conditions. Third, the implications and limitations of the prediction models are assessed.

5.3. Methods: Data Analysis

Based on an exploratory analysis conducted 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).

Force-generation strategy (FGS) classification identifies the bracing forces (contralateral hand and/or thigh) and whether the thigh force is aligned or opposed. Thereby, Chapter Five presents the development and evaluation of logistic models that assess the association between task configuration and subject characteristic variables and predicts the likelihood of adopting each of the identified FGS for nominal backward, forward and upward task hand force directions.

Statistical analyses involved multiple explanatory variables, which were evaluated for logistic prediction of FGS selection. Therefore, the probability of a set of predicted outcome variables is modeled as a function of the linear combination of several explanatory variables. Logistic regression was used to model the likelihood of each strategy as a function of a set of predictor variables. The predictors considered were fore-aft task handle location (A_1), vertical task handle height (A_2), second-order term for vertical task handle height (A_3), task hand force along the requested nominal direction (A_4), prescribed level of bracing available (A_5), stature (A_6), body mass index (BMI) (A_7), isolated arm strength (A_8), torso strength (A_9) and leg strength (A_{10}). First-order interactions between these variables were also considered. All of these variables were modeled as continuous, except for bracing availability, which was modeled as four categorical levels: no bracing, thigh only, hand only, and both hand and thigh. All calculations were performed using JMP Version 9.0 statistical software.

The logistic model fits probabilities of occurrence (nominal Y responses) for each of the nominal responses (the five FGSs) to a linear model of A_j terms. The formulation of the fit model takes the form of:

$$\log\left(\frac{\left(P\left(Y = j^{\text{th}}\,\text{FGS}\right)\right)}{P\left(Y = r^{th}\,\text{FGS}\right)}\right) = A_j \beta_{nj}$$

where,

Y is the set of *r* (=5) FGSs, *j* ranges from 1 to *r*-1,

A_j are the task configuration, anthropometric and strength variables used to differentiate between the FGSs,

β_{nj} are the *n* linear parameters corresponding to the *n* A_j variables specified for the j^{th} FGS.

Further, the fitting principal of maximum likelihood means that the β_{nj} values are chose to maximize the joint probability attributed by the model to the responses that occurred in the data. The fitting of the β_{nj} parameters is equivalent to minimizing the negative log-likelihood (Log*Likelihood*) as attributed by the model. The negative log-likelihood is given by:

$$-\log likelihood = -\log\left(P\left(\sum_{i=1}^{a} i^{th} \text{ trial classified as } Y_{\mathrm{j}}^{th} \text{ FGS}\right)\right)$$

where,

a is the total number of experimental trials in the data set

The β_{nj} parameters of the five nominal FGSs with respect to nominally backward, forward and upward task hand force exertions are presented in Table 5.4.1, Table 5.4.4 and Table 5.4.7 along with the summary statistics of the performance of the whole model fit. The following logistic model calculates the probability that a requested task hand force exertion would demonstrate the reference FGS $\hat{p}\left(Y_{\text{FGS Reference Strategy}}\right)$:

$$\hat{p}\left(Y_{\text{FGS Reference Strategy}}\right) = \frac{1}{1 + \sum_{j=1}^{r-1} e^{\alpha_j + \beta_{nj} \mathrm{A}_j}}$$

where,

$\alpha_j = \left[\alpha_i \ldots\ldots \alpha_j\right]$ intercept constants

The subsequent probabilities ($\hat{p}$ (Y_{j}^{th})) of the alternative FGSs (Y_{j}^{th}) are derived by the following generalized logistic model:

$$\hat{p}\left(Y_{\mathrm{j}}^{th}\right) = \frac{e^{\alpha_j + \beta_{nj} \mathrm{A}_j}}{1 + e^{\alpha_j + \beta_{nj} \mathrm{A}_j}}$$

The predicted FGS is the one with the highest estimated probability, although the distribution of predicted probabilities across strategies is also of interest. Using the predictive tools given above to forecast the task configuration, anthropometric and strength variables, the selection of FGS can therefore be predicted.

Model Performance Measures

Performance of predictive logistic regressions models are commonly evaluated using the following measures: 1) the uncertainty coefficient (R^2), 2) Akaike's information criterion (AIC), 3) area under the receiver operating characteristic (ROC) curve and 4) confusion matrices.

The Akaike's information criterion (AIC) is a statistical model fit measure and is used as an aid to choose between competing models. AIC provides a measure of model quality by simulating the situation where the model is tested on a different data set. Alternative models can be compared using this criterion, defined as:

$$AIC = -2L_m + 2m$$

where,

L_m is the maximized log-likelihood, and

m is the number of parameters in the models.

The AIC score takes into account both the statistical goodness of fit and the number of parameters that have to be estimated to achieve this particular degree of fit, by imposing a penalty for increasing the number of parameters. According to Akaike's theory, the best model has the smallest AIC, that is, the one with the fewest parameters that still provides an adequate fit to the data (Akaike, 1974; 1980).

Receiver operating characteristic (ROC) plots provides another method to examine the performance of classifiers (Swets, 1988). Figure 4.3.2 is a representative example of an ROC plot with the false positive rate on the X-axis and the true positive rate on the Y-axis. The point (0,1) is the perfect classifier: it classifies all positive FGSs and negative FGSs correctly. The point (0,0) represents a classifier that predicts all nominal responses to be negative, while the point (1,1) corresponds to a classifier that predicts every nominal response to be positive. Point (1,0) is the classifier that is incorrect for all FGS classifications. The area underneath an ROC curve (area under the curve, or AUC) can be used as a measure of accuracy in many applications (Swets, 1988), because it characterizes the model performance independent of the particular choice of decision criterion. An AUC value of 1 indicates perfect performance, while an AUC of 0.5 indicates performance no better than chance.

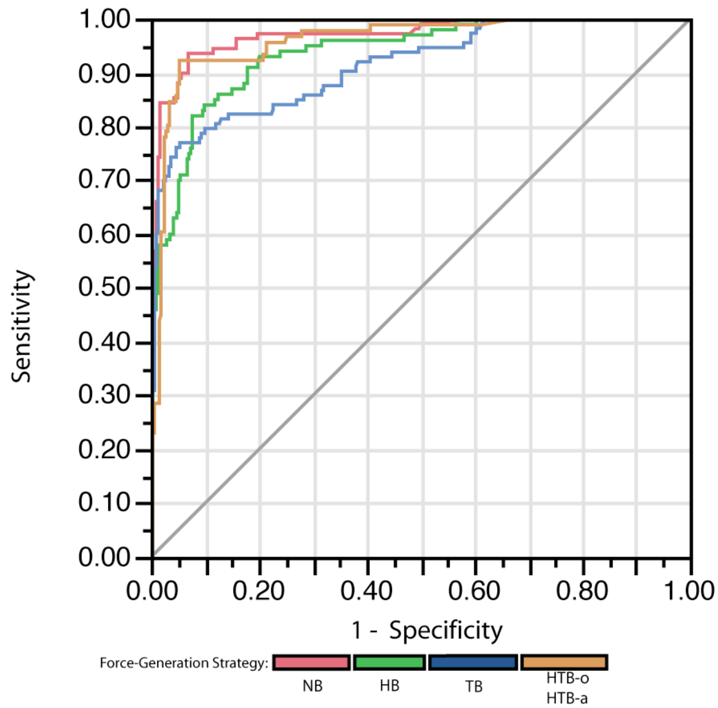

Figure 5.3.1. Representative plot of the receiver operating characteristic (ROC) curve. The four ROC curves are color coded by FGS. The diagonal line denotes random prediction.

A confusion matrix presents counts of actual and predicted FGSs, in this case generated by a logistic regression model (Kohavi and Provost, 1998). A confusion matrix is a square matrix that represents the count of the logistic model's predictions with respect to the actual classification of FGS by the objective criterion presented in Chapter Four.

The entries in the confusion matrix have the following meaning in the context of predicting FGS in a task configuration for which there is a choice of only two appropriate strategies:

- a is the number of *correct* predictions that an instance is classified as HB FGS,
- b is the number of incorrect predictions that an instance is classified HTB-opposed FGS,
- c is the number of incorrect predictions that an instance classified HB FGS, and
- d is the number of *correct* predictions that an instance classified HTB-opposed FGS.

		Predicted	
		HB	**HTB-o**
Actual	**HB**	**a**	b
	HTB-o	c	**d**

Succinctly, confusion matrices provide a measure of the overall accuracy of a model. High values on the diagonal indicate good model performance.

Model Validation

The preceding logistic models were generated on 80% of the entire data set. Twenty percent of the trial data were withheld for each subject by randomly sampling across all test configuration variables. Model performance was then evaluated by exercising the logistic prediction models across the task configurations and requested nominal task hand force directions, in an effort to ensure that models developed do not over-fit the data set.

5.4. Results

Development of a Force-Generation Strategy (FGS) Prediction Model

Model Inputs

Model inputs were restricted to task parameters and worker characteristics readily available to ergonomists analyzing industrial tasks. Inputs include the required task hand force magnitude and direction, vertical task handle height, fore-aft task handle location, and the available bracing surfaces. Subject input variables were stature, gender, body mass index and isolated strength measures.

Chapter Four illustrated the distribution of the classification FGS responses (modes) across the data set. Amongst all subject and task configuration inputs, requested nominal force direction was a key determinant for stratifying the test conditions and categorizing into appropriate FGSs. Given task and subject descriptors, the models predict the likelihood of adopting each of the identified FGSs for a specified nominal task hand force direction.

Critical Predictors of Force-Generation Strategy (FGS) Selection

The most powerful single classifier ($p<0.0001$) across all of the requested nominal task hand force directions and FGS classification dataset was level of bracing availability. Likelihood ratio (L-R) and Pearson Chi-square (χ^2) statistical tests were completed on the data, presented in Table 5.4.1, Table 5.4.4 and Table 5.4.7, and indicated that the prescribed level of bracing was statistically significant ($p<0.0001$) for determining the selection of FGS, with χ^2 values of 541, 291 and 466 for backward, forward and upward exertions respectively. Figure 5.4.1 visualizes the results of contingency analyses tests with the levels of bracing availability corresponding to the choice of FGS selection for each of the nominal task hand force directions. As an example, using test conditions in which bracing at all of the available surfaces was permitted, 74% chose the HTB-opposed FGS, utilizing all of the bracing affordances. Of the tests conditions in which subjects were not permitted to exert force at the bracing surface 98% subjects performed the backward exertion without bracing (NB strategy), 95% performed the exertion with HB strategy when only the handrail was available, 89% adopted the TB strategy for the Thigh Only bracing level condition.

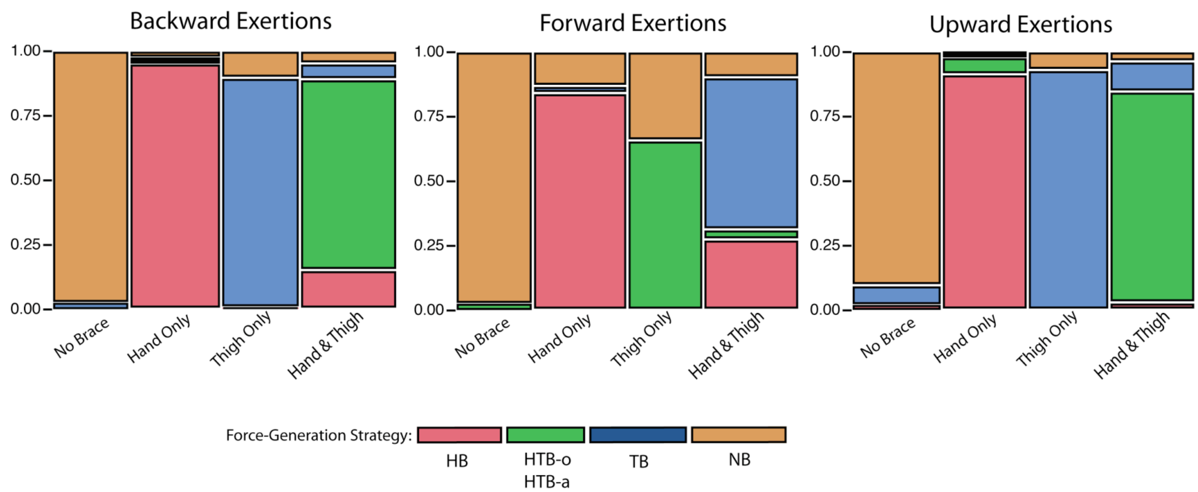

Figure 5.4.1 Mosaic plots of the distribution of the FGSs across the levels of bracing availability for each requested nominal task hand force direction.

Figure 5.4.2 graphically depicts task hand force generation capability for each of the FGS across backward, forward and upward exertions. The nominal task hand force was also influenced the selection of FGSs, with χ^2 values of 142, 66 and 131 for backward, forward and upward exertions respectively. As an example, on average subjects generated 86 N in upward trials in which the NB FGS was observed. In trials with the HB FGS, the mean task hand force was 159 N across task handle location. The addition of thigh bracing yielded a significant greater task hand force-exertion capability, 238 N and 260 N on average, for TB and HTB-opposed FGSs respectively.

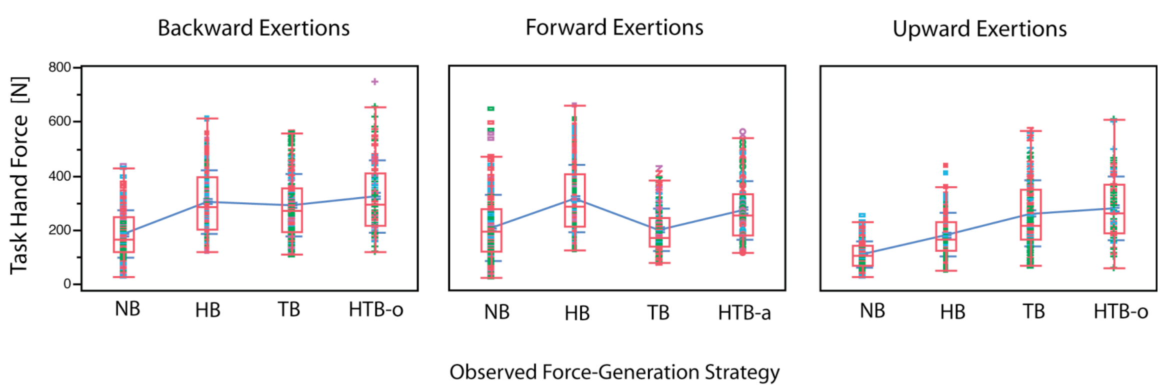

Figure 5.4.2 Variation of task hand force exertion capability [Newton] across nominal task hand force directions and between FGS classifications defined by the objective criteria.

Statistical analysis of the 80% of the dataset also indicated that the interaction of prescribed level of bracing availability and task hand force in the nominal direction was a significant factor ($p<0.001$) influencing FGS selection. The interaction term contribution to the selection of a FGS had a stronger effect on backward and upward tasks, with χ^2 values of 93 and 145, in contrast to nominally forward exertions, with a χ^2 value of 17. Each of the terms in the following logistic prediction models are significant at $p<0.001$, and the final models are subsequently significant ($p<0.0001$). Therefore, each of the factors included in the model are strongly believed to influence FGS selection.

Force-Generation Strategy (FGS) Selection Models

Backward Exertions

Five of the ten independent variables, for which between-group differences achieved significance, were selected for the nominal logistic regression prediction function. Likelihood ratio (L-R) tests, an indicator of the importance of a variable to the logistic model, were performed for each included model regressor and each was found to be significant with $p< 0.001$. The prescribed level of bracing availability (L-R χ^2 = 541), task hand force component along the horizontal, nominal axis (L-R χ^2 = 142) and interaction between bracing availability and task hand force (L-R χ^2 = 93) yielded the most significant contribution to the prediction of FGS selection. Table 5.4.1 summarizes the statistically significant ($p<0.001$) regressor effects and interactions that predict FGS for backward exertions.

Table 5.4.1 Force-generation strategy (FGS) logistic regression parameters for backward exertions with associated model performance measures*.

Variable	HTB-o	NB/HTB-o	HB/HTB-o	TB/HTB-o	Likelihood Ratio Test Chi-Square	Prob > χ^2
Intercept	Reference Strategy *R*	24.3	8.29	6.22	N/A	N/A
Task Handle-x (Normalized to Stature)	*R*	19.6	13.3	5.92	25	p<0.0001
Task Handle-z (Normalized to Stature)	*R*	-19.6	-2.24	0.39	12	0.0087
Task Hand Force [N] (F_x Nominal Comp.)	*R*	-0.02	0.02	0.02	142	p<0.0001
Brace Level#	*R*	-13.7	-8.27	-5.56	541	p<0.0001
Stature [mm]	*R*	0.02	0.01	0.01	35	p<0.0001
Task Handle-z * Task HF	*R*	-0.23	-0.15	-0.06	43	p<0.0001
Brace Level * Task Handle-z	*R*	-21.1	-12.7	-2.41	23	p<0.0001
Brace Level * Task HF	*R*	-0.05	-0.03	-0.02	93	p<0.0001

* 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.
R indicates the reference strategy to which all the other FGS probabilities of occurrences are referenced.
Brace level is a nominal variable and only one value from each strategy should enter the regression equation at any one time.

Performance Measures

The logistic model used to predict FGS for backward exertions based upon task configuration and anthropometric variables, summarized in Table 5.4.1, fits the data with an uncertainty coefficient (similar to R^2 measure for regression models) of 0.63. The R^2 uncertainty coefficient provides a global measure of how well the model fits to the observations, however it is understood that nominal responses typically yield low R^2 values and that additional performance measures are crucial for the assessment of the validity of nominal logistic regression results.

The proposed logistic regression model yielded an Akaike's information criterion (AIC) score of 515. This criterion indicates that the chosen model that seeks a model that had a good fit to the data, while minimizing the number of regressors (Andersson and Burnham, 2002).

The area under the ROC curve (AUC) ranged from 0.92 for HB strategy to 0.98 for NB strategy. Each of the FGS prediction models was observed to have high level of sensitivity and discriminating ability.

The confusion matrix results reported in Table 5.4.2 show strong alignment between the actual dataset predicated on the FGS objective criterion and predicted FGS selection. The percentage of correct predictions, 94% for NB strategy, 81% for HB strategy, 77% for TB strategy and 96% for HTB-opposed strategy, for the respective FGSs is a measure of the logistic models accuracy. The overall accuracy measure of the logistic FGS prediction model for backward exertions is 87%.

Table 5.4.2 Confusion matrix classification of the actual vs. predicted force-generation strategies (FGS) for backward exertion tasks.

		Predicted			
		NB	**HB**	**TB**	**HTB-o**
Actual	**NB**	**111**	7	0	0
	HB	10	**105**	6	9
	TB	5	11	**82**	8
	HTB-o	0	1	3	**88**

Validation

The foregoing prediction model was developed using 80% of backward exertion dataset, while the remaining 20% of the backward trials were withheld for model validation. These validation trials were randomly sampled across the task configuration variables and withheld for the purpose of exercising and assessing model performance. Figure 5.4.3 depicts the bivariate mosaic plot between the predicted FGS selection (x-axis) and the observed FGS selection (y-axis) for the validation data. The plot on right in Figure 5.4.3 shows the observed FGS frequency. The plot on the left illustrates the predicted strategy on the horizontal axis and the distribution of observed FGSs on the vertical axis. If the model were 100% accurate, the mosaic plots would show vertical column with a single color for each FGS.

The NB FGS was predicted correctly 90% of the time for the trials in which the same FGS was observed. HB FGS was the most frequent strategy as it was observed for 32% of the trials and predicted 86% of the times. Force-generation strategies that involved some form of thigh bracing were predicted correctly 75% and 82% of the time for the TB and HTB-opposed strategies respectively.

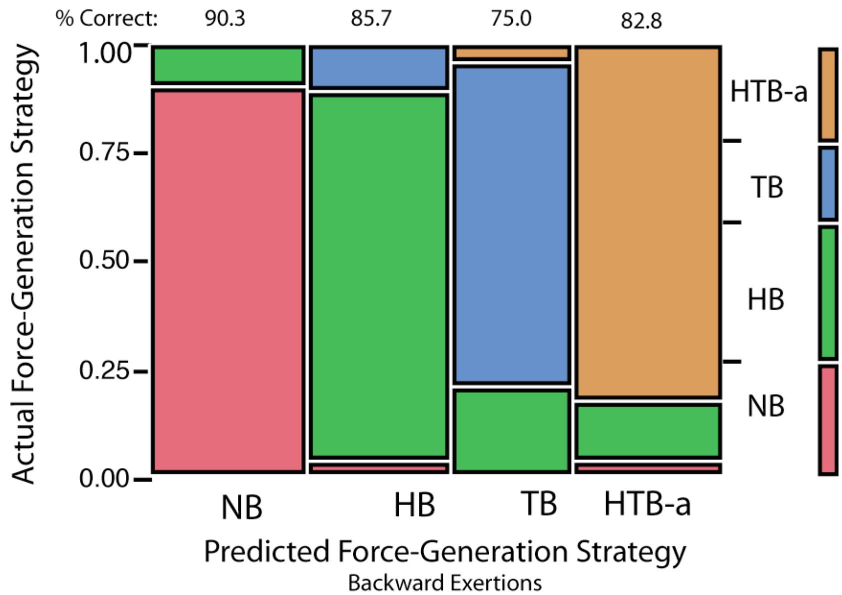

Figure 5.4.3 Bivariate mosaic plot of FGS multinomial selection prediction versus the actual classified FGSs from the experimental trials for nominal backward exertions.

The confusion matrix reported in Table 5.4.3 indicates the overall accuracy measure of the logistic FGS prediction model for backward exertions is 84%.

Table 5.4.3 Confusion matrix obtained by exercising prediction model for backward exertions on withheld data.

		Predicted			
		NB	**HB**	**TB**	**HTB-o**
Actual	**NB**	**28**	3	0	0
	HB	1	**24**	3	0
	TB	0	5	**18**	1
	HTB-o	1	4	0	**24**

Forward Exertions

Four of the ten independent variables for which the between-strategy differences achieved significance were selected into the proposed logistic regression model. The variables included were the prescribed level of bracing availability, F_x-component of the task hand force (nominal task hand force), fore-aft task handle location and body mass index (BMI). Based on the likelihood-ratio (L-R) χ^2 tests, the analysis revealed that both normalized fore-aft task handle location (L-R χ^2 =22) and BMI (L-R χ^2 =20) contributed significantly and independently to FGS selection. Bracing levels (χ^2 =291) and to a lesser extent the nominal task hand force component (L-R χ^2 = 66) contributed both as independent and as interacting effect with bracing level availability (L-R χ^2 = 17). Table 5.4.4 summarizes the statistically significant (p<0.001) regressor effects.

Table 5.4.4 Force-generation strategy (FGS) logistic regression parameters for forward exertions with associated model performance measures*.

Variable	**HTB-a**	**NB/HTB-a**	**HB/HTB-a**	**TB/HTB-a**	**Likelihood Ratio Test Chi-Square**	**Prob > χ^2**
Intercept	Reference Strategy *R*	27.6	21.5	14.9	N/A	N/A
Task Handle-x (Normalized to Stature)	*R*	11.3	10.2	6.08	22	p<0.0001
Task Hand Force [N] (F_x Nominal Comp.)	*R*	0.01	-0.01	0.01	66	p<0.0001
Brace Level#	*R*	-4.78	-3.54	-2.66	291	p<0.0001
BMI [kg/m^2]	*R*	-0.30	-0.27	-0.11	20	0.0002
Brace Level * Task HF	*R*	0.01	0.00	0.00	17	0.0007

* 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.
R indicates the reference strategy to which all the other FGS probabilities of occurrences are referenced.
Brace level is a nominal variable and only one value from each strategy should enter the regression equation at any one time.

Performance Measures

Table 5.4.4 outlines the logistic model used to predict FGS for forward exertions based upon task configuration and anthropometric variables. The uncertainty coefficient (R^2) for the proposed logistic model of FGS selection process for forward exertions was 0.35, while the AIC criterion score equaled 759. Sensitivity of the predicted FGSs as indicated by the area under the ROC curves, are highest for the HTB-aligned strategy at 0.95, followed by NB strategy at 0.88, TB FGS at 0.88 and the least discriminate prediction model is for HB FGS at 0.83.

The confusion matrix shown in Table 5.4.5 indicates that the model accurately predicts FGS for a large percentage of trials. Accuracy of the predictive logistic model to classify FGSs was greatest for the HTB-aligned strategy at 87%, as compared to NB strategy at 83%, HB strategy at 43% and the TB FGS at 42% accuracy. The overall accuracy measure of the logistic FGS prediction model for forward exertions is 65%.

Table 5.4.5 Confusion matrix classification of the actual vs. predicted force-generation strategies (FGSs) for forward exertion tasks.

		Predicted			
		NB	**HB**	**TB**	**HTB-a**
Actual	**NB**	**128**	19	4	3
	HB	49	**53**	6	15
	TB	13	22	**29**	6
	HTB-a	2	7	0	**60**

Validation

The foregoing prediction model was validated against the 20% of the forward trials that were withheld from model development. Figure 5.4.4 provides a visualization of the predicted FGS selection (x-axis) and the observed FGS selection (y-axis). The forward exertion logistic regression model performed with moderate accuracy with respect to correct FGS prediction. The HB strategy was predicted correctly 70% of the time, followed by 68% accuracy for NB strategy, while TB and HTB-aligned FGSs were predicted approximately 60% of the time for the trials in which the same FGS was observed. The overall accuracy measure of the logistic FGS prediction model for forward exertions is 65% (Table 5.4.6).

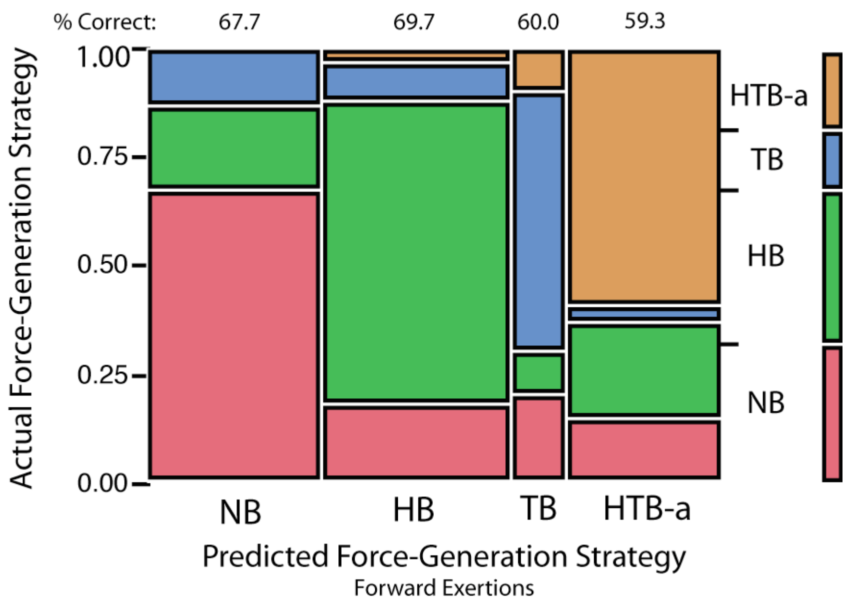

Figure 5.4.4 Bivariate mosaic plot of FGS multinomial selection prediction versus the actual classified FGSs from the experimental trials for nominal forward exertions.

Table 5.4.6 Confusion matrix obtained by exercising prediction model for forward exertions on withheld data.

		Predicted			
		NB	**HB**	**TB**	**HTB-a**
Actual	**NB**	**21**	6	4	0
	HB	6	**23**	3	1
	TB	2	1	**6**	1
	HTB-a	4	6	1	**16**

Upward Exertions

Similar to the backward exertion prediction model, the logistic regression prediction function for upward exertions includes five of the ten independent variables. The relative contribution of each regressor is indicated by the likelihood-ratio (L-R) χ^2 test scores reported in Table 5.4.7, given that each independent and interaction variable is found to be statistically significant at $p < 0.001$. Analogous to the backward exertion FGS predictions, prescribed level of bracing availability (L-R χ^2 = 466), task hand force component along the nominal vertical axis (L-R χ^2 = 131) and interaction between bracing availability and task hand force (L-R χ^2 = 145) resulted in the most significant contribution to the prediction of FGS selection during upward tasks.

Table 5.4.7 Force-Generation Strategy (FGS) logistic parameters for upward exertions with associated model performance measures*.

Variable	HTB-o	NB/HTB-o	HB/HTB-o	TB/HTB-o	Likelihood Ratio Test Chi-Square	Prob > χ^2
Intercept	Reference Strategy *R*	87.4	10.4	17.5	N/A	N/A
Task Handle-x (Normalized to Stature)	*R*	38.2	17.1	3.11	32	p<0.0001
Brace Level	*R*	-24.2	-8.98	-3.45	466	p<0.0001
Task Hand Force [N] (Fx Nominal Component)	*R*	-0.23	0.00	0.03	131	p<0.0001
BMI [kg/m^2]	*R*	-1.42	-0.16	-0.34	11	0.0116
Stature [mm]	*R*	0.02	0.02	0.01	20	0.0002
BMI * Task Handle-x	*R*	8.36	6.40	1.46	16	0.0010
Brace Level * Task HF	*R*	-0.24	-0.08	-0.02	145	p<0.0001
Brace Level * BMI	*R*	0.02	0.80	0.28	21	0.0001
BMI * Task HF	*R*	-0.02	-0.01	0.00	20	0.0002
BMI * Stature	*R*	0.01	0.01	0.00	28	p<0.0001

* 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.
R indicates the reference strategy to which all the other FGS probabilities of occurrences are referenced.
Brace level is a nominal variable and only one value from each strategy should enter the regression equation at any one time.

Performance Measures

The inclusion of the interaction terms in the prediction model increased the uncertainty coefficient (R^2) from 0.59 to 0.71, and decreased the AIC criterion tem by 77 to a score of 340. The sensitivity of the predicted FGSs was also improved by the interaction terms. AUC was highest for the NB strategy at 0.99, followed by HB strategy at 0.98, HTB-opposed FGS at 0.97 and the TB FGS at 0.95.

The results of the confusion matrix, reported in Table 5.4.8, demonstrate strong alignment between the actual classified dataset for upward exertions and predicted FGS selection. The percentage of correct prediction were as follows: 97% for NB strategy, 92% for HTB-opposed strategy, 87% for HB strategy and 76% for TB strategy for each the respective FGSs. The overall accuracy measure of the logistic FGS prediction model for upward exertions is 88%.

Table 5.4.8 Confusion matrix classification of the actual vs. predicted force-generation strategies (FGSs) for forward exertion tasks.

		Predicted			
		NB	**HB**	**TB**	**HTB-o**
Actual	**NB**	**86**	2	0	1
	HB	6	**72**	3	2
	TB	3	6	**66**	12
	HTB-o	0	1	5	**67**

Validation

Figure 5.4.5 depicts the bivariate mosaic plot between the predicted FGS selection (x-axis) and the observed FGS selection (y-axis) for upward exertion validation data. TB FGS was the most frequent strategy as it was observed for 32% of the trials and predicted 94% of the time. The NB FGS was predicted correctly 80% of the time for the trials in which the same FGS was observed. Force-generation strategies that involved some form of contralateral hand bracing were predicted correctly 77% and also 77% of the time for the HB and HTB-opposed strategies respectively.

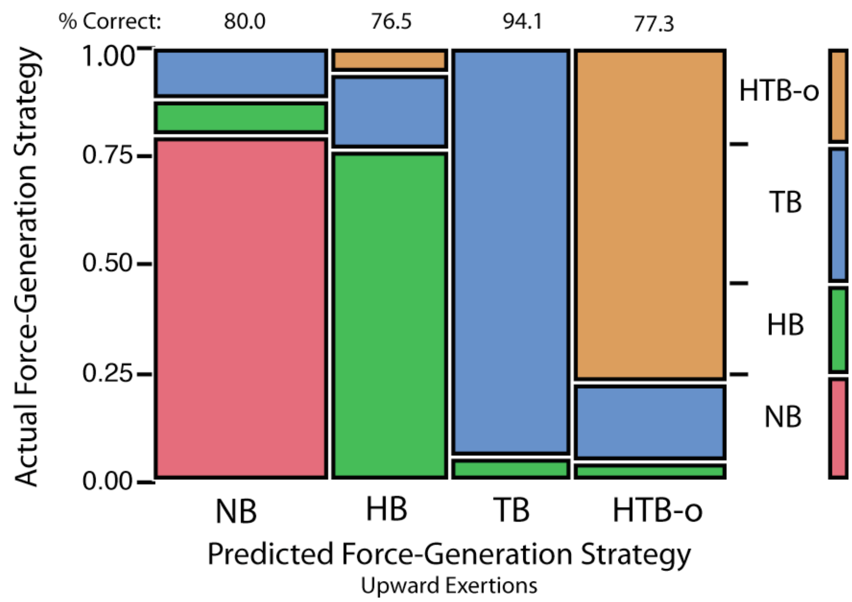

Figure 5.4.5 Bivariate mosaic plot of FGS multinomial selection prediction versus the actual classified FGSs from the experimental trials for nominal upward exertions.

The confusion matrix reported in Table 5.4.9 indicates the overall accuracy measure of the logistic FGS prediction model for backward exertions is 82%.

Table 5.4.9 Confusion matrix obtained by exercising prediction model for upward exertions on withheld data.

		Predicted			
		NB	**HB**	**TB**	**HTB-o**
Actual	**NB**	**20**	2	3	0
	HB	0	**13**	3	1
	TB	0	1	**16**	0
	HTB-o	0	1	4	**17**

5.5. Discussion

The models presented in this chapter provide, for the first time, a quantitative method to predict the FGSs that a person will choose to perform a range of one-hand, isometric force exertions. The theoretical framework and quantitative objective criteria presented in Chapter Four provided the basis for classifying FGSs. Data from the laboratory study illustrated that five qualitatively distinct patterns of force generation at the task hand and available bracing surfaces were observed across the range of task configurations. Subsequently, given the task configuration, including the location of the force application, nominal task hand force magnitude, definition of the bracing affordances available within the environment, and certain subject anthropometry, the logistic regression models developed here are able to predict the probability distribution of FGSs are observed for a specified task hand force direction.

The logistic regression models reported here were built using stepwise regression. Models were constructed twice to confirm that the order of predictors did not affect the final model. The initial models were constructed by including task configuration parameters before subject anthropometric and strength variables. Models were also built by including subject characteristic variables followed by task configuration variables. All models gave similar results. This effort provided confidence that the set of predictors reported in Table 5.4.1, Table 5.4.4 and Table 5.4.7 were not an artifact of the modeling procedure used. Although the task configuration and subject anthropometric parameters may be related, they could not independently substitute for each other in the models.

The level of bracing availability was the most influential classifier associated with FGS selection or exclusion across the nominal task hand force directions, because prohibiting the use of one or more bracing surfaces precluded the FGS that required the use of those surfaces.

Increase in force level and the subsequent interaction between bracing availability and force level were also associated with FGS selection during backward, forward, and upward exertion tasks. Fore-aft task handle location was also a predictor of FGS selection across all of the nominal task hand force directions. In general, the task configuration conditions were effective at eliciting distinct force-generation patterns. The result is that the bracing behavior within each FGS is similar but substantially different from the behavior observed with other FGSs (Hair and Black, 2000).

Stature and body mass index (BMI) were the only subject characteristics that were predictive of FGS, keeping in mind that the geometry of the task environment was scaled to stature. The association between stature and FGS selection was significant in nominal backward and upward tasks, while BMI was predictive in nominal forward and upward tasks. BMI was the predominant subject factor associated with FGS selection for upward tasks, in that it resulted in both independent and interacting associations with stature, level of bracing availability and task hand force magnitude. Caution must be exercised in interpreting the predictive effect of BMI, given that this study is limited by the young age and relatively fit characteristics of the student-based subject pool. It is also noteworthy that isolated measures of strength had no association with FGS across the entire data set. In general, subject anthropometric characteristics contributed very little to FGS selection, in contrast to aforementioned task configuration variables. Subject variables are only identified as significant because of the relatively large subject pool and number of trials.

Validation and overall accuracy measures of the FGS selection models across the nominal task hand force direction were presented in the form of confusion matrices. The confusion matrices derived from the validation efforts demonstrated strong alignment between the actual classified dataset for nominal exertions and predicted FGS selection. On average, the models accurately predicted the FGS for 83% of nominal backward and upward exertions and 65% of nominal forward exertions among the validation samples. By design, the models use inputs that are readily available in industrial ergonomics applications, and hence these results should be applicable for predicting worker behavior. However, more research will be needed to extend the model applicability beyond the current experimental conditions. Among the limitations of the current study, the most important are the relatively high forces (typical industrial tasks will have lower force levels), the young, fit, and inexperienced subject pool, and the short-duration, isometric nature of the tasks.

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. Multinomial classification of the bracing data into homogenous FGSs (Chapter Four) afforded a more appropriate technique for the current problem of interest (i.e. to predict patterns of bracing force at the contralateral hand and thigh).

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, multinomial classification approach 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

The ability to cluster or partition the data into individual, discrete FGSs increases the accuracy of predictive models, as each FGS is more homogenous than the entire data set. The logistic models relate task configuration variables and subject characteristics to the likelihood of adopting each of the identified FGSs, adopted during a range of kinematically constrained one-hand isometric force exertions across the nominal task hand force directions. Classifiers associated with FGS selection or exclusion includes: level of bracing availability, increase in task hand force and the subsequent interaction between bracing availability and force exertion. Fore-aft task handle location was also a predictor of FGS selection across all of the nominal task hand force directions. In general, the task configuration conditions were the most effective parameters at eliciting distinct force-generation patterns. 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 workstation and/or product design.

5.6. Conclusions

This chapter develops logistic regression models that relate task configuration variables and subject characteristics to the likelihood of adopting each of the identified FGSs. The selection of a FGS is based on task parameters, such as the fore-aft and vertical location of the task handle, levels of bracing available, requested task hand force exertion level and nominal direction, in addition to subject anthropometric and strength characteristics. Validation of the models demonstrated strong alignment between the actual classified dataset for kinematically constrained, nominal task hand exertions and predicted FGS selection.

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CHAPTER 6

PREDICTING TASK HAND FORCE AND BRACING FORCES FROM TASK AND SUBJECT PARAMETERS

6.1. Abstract

Realistic and valid biomechanical analyses of tasks that involve environmental obstructions and subsequent bracing availability require accurate prediction of bracing force. Given a task requirement, the task and bracing hand forces and thigh bracing force are required inputs to the assessment of strength and balance capabilities. This chapter statistically models task hand and bracing forces for force-exertion tasks in which the obstruction imposes a kinematic constraint and provides an opportunity to generate such forces. The models are intended for ergonomic evaluation of industry jobs and only require information that is readily available to ergonomists. Knowledge of the relationship between task configuration, subject and task hand force can be used to within the context of existing ergonomic analysis tools, including biomechanical simulation of kinematically constrained tasks.

6.2. Introduction

Accurate prediction of force exertion tasks is critical to ergonomic assessment of worker capability. Realistic and valid biomechanical analyses and simulations of tasks that involve environmental obstructions and subsequent bracing availability requires accurate prediction of the bracing forces people chose to generate. Task hand force capability has also been shown to depend on the availability of such bracing forces and friction at the feet (Chapter Three). Given a task posture, the task and bracing hand forces and body bracing force are required inputs to the assessment of strength and balance capabilities. Moreover, when the posture is unknown, knowledge of the forces generated at the individual contact surfaces and subsequent force-generation strategy (FGS) can be used to predict the postures used for the task.

In current industrial applications, it is difficult to accurately measure and characterize bracing forces. Biomechanical analyses of kinematically constrained tasks are therefore difficult to conduct because the addition of the bracing forces produces a mechanically indeterminate system. That is, even after accounting for the primary (task) hand force and body weight effects, the forces at the bracing hand and other externally braced contact points cannot be determined from the posture. Consequently low back, shoulder, and other important moments cannot be computed.

The overall goal of this chapter is to provide ergonomists a means to accurately predict task hand, brace hand and body-bracing forces for force-exertion tasks in which the obstruction imposes a kinematic constraint and provides an opportunity to generate such forces. A model intended for ergonomic evaluation of industry jobs must only require information that is readily available to ergonomists. The model must produce accurate force-exertion and postures for the range of task conditions observed in industry and be capable of replicating different force-generation strategies and associated postural behaviors prevalent in industry. Model performance should be assessed based on the model's ability to yield, for a given kinematically constrained force-exertion task, ergonomic outcome measures consistent with analysis of the actual pattern of task and brace force exertion and working posture.

Based on an exploratory analysis conducted in Chapter Four, five distinct patterns of bracing force generation, termed *force-generation strategies (FGSs)*, were identified.

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

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

3. *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).

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

5. *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).

Chapter Five presented, for the first time, a quantitative method to predict the force-generation strategies that a person will choose to perform a range of one-hand, isometric force exertions. Multiple logistic regression models defined the association between task configuration and subject characteristic variables, and predicted the likelihood of adopting each of the force-generation strategy for task hand force exertions performed in the sagittal plane.

With knowledge that there are five distinct FGS prevalent across industry tasks and the ability to predict these force-generation strategies; and given a set of know task configuration and subject characteristics, it is a logical choice to predict task hand force and bracing forces within nominal task hand force direction and force-generation strategy classification. In practice, an individual might want to evaluate alternative force-generation strategies depending on the task, but the logistic models in Chapter Five addresses this.

The current analysis investigates the effects of task configuration, subject anthropometric and strength variables on task hand and bracing forces, which were shown in Chapter Four to have important effects on task-hand force generation capability. These data and findings were used in subsequent chapters to develop into an integrated conceptual model that predicts bracing force generation and the associated 3D whole-body posture for use with commercially available digital human models (Chapter Eight). This chapter presents a series of regression models from which for a given nominal force direction, exertion level and force-generation strategy, ergonomists can predict magnitude and direction of task and contralateral hand force vectors and body-bracing force.

The following hypotheses formulated through the data analysis presented in Chapter Three, Four and Five guided the work:

1. Task hand force exertion capability can be predicted within force-generation strategy. This in addition to the known effects of nominal direction of the force application and location of the exertion handle.

2. The brace hand force vector magnitude and direction will be correlated with task hand force vector magnitude and direction.

3. Body bracing force will be dependent on the direction of task hand force and task handle location.

6.3. Methods: Data Analysis

Analysis of the force data was conducted on the magnitude, direction and absolute angle deviation relative to nominal direction of the task hand, contralateral hand and thigh bracing forces. Forces on the exertion handle are positive upward (Z-axis) and rearward (X-axis). The angle of the resultant force direction is relative to horizontal and is defined positive upward for horizontal forward and backward exertions. This angle is used to quantify the force direction in the XZ (sagittal) plane, with an angle of zero degrees corresponding to the backward exertion, and an angle of 180 degrees to a nominal forward exertion. The direction of upward exertions was defined relative to a nominal angle of 90 degrees, with a positive direction oriented rearward along the positive x-axis. All task configuration variables were normalized to stature.

The subject pool contained females and males of similar BMI. There were differences with respect to the range of stature, 191 mm and 282 mm for females and males respectively. Standardized measures of isolated arm, torso and leg strength also revealed gender differences. An ANOVA was conducted to determine if the effects of the test variables differed between females and males. No significant interactions with gender were observed, indicating that the test variables affect the task hand force-generation capability of females and males similarly. Given that gender was not observed to have a significant effect on task and brace hand forces or body-bracing forces, trials are pooled together across gender for this analysis.

Regression analysis was used to assess potential non-linearities and also to determine relationships between anthropometric, strength and test configuration variables.

Stature and body mass index (BMI) were considered as potential regressors. BMI was calculated by dividing the body mass by stature squared (kg/m^2) and is intended to represent a measure of body mass that is less correlated with stature than mass. In these data, the correlation between BMI and stature is -0.21. Of particular interest were the potential for interaction between the test configuration variables and three standardized strength test measurements of arm, torso, and lower extremities.

Regression analyses were performed using step-wise procedure. Test configuration variables, anthropometric and strength 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. In an effort to obtain a more parsimonious model an interactive procedure was followed, whereby removing variables contributing less than 0.02 to the adjusted R^2 value. All terms, and each model, are statistically significant with $p<0.001$. Table6.4.1: Table 6.4.9 (odd Tables) 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 6.4.2 : Table 6.4.8 (even Tables) show the resulting values.

6.4. Results

Prediction of Resultant Task Hand Force Magnitude

The data analyses presented in Chapter Three demonstrated that fore-aft location of the task handle, task handle height, levels of bracing availability, nominal force direction and exertion level have statistically significant but largely independent effects of task hand force. The range estimates, R^2 values, and root-mean-square-error (RSME) values in Table6.4.1 and Table 6.4.2 indicate the relative contribution of the anthropometric, strength and task configuration variables in determining task hand force magnitude and direction. Fore-aft location of the task handle is a consistent determinant of task hand force strength across the nominal backward and upward tasks. Isolated leg strength and stature also account for a large percentage of the variance in task hand force magnitude across nominal backward and forward task hand force directions and associated FGSs. The remaining task configuration, anthropometric, and strength variables have varying levels of importance depending upon the FGS employed, nominal task hand force direction and task hand force level.

Backward Exertions

Leg strength and stature are the most important determinants of maximal task handle force during backward exertions across the range of FGSs and task configurations studied. Backward tasks executed with the NB and HB strategies are also largely affected by the fore-aft task handle location, indicating that subjects are less capable of generating task hand force under conditions in which the bracing structure imposes a greater degree of kinematic constraint due to the extended reach to the task handle and yet does the afford the opportunity to utilize the brace surface. Subsequently, the level of bracing availability is also a strong predictor of pulling strength for NB trials. Task hand force magnitude generated during NB and HB trials is well predicted for backward exertions, with R^2 adjusted values ranging from 0.50 to 0.70. Backward exertions that employing TB and HTB-o FGSs, were predominated predicted by anthropometric variables, specifically stature and leg strength. Stature had a strong effect, 165 N for a 399 mm range, while leg strength evoked a moderate effect accounting 175 N with respect to a 1259 N range.

Forward Exertions

The task-hand force magnitudes for forward exertions with the NB and TB FGSs are unaffected by the test variables and are poorly predicted overall by the anthropometric or strength variables. The RSME values indicate that the range of force magnitude is fairly large, but there is a poor relationship between the potential predictors and forward exertions. In contrast, task hand force magnitude for forward exertions generated with the HB strategy is well predicted, with R^2 adjusted of 0.60. The most powerful predictor of forward task strength for HB trials is leg strength, followed by stature. Leg strength is the only predictor of forward task hand strength for tasks employing the HTB-a strategy. Test configuration variables had no significant effect on forward tasks employing HB, TB or HTB-a FGS.

Upward Exertions

The effect of fore-aft task handle location was similar for upward and backward exertions. Fore versus aft task handle locations resulted in significant differences in task hand force for upward exertions that were employed NB and HB FGSs. Vertical task handle position also affected upward task hand force strength for NB trials, in that task hand force decreased with the vertical task handle height. In combination with the task configuration effects, stature and torso strength are also predictors of task hand force. The R^2 adjusted values range from 0.2 to 0.6, indicating that upward exertions performed by employing the NB and HB strategy are predicted moderately well. The regressors of upward task hand force strength exerted during TB trials differ for sub-maximal and maximal force levels. Sub-maximal task force is affected by BMI and stature, while arm strength is an important determinant of upward, maximal exertions. HTB-o trials are largely unaffected by the task configuration variables and stature is the only anthropometric variable to effect upward task strength. The RSME values indicate that range of upward exertions in the data is fairly large, but the R^2 values of 0.2 and the lack of significance for maximal exertions indicate that poor relationships between the potential predictors and upward task hand force.

Table6.4.1: Models for predicting task hand force (F_{Task} resultant magnitude)*

Nominal Force Direction	Task Hand Force Level	FGS	F_{Task} / Task Configuration & Subject Parameters	DoF	R^2 Adj	RSME
Backward	50%	NB	F_{Task} = 295.5TaskLoc$_x$ -19.15BraceLevel – 2.29BMI	76	0.47	34.60
		HB	F_{Task} = 181.5TaskLoc$_x$ -121.6TaskLoc$_z$ + 0.15Stature – 0.08Leg	80	0.65	30.27
		TB	F_{Task} = 0.21Stature + 0.07Leg	64	0.59	31.00
		HTB-o	F_{Task} = 0.11Leg	57	0.48	39.29
	Max	NB	F_{Task} = 587.5TaskLoc$_x$ -72.85BraceLevel + 0.09Leg	70	0.58	62.26
		HB	F_{Task} = 333.9TaskLoc$_x$ + 0.34Stature + 0.15Leg	84	0.62	57.33
		TB	F_{Task} = 0.41Stature + 0.14Leg	63	0.54	66.15
		HTB-o	F_{Task} = 0.46Stature + 0.18Leg	59	0.64	68.69
Forward	50%	NB	F_{Task}	89	~	56.15
		HB	F_{Task} = - 4.13BMI - 0.48Stature + 0.088Arm + 0.21Torso + 0.17Leg – 0.17BMI*Stature + 0.09BMI*Torso – 0.004Stature*Arm + 0.001Torso*Leg	73	0.59	31.38
		TB	F_{Task} = 0.05Leg	49	0.17	36.19
		HTB-a	F_{Task} = 0.09Leg	46	0.37	44.78
	Max	NB	F_{Task}	86	~	119.19
		HB	F_{Task} = - 18.8BMI – 0.97Stature + 0.09Arm + 0.45Torso + 0.41Leg - 0.29BMI*Stature + 0.21BMI*Torso – 0.009Stature*Arm + 0.003Torso*Leg	86	0.63	60.56
		TB	F_{Task}	35	~	71.26
		HTB-a	F_{Task} = 0.15Leg	38	0.33	77.44
Upward	50%	NB	F_{Task} = 243.4TaskLoc$_x$	54	0.31	29.90
		HB	F_{Task} = 245.01TaskLoc$_x$	50	0.16	44.37
		TB	F_{Task} = 8.59BMI – 0.22Stature	55	0.30	43.48
		HTB-o	F_{Task}	-	~	56.41
	Max	NB	F_{Task} = 321.9TaskLoc$_x$ + 212.2 TaskLoc$_x^2$ + 0.16Stature	44	0.55	29.59
		HB	F_{Task} = 505.9TaskLoc$_x$ + 0.22Torso	48	0.43	59.38
		TB	F_{Task} = 66.56TaskLoc$_z$ + 0.17Arm	58	0.37	93.88
		HTB-o	F_{Task} = 0.52Stature	48	0.26	93.49

*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.

BraceLevel 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; Arm denotes isolated arm strength; Torso denotes isolated torso strength; Leg denotes isolated leg strength

Table 6.4.2 Range estimates of task hand force (F_{Task} resultant magnitude) using regression models*

Nominal Force Direction	Task Hand Force Level	FGS	$Task_x$	$Task_z$	Brace Level#	BMI	Stature	Arm	Torso	Leg	DoF	R^2 Adj	RSME
RANGE: Forward & Backward			**0.3**	**0.4**	**3.0**	**13.9**	**399.0**	**813.6**	**651.2**	**1258.9**			
RANGE: Upward			**0.3**	**0.2**									
Backward	50%	NB	84.2	-	-57.4	-31.9	-	-	-	-	76	0.5	34.6
		HB	51.7	-43.3	-	-	58.7	-	-	105.7	80	0.7	30.3
		TB	-	-	-	-	82.2	-	-	91.9	64	0.6	31.0
		HTB-o	-	-	-	-	0.0	-	-	136.0	57	0.5	39.3
	Max	NB	167.4	-	-218.5	-	-	-	-	110.9	70	0.6	62.3
		HB	95.2	-	-	-	136.5	-	-	182.5	84	0.6	57.3
		TB	-	-	-	-	165.2	-	-	175.0	63	0.5	66.2
		HTB-o	-	-	-	-	182.3	-	-	226.6	59	0.6	68.7
Forward	50%	NB	-	-	-	-	-	-	-	-	89	~	56.1
		HB	-	-	-	-57.6	-192.3	71.5	134.8	215.3	73	0.6	31.4
		TB	-	-	-	-	-	-	-	65.2	49	0.2	36.2
		HTB-a	-	-	-	-	-	-	-	119.1	46	0.4	44.8
	Max	NB	-	-	-	-	-	-	-	-	86	~	119.2
		HB	-	-	-	-263	-387.8	69.6	289.8	514.9	86	0.6	60.6
		TB	-	-	-	-	-	-	-	-	35	~	71.3
		HTB-a	-	-	-	-	-	-	-	190.1	38	0.3	77.4
Upward	50%	NB	69.4	-	-	-	-	-	-	-	54	0.3	29.9
		HB	69.8	-	-	-	-	-	-	-	50	0.2	44.4
		TB	-	-	-	119	85.7	-	-	-	55	0.3	43.5
		HTB-o	-	-	-	-	-	-	-	-	-	~	56.4
	Max	NB	91.8	-	-	-	64.6	-	-	-	44	0.6	29.6
		HB	144.2	-	-	-	-	-	144.6	-	48	0.4	59.4
		TB	-	-	199.8	-	-	139.5	-	-	58	0.4	93.9
		HTB-o	-	-	-	-	209.1	-	-	-	48	0.3	93.5

BraceLevel 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; Arm denotes isolated arm strength; Torso denotes isolated torso strength; Leg denotes isolated leg strength

Prediction of Resultant Task Hand Force Direction

Backward Exertions

The available variables account for a large percentage of variance in direction of task hand force, R^2 values ranged from 0.6 to 0.9, for backward exertions and FGSs. Vertical handle position is by far the most important determinant of task force direction. The fore-aft location of the exertion handle also affects the direction of the task hand force. Prescribed level of bracing availability affected the direction of task hand force for NB and TB trials only. Anthropometric variables, stature and to a lesser extent BMI, and all of the strength variables, affect task hand force direction as both an independent and interacting affects for sub-maximal trials employing the HB strategy. Of the potential predictors, vertical and fore-aft task handle position, are the most predominate predictors of task hand force direction for both TB and HTB-o FGSs.

Forward Exertions

The task hand force direction for forward exertion tasks are effectively predicted by the task configuration variables across the FGSs. The R^2 values, ranging from 0.5 to 0.9 across the force levels and FGSs, indicate strong relationships between the vertical handle position and force direction. Arm and leg strength variables have an affect on task hand force direction for HB strategy only.

Upward Exertions

Task hand force direction of upward exertion is predicted moderately well by the predictors across the FGSs. Task configuration variables, fore-aft and vertical handle positions, both have an affect on task hand force direction. The RSME values indicate that the range of task hand force direction in the data is fairly large, as compared to the backward and forward nominal directions, but the R^2 values of 0.3, 0.3 and 0.2 for NB, TB and HTB-o strategies for sub-maximal force levels, respectively, indicate poor relationships between the potential predictors and task hand force direction.

Table6.4.3: Models for predicting task hand force direction (θ_{Task})*

Nominal Force Direction	Task Hand Force Level	FGS	θ_{Task} / Task Configuration & Subject Parameters	DoF	R^2 Adj	RSME
Backward	50%	NB	$\theta_{Task} = 55.24TaskLoc_x - 124TaskLoc_z - 78.0TaskLoc_x*BraceLevel$	76	0.59	10.97
		HB	$\theta_{Task} = 48.94TaskLoc_x - 107.6TaskLoc_z - 0.3BMI - 0.08Stature + 0.02Arm + 0.02Torso + 0.006Leg - 0.02BMI*Stature + 0.02BMI*Torso - 0.0006Stature*Arm + 0.0001Torso*Leg$	80	0.86	4.40
		TB	$\theta_{Task} = 35.56TaskLoc_x - 98.1\ TaskLoc_z^2$	64	0.73	5.70
		HTB-o	$\theta_{Task} = 28.35TaskLoc_x - 124.4TaskLoc_z$	56	0.75	6.02
	Max	NB	$\theta_{Task} = -553.9TaskLoc_z + 385.9Task\ Loc_z^2 + 14.19BraceLevel$	70	0.77	8.66
		HB	$\theta_{Task} = 26.66\ Task\ Loc_x - 93.1Task\ Loc_z$	84	0.72	5.56
		TB	$\theta_{Task} = -97.8TaskLoc_z + 9.75BraceLevel$	61	0.59	7.48
		HTB-o	$\theta_{Task} = 30.55Task\ Loc_x - 80.4TaskLoc_z^2$	59	0.65	6.02
Forward	50%	NB	$\theta_{Task} = 106.4TaskLoc_z$	87	0.54	9.23
		HB	$\theta_{Task} = 119.9TaskLoc_z - 0.02\ Arm + 0.013Leg - 0.0001Arm*Leg$	72	0.89	4.30
		TB	$\theta_{Task} = 149.7TaskLoc_z$	50	0.77	6.65
		HTB-a	$\theta_{Task} = 150.5TaskLoc_z$	46	0.77	6.49
	Max	NB	$\theta_{Task} = 121.5TaskLoc_z$	77	0.70	7.28
		HB	$\theta_{Task} = 122.2TaskLoc_z$	82	0.84	5.26
		TB	$\theta_{Task} = 152.8TaskLoc_z$	32	0.67	9.00
		HTB-a	$\theta_{Task} = 137.2TaskLoc_z$	39	0.83	5.26
Upward	50%	NB	$\theta_{Task} = 147.3TaskLoc_x + 204.9TaskLoc_z^2 - 3361.7\ TaskLoc_x*TaskLoc_z^2$	54	0.20	21.53
		HB	$\theta_{Task} =$	53	~	24.08
		TB	$\theta_{Task} = -107.1TaskLoc_x$	54	0.27	14.75
		HTB-o	$\theta_{Task} = -100.9TaskLoc_x$	42	0.30	12.87
	Max	NB	$\theta_{Task} =$	-	~	19.51
		HB	$\theta_{Task} = 105.4TaskLoc_z$	48	0.24	12.06
		TB	$\theta_{Task} = -82.1TaskLoc_x + 101.1TaskLoc_z$	57	0.70	7.04
		HTB-o	$\theta_{Task} = -89.5TaskLoc_x + 103.7TaskLoc_z$	47	0.69	7.99

*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.

BraceLevel is a nominal variable and only one value from each strategy should enter the regression equation at any onetime.

$TaskLoc_x$ denotes fore-aft task handle location; $TaskLoc_z$ ($_z^2$)denotes vertical task handle position; Arm denotes isolated arm strength; Torso denotes isolated torso strength; Leg denotes isolated leg strength

Table 6.4.4 Range estimates of task hand force direction (θ_{Task}) using regression models*

Nominal Force Direction	Task Hand Force Level	FGS	$Task_x$	$Task_z$	$Task_z^2$	Brace Level#	BMI	Stature	Arm	Torso	Leg	DoF	R^2 Adj	RSME
RANGE: Forward & Backward			**0.3**	**0.4**	**0.4**	**3.0**	**13.9**	**399.0**	**813.6**	**651.2**	**1258.9**			
RANGE: Upward			**0.3**	**0.2**	**0.2**									
Backward	50%	NB	15.7	-37.2	-	18.8	-	-	-	-	-	76	0.6	11.0
		HB	13.9	-38.3	-	-	-4.2	-33.5	14.7	11.1	7.6	80	0.9	4.4
		TB	10.1	-	-40.6	-	-	-	-	-	-	64	0.7	5.7
		HTB-o	8.1	-44.3	-	-	-	-	-	-	-	56	0.8	6.0
	Max	NB	-	-197.2	159.8	42.6	-	-	-	-	-	70	0.8	8.7
		HB	7.6	-33.1	-	-	-	-	-	-	-	84	0.7	5.6
		TB	-	-34.8	-	29.2	-	-	-	-	-	61	0.6	7.5
		HTB-o	8.7	-	-33.3	-	-	-	-	-	-	59	0.7	6.0
Forward	50%	NB	-	37.9	-	-	-	-	-	-	-	87	0.5	9.2
		HB	-	42.7	-	-	-	-	-13.7	-	16.2	72	0.9	4.3
		TB	-	53.3	-	-	-	-	-	-	-	50	0.8	6.6
		HTB-a	-	53.6	-	-	-	-	-	-	-	46	0.8	6.5
	Max	NB	-	43.3	-	-	-	-	-	-	-	77	0.7	7.3
		HB	-	43.5	-	-	-	-	-	-	-	82	0.8	5.3
		TB	-	54.4	-	-	-	-	-	-	-	32	0.7	9.0
		HTB-a	-	48.9	-	-	-	-	-	-	-	39	0.8	5.3
Upward	50%	NB	42.0	-	49.8	-	-	-	-	-	-	54	0.2	21.5
		HB	-	-	-	-	-	-	-	-	-	53	~	24.1
		TB	-30.5	-	-	-	-	-	-	-	-	54	0.3	14.8
		HTB-o	-28.8	-	-	-	-	-	-	-	-	42	0.3	12.9
	Max	NB	-	-	-	-	-	-	-	-	-	-	~	19.5
		HB	-	24.6	-	-	-	-	-	-	-	48	0.2	12.1
		TB	-23.4	23.6	-	-	-	-	-	-	-	57	0.7	7.0
		HTB-o	-25.5	24.2	-	-	-	-	-	-	-	47	0.7	8.0

BraceLevel 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; Arm denotes isolated arm strength; Torso denotes isolated torso strength; Leg denotes isolated leg strength

Prediction of Resultant Contralateral Hand Force

The task hand force was found to be a highly significant predictor of contralateral hand forces generated during backward, forward and upward exertions. The relationship is significant for all nominal force directions, force levels, task configurations and FGSs. A linear trend between task hand force and brace hand force is observed over a 540 N task hand force range, and the task force effect is very similar for all FGSs in which the contralateral (bracing) hand is involved.

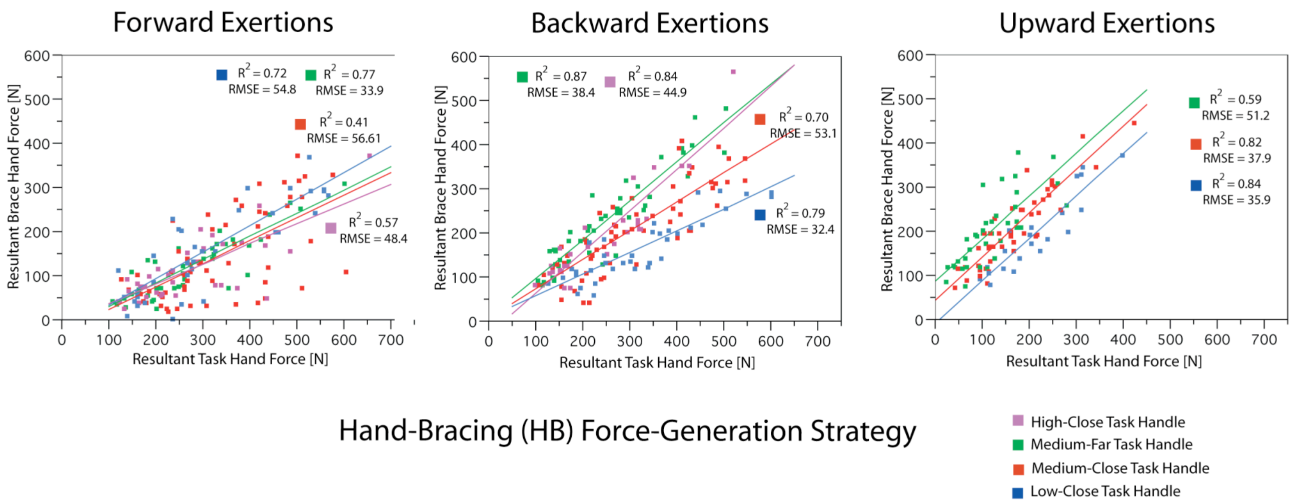

Figure 6.4.1 Contralateral hand bracing force during nominal backward, forward and upward exertions at the four task configurations for HB FGS. Differences in bracing hand forces are significant for the task handle locations by the linear fit (p<0.01).

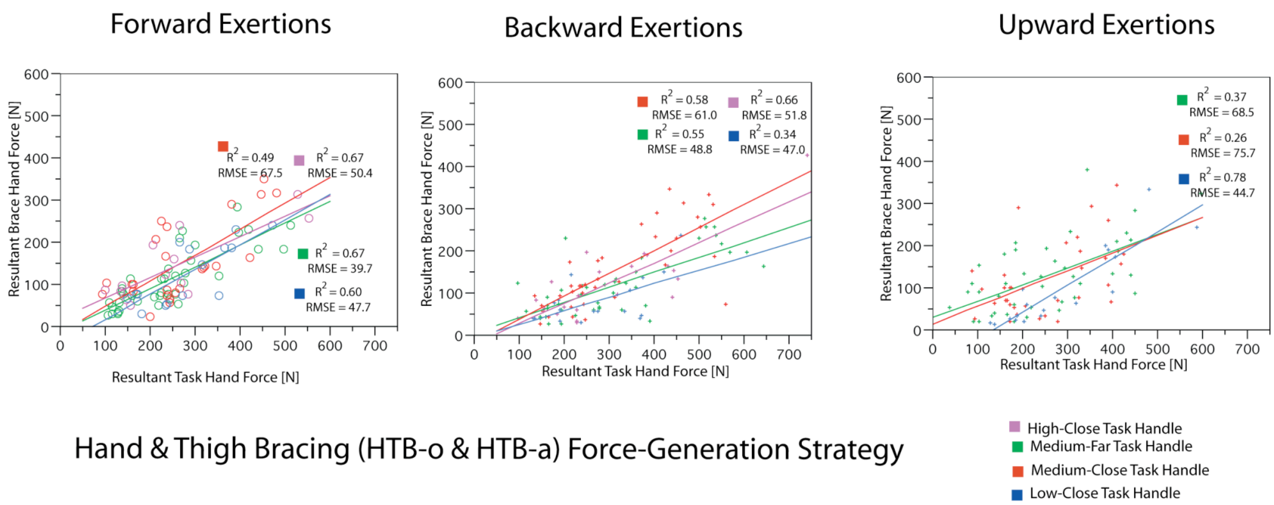

Figure 6.4.2 Contralateral hand bracing force during nominal backward, forward and upward exertions at the four task configurations for HB FGS. Differences in bracing hand forces are significant for the task handle locations by the linear fit (p<0.01).

Backward Exertions

Task hand force is the most important determinant of brace hand force for backward exertions that employed both HB and HTB-o FGSs and across the task configurations. Change in the fore-aft location and vertical position of the task handle were both predictors of contralateral hand force. For backward exertions the task configuration variables contribution to brace hand force is dependent upon the force-generation strategy employed. Greater bracing hand force was observed for medium-close vs. medium-far task handle positions. Vertical task handle position effects were dependent upon the force-generation strategy employed. Hand bracing strategies increased brace hand force as the height of the task handle location was lowered, while HTB-opposed strategies increased brace hand force as the handle increased in height. Sub-maximal and maximal backward exertions were well predicted for HB and HTB-o FGS, R^2 adjusted ranged from 0.50 to 0.71, with exception of sub-maximal HTB-o trials (R^2 adj = 0.23).

Forward Exertions

Brace hand force magnitude is moderately well predicted (adjusted R^2 range of 0.36 to 0.57) for forward exertions performed with HB and HTB-a FGS. Leg strength, BMI, and stature contribute as regressors. Sub-maximal exertions with the HB strategy are not predictable by the available anthropometric, strength and task configuration variables. Brace hand force generated during maximal forward exertions was affected by the vertical task handle position. As the task handle location transitioned from low to high height brace hand force increased. Task hand forces also have important effects for those exertions performed with hand bracing only. Arm strength and BMI affect hand-bracing force for HTB-a trials.

Upward Exertions

Similar to backward exertions, task hand force had a significant affect on brace hand force for upward exertions performed with both HB and HTB-o FGSs. Vertical task handle position was a predictor of contralateral hand force for HB trials only. The level of bracing available to the subjects affected HTB-o trials. Upward exertions that employed HTB-o FGS, were also affected by arm strength variable. Contralateral hand force magnitude generated during HB and HTB-o trials is predicted only moderately well for upward exertions, with R^2 adjusted values ranging from 0.33 to 0.57.

Table 6.4.5 Regression equations predicting contralateral hand bracing force (F_{Brace} resultant magnitude)*

Nominal Force Direction	Task Hand Force Level	FGS	F_{Brace} / Task Configuration & Subject Parameters	DoF	R^2 Adj	RSME
Backward	50%	HB	$F_{Brace} =$ -208.2TaskLoc$_x$ + 174.6TaskLoc$_z$ - 23.7BraceLevel + 0.71TaskHF	80	0.50	36.7
		HTB-o	$F_{Brace} =$ 0.39TaskHF	57	0.23	37.7
	Max	HB	$F_{Brace} =$ -434.6TaskLoc$_x$ + 175.0TaskLoc$_z$ + 226.3TaskLoc$_z^2$ + 0.79TaskHF + 2.35 TaskLoc$_z^2$*TaskHF	84	0.71	47.8
		HTB-o	$F_{Brace} =$ 340.8TaskLoc$_x$ + 4793.4TaskLoc$_z$ - 3941.6TaskLoc$_z^2$ + 0.16Leg	59	0.55	60.5
Forward	50%	HB	F_{Brace}	77	~	41.7
		HTB-a	$F_{Brace} =$ 4.54BMI + 0.07Stature + 0.07Leg + 0.13BMI*Stature – 0.06BMI*Leg	46	0.57	23.7
	Max	HB	$F_{Brace} =$ -215.6TaskLoc$_z$ + 0.43TaskHF	82	0.36	67.8
		HTB-a	$F_{Brace} =$ -1807.9TaskLoc$_z$ + 1809.3TaskLoc$_z^2$ + 3.57BMI + 0.45Arm – 128.1TaskLoc$_z^2$*BMI	35	0.55	59.8
Upward	50%	HB	$F_{Brace} =$ 261.2TaskLoc$_z$ + 0.66TaskHF + 0.05Arm	50	0.57	31.2
		HTB-o	$F_{Brace} =$ -36.7BraceLevel + 0.05Arm	42	0.133	31.0
	Max	HB	$F_{Brace} =$ 453.6TaskLoc$_z$ + 0.72TaskHF	48	0.49	51.4
		HTB-o	$F_{Brace} =$ -72.9BraceLevel + 0.43TaskHF	48	0.33	68.7

*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.

BraceLevel 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; Arm denotes isolated arm strength; Torso denotes isolated torso strength; Leg denotes isolated leg strength; TaskHF– task hand force level.

Table 6.4.6 Range estimates of contralateral hand bracing force (F_{Brace} resultant magnitude) using regression models*

Nominal Force Direction	Task Hand Force Level	FGS	Task HF Range	$Task_x$	$Task_z$	$Task_z^2$	Brace Level#	Task HF	BMI	Stature	Arm	Leg	DoF	R^2 Adj	RSME
RANGE: Forward & Backward **RANGE:** Upward				**0.3**	**0.4** **0.2**	**0.4** **0.2**	**3.0**		**13.9**	**399.0**	**813.6**	**1258.9**			
Backward	50%	HB	**212.0**	-59.3	62.2	-	-71.0	150.3	-	-	-	-	80	0.50	36.7
		HTB-o	**283.2**	-	-	-	-	110.4	-	-	-	-	57	0.23	37.7
	Max	HB	**430.5**	-123.9	62.3	93.7	-	338.8	-	-	-	-	84	0.71	47.8
		HTB-o	**539.3**	97.1	1706.4	1631.8	-	-	-	-	-	199.7	59	0.55	60.5
Forward	50%	HB	**213.0**	-	-	-	-	-	-	-	-	-	77	~	41.7
		HTB-a	**276.0**	-	-	-	-	-	63.3	27.5	-	83.7	46	0.57	23.7
	Max	HB	**420.4**	-	-76.7	-	-	180.2	-	-	-	-	82	0.36	67.8
		HTB-a	**346.9**	-	-643.6	749.0	-	-	49.7	-	364.8	-	.35	0.55	59.8
Upward	50%	HB	**189.9**	-	60.9	-	-	125.3	-	-	39.4	-	50	0.57	31.2
		HTB-o	**277.5**	-	-	-	-109.9	-	-	-	42.9	-	42	0.33	31.0
	Max	HB	**337.6**	-	105.7	-	-	244.3	-	-	-	-	48	0.49	51.4
		HTB-o	**511.1**	-	-	-	-218.6	221.7	-	-	-	-	48	0.33	68.7

#BraceLevel 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; Arm denotes isolated arm strength; Torso denotes isolated torso strength; Leg denotes isolated leg strength; TaskHF– task hand force level.

Prediction of Brace Hand Direction

Task hand force magnitude is the most effective predictor of brace hand force direction for those exertions performed with HB FGS. Task hand force and brace hand force are moderately correlated, and to a lesser degree task and brace hand directions, across test configuration variables.

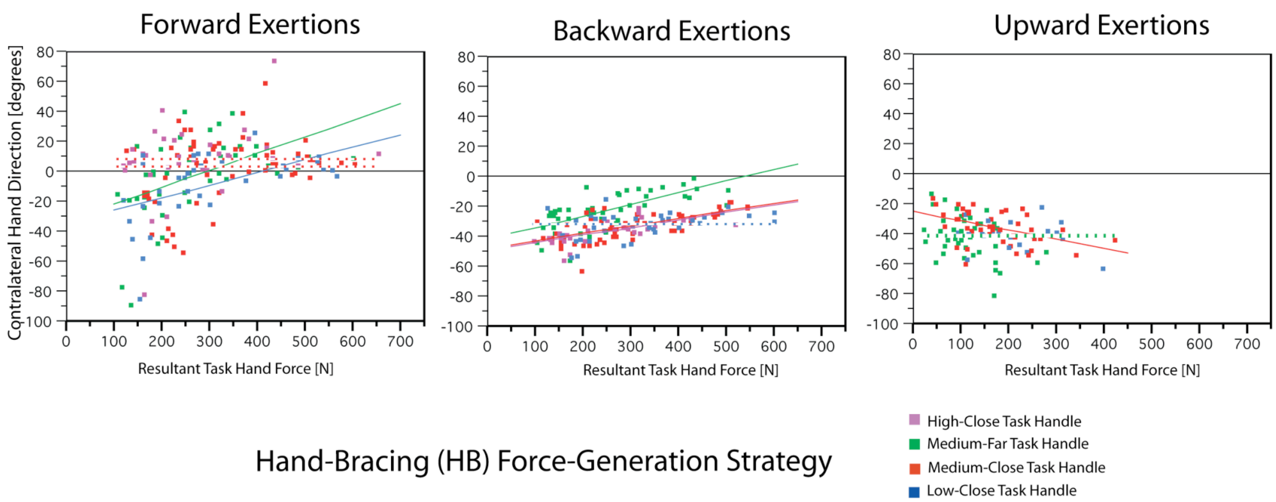

Figure 6.4.3 Contralateral hand force direction during forward, backward and upward exertions adopting HB FGS. Linear fit denoted by solid line, (color-coded for task handle location) are significant ($p<0.01$); mean values denoted by the hatch lines (color-coded for task handle location).

Brace hand force direction is largely unaffected by the test configuration variables and also not well predicted by anthropometric and strength variables. The RSME values indicate that the range of brace hand force vectors is fairly large, but the R^2 values which range from 0.17 to 0.65, indicate moderate relationships between the potential predictors and brace hand direction.

Table6.4.7: Models for predicting contralateral hand bracing force direction (θ_{Brace})*

Nominal Force Direction	Task Hand Force Level	FGS	θ_{Brace} / Task Configuration & Subject Parameters	DoF	R^2 Adj	RSME
Backward	50%	HB	θ_{Brace} = -62.7TaskLoc$_x$ + 0.04Stature + 0.011Arm + 0.004Torso + 0.0006Stature*Arm – 0.0003Arm*Torso	80	0.52	6.79
		HTB-o	θ_{Brace} =	57	~	13.68
	Max	HB	θ_{Brace} = -82.9TaskLoc$_x$ + 0.04TaskHF + 0.0005Stature*Leg – 0.001Arm*Torso	84	0.5	6.72
		HTB-o	θ_{Brace} = 0.04Stature + 0.06Arm + 0.02Torso - 0.03Leg	59	0.3	14.16
Forward	50%	HB	θ_{Brace} = 60.6TaskLoc$_z$ + 0.25TaskHF + 0.4TaskHF$_\theta$ - 0.1Stature - 0.004Torso + 5.94 TaskLoc$_z$*TaskHF – 3.20TaskLoc$_z$*Stature – 0.05TaskHF*TaskHF$_\theta$ + 0.001TaskHF* Torso + 0.026Stature*TaskHF$_\theta$	75	0.51	19.95
		HTB-a	θ_{Brace} = 157.1TaskLoc$_x$	46	0.18	29.6
	Max	HB	θ_{Brace} =	90	~	14.1
		HTB-a	θ_{Brace} = 53.9BraceLevel - 0.05TaskHF	42	0.65	11.9
Upward	50%	HB	θ_{Brace} = 70.5TaskLoc$_x$ - 0.12TaskHF	50	0.25	10.3
		HTB-o	θ_{Brace} =	42	~	21.8
	Max	HB	θ_{Brace} = 93.5TaskLoc$_x$ - 0.08TaskHF	48	0.26	11.1
		HTB-o	θ_{Brace} = 25.7BraceLevel - 0.115Stature	48	0.39	21.0

*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.

BraceLevel 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; Arm denotes isolated arm strength; Torso denotes isolated torso strength; Leg denotes isolated leg strength; TaskHF– task hand force level; TaskHF$_\theta$– task hand force direction.

Table 6.4.8 Range estimates of contralateral hand bracing force direction (θ_{Brace}) using regression models*

Nominal Force Direction	Task Hand Force Level	FGS	TaskHF Range	$Task_x$	$Task_z$	Brace Level#	Task HF	Task HF_θ	Stature	Arm	Torso	Leg	DoF	R^2 Adj	RSME
RANGE: Forward & Backward				**0.3**	**0.4**	**3.0**			**399.0**	**813.6**	**651.2**	**1258.9**			
RANGE: Upward				**0.3**	**0.2**										
Backward	50%	HB	**44.6**	-17.9	-	-	-	-	14.28	9.36	2.52	-	80	0.52	6.79
		HTB-o	**68.8**	-	-	-	-	-	-	-	-	-	57	~	13.68
	Max	HB	**41.1**	-23.6	-	-	17.7	-	-	-	-	-	84	0.50	6.72
		HTB-o	**58.7**	-	-	-	-	-	15.95	46.52	12.73	-32.35	59	0.30	14.16
Forward	50%	HB	**59.8**	-	21.6	-	53.2	23.7	-40.54	-	-2.50	-	75	0.51	19.95
		HTB-a	**57.2**	44.8	-	-	-	-	-	-	-	-	46	0.18	29.6
	Max	HB	**56.0**	-	-	-	-	-	-	-	-	-	90	~	14.1
		HTB-a	**51.5**	-	-	161.6	-18.8	-	-	-	-	-	42	0.65	11.9
Upward	50%	HB	**112.7**	20.1	-	-	-22.6	-	-	-	-	-	50	0.25	10.3
		HTB-o	**61.5**	-	-	-	-	-	-	-	-	-	42	~	21.8
	Max	HB	**64.2**	26.7	-	-	-27.1	-	-	-	-	-	48	0.26	11.1
		HTB-o	**54.3**	-	-	77.2	-	-	-45.97	-	-	-	48	0.39	21.0

BraceLevel 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; Arm denotes isolated arm strength; Torso denotes isolated torso strength; Leg denotes isolated leg strength; TaskHF– task hand force level; $TaskHF_\theta$– task hand force direction.

Prediction of Resultant Thigh Force

Nominal task hand force is a significant predictor of resultant thigh forces generated for backward and upward exertions performed with TB and HTB-o FGS and across all task handle locations. The effect of resultant task hand force magnitude on resultant thigh force generation is approximately linear over the 540 N range. It was also observed that the nominal task hand force is not a significant predictor of thigh force for forward exertions.

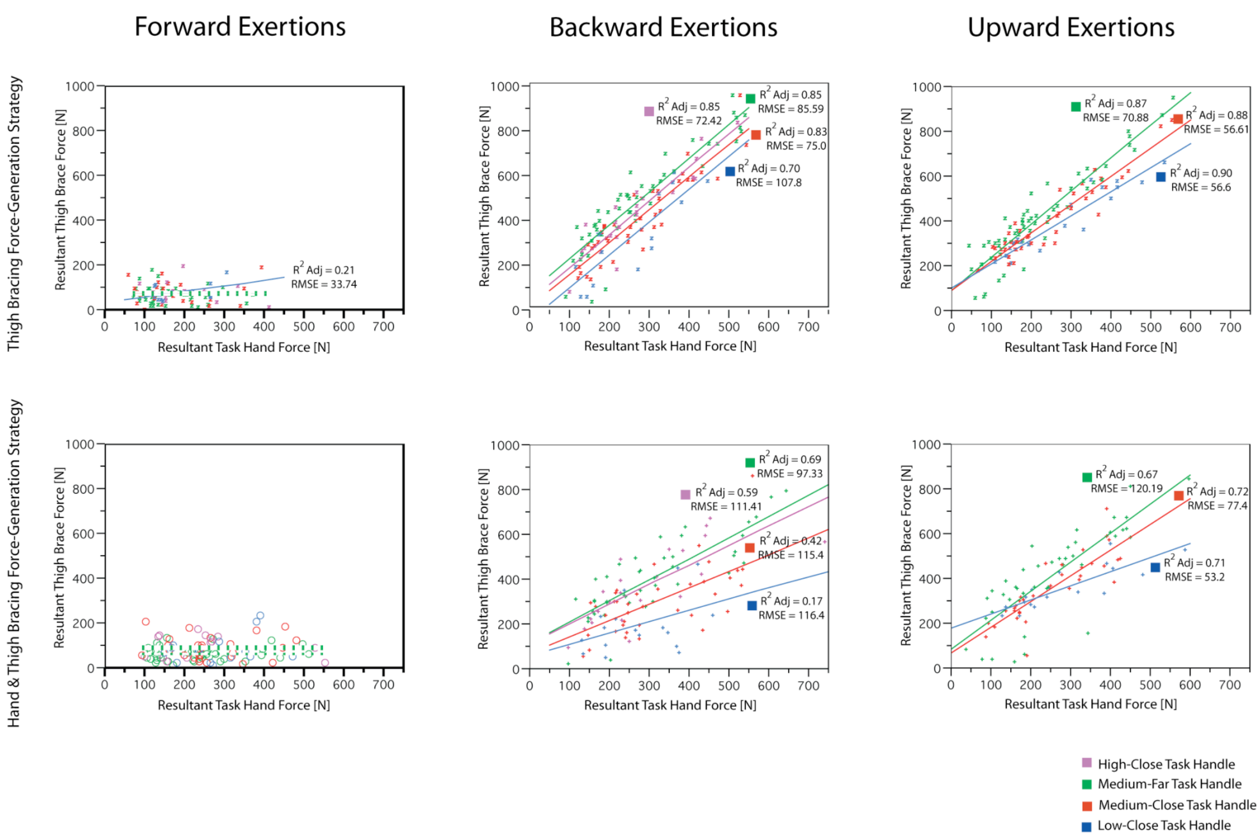

Figure 6.4.4 Thigh body-force during nominal forward, backward and upward exertions at the four task configurations for TB and HTB-o FGS. Differences in thigh body-bracing forces are significant for the task handle locations by the linear fit ($p<0.01$).

Backward Exertions

For TB and HTB-o trials and task hand force levels body-bracing forces exerted during backward exertions are predicted moderately well by the regressors. The most powerful predictor of resultant thigh force is task hand force. Fore-aft location of the task handle also contributes significantly to average body-bracing force generation. Vertical task handle height is also an important determinant that is unique to maximal backward exertions adopting both TB and HTB-o FGS. Body-bracing force magnitude generated during TB and HTB-o trials is therefore predicted well for backward exertions, with R^2 adjusted values ranging from 0.4 to 0.94.

Forward Exertions

Test configuration, strength and anthropometric variables fail to account for a large percentage of variance in average thigh bracing force generated during forward exertion tasks. The RSME values indicate that the range of thigh bracing in the data is fairly small, but the lack of significant R^2 values indicates poor relationships between the potential predictors and thigh force magnitude. Thigh bracing force produced while employing TB strategy during maximal forward exertion task was the only task configuration to predict thigh forces. BMI, arm strength, stature and fore-aft location of the task handle also have moderate effects on TB trials, most strongly by BMI.

Upward Exertions

Thigh bracing forces magnitude is well predicted, as the adjusted R^2 values ranged from 0.80 to 0.86) for upward exertions performed with TB and HTB-o FGSs. The most powerful predictor of resultant thigh force is task hand force, given the positive, linear correlation between these two dependent variables across the task handle locations and FGS (). Fore-aft location of the task handle also significantly contributes to average body-bracing force generation. Prescribed level of bracing availability also has an effect on upward exertions for both TB and HTB-o FGS.

Table 6.4.9 Regression equations predicting thigh (body)- bracing force (F_{Thigh} resultant magnitude)*

Nominal Force Direction	Task Hand Force Level	FGS	F_{Thigh} / Task Configuration & Subject Parameters	DoF	R^2 Adj	RSME
Backward	50%	TB	F_{Thigh} = -506.8TaskLoc$_x$ + 2.24TaskHF - 0.19Arm	64	0.75	65.0
		HTB-o	F_{Thigh} = -525.1TaskLoc$_x$ + 1.001TaskHF	56	0.4	84.1
	Max	TB	F_{Thigh} = -1047TaskLoc$_x$ - 6390TaskLoc$_z$ + 5175TaskLoc$_z^2$ - 19.53BraceLevel + 1.45TaskHF - 0.004Stature + 128266.9TaskLoc$_x$*TaskLoc$_z$ - 97539TaskLoc$_x$*Task Loc$_z^2$ - 1694BraceLevel*TaskLoc$_x$ - 0.002Stature*Leg	61	0.94	47.1
		HTB-o	F_{Thigh} = -766.7TaskLoc$_x$ + 904.9TaskLoc$_z$ + 0.8TaskHF	59	0.57	120.1
Forward	50%	TB	F_{Thigh} =	52	~	39.0
		HTB-a	F_{Thigh} =	49	~	41.0
	Max	TB	F_{Thigh} = 247.1TaskLoc$_x$ - 0.12TaskHF + 14.21BMI - 0.032Stature + 0.18Arm + 82.11TaskLoc$_x$*BMI – 3.38TaskLoc$_x$*Stature + 3.09TaskLoc$_x$*Arm + 0.003TaskHF*Stature	32	0.82	18.2
		HTB-a	F_{Thigh} =	42	~	55.3
Upward	50%	TB	F_{Thigh} = -375.7TaskLoc$_x$ + 58.4BraceLevel + 1.31TaskHF	54	0.8	42.9
		HTB-o	F_{Thigh} = -458.8TaskLoc$_x$ + 104.8BraceLevel + 1.26TaskHF	42	0.83	43.4
	Max	TB	F_{Thigh} = -589.8TaskLoc$_x$ + 57.3BraceLevel + 1.28TaskHF	57	0.86	67.4
		HTB-o	F_{Thigh} = -706.3TaskLoc$_x$ + 185.2BraceLevel + 0.74TaskHF	47	0.81	75.4

*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.

BraceLevel 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; Arm denotes isolated arm strength; Torso denotes isolated torso strength; Leg denotes isolated leg strength; TaskHF– task hand force level.

Table 6.4.10 Range estimates of thigh (body)- bracing force (F_{Thigh} resultant magnitude) using regression models*

Nominal Force Direction	Task Hand Force Level	FGS	Task HF Range	$Task_x$	$Task_z$	$Task_z^2$	Brace Level #	Task HF	BMI	Stature	Arm	Leg	DoF	R^2 Adj	RSME
RANGE: Forward & Backward **RANGE:** Upward				**0.3**	**0.4** **0.2**	**0.4** **0.2**	**3.0**		**13.9**	**399.0**	**813.6**	**1258.9**			
Backward	50%	TB	191.4	-144.4	-	-	-	428.3	-	-	-154.3	-	64	0.75	65.0
		HTB-o	283.2	-149.6	-	-	-	283.4	-	-	-	-	56	0.4	84.1
	Max	TB	387.1	-298.4	-2275	2142	-58.6	562.9	-	399.0	-	-28.7	61	0.94	47.1
		HTB-o	539.3	-218.5	322.2	-	-	433.6	-	-	-	-	59	0.57	120.1
Forward	50%	TB	190.9	-	-	-	-	-	-	-	-	-	52	~	39.0
		HTB-a	276.0	-	-	-	-	-	-	-	-	-	49	~	41.0
	Max	TB	183.7	70.4	-	-	-	-21.9	198	-12.9	149.0	-	32	0.82	18.2
		HTB-a	346.9	-	-	-	-	-	-	-	-	-	42	~	55.3
Upward	50%	TB	276.2	-107.1	-	-	175.3	277.5	-	-	-	-	54	0.8	42.9
		HTB-o	277.5	-130.7	-	-	314.5	278.8	-	-	-	-	42	0.83	43.4
	Max	TB	475.9	-168.1	-	-	171.9	609.7	-	-	-	-	57	0.86	67.4
		HTB-o	511.1	-201.3	-	-	555.5	377.8	-	-	-	-	47	0.81	75.4

#BraceLevel 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; Arm denotes isolated arm strength; Torso denotes isolated torso strength; Leg denotes isolated leg strength; TaskHF– task hand force level.

6.5. Discussion

Being able to categorize and predict how a person would utilize bracing surfaces in the environment to increase task hand force exertion capability is critical to accurate biomechanical and ergonomic analyses. A classification-based approach to predictive modeling of task and bracing forces within (predicted) force-generation strategies (FGS) exerted during kinematically constrained one-handed isometric tasks are therefore presented.

Quantitative analysis reaffirmed that average task hand and contralateral hand force exertion and body-bracing forces are significantly affected by the task configuration, and determined that subject strength and anthropometric variables also affect task and bracing forces. Coherence of these empirical findings regarding task and bracing forces generation with respect to FGS classification supports the utility of the behavior-based approach to modeling bracing force generation.

The principal observations are:

- Fore-aft task handle location, vertical handle height, and choice of force-generation strategy each have significantly, largely independent effects on task and contralateral hand force vectors and body-bracing forces.
- The effects of the anthropometric and strength variables are independent of gender.
- Leg strength and stature have highly significant effects on task hand force exertion capability; most importantly for NB and HB FGSs and task configurations, which impose the least degree of kinematic constraint.
- Vertical task handle location is the primary determinant of task hand force direction relative to nominal direction.
- Task hand force is the most influential predictor of contralateral hand bracing force and body-bracing force.
- Brace forces, exerting by the contralateral hand and body-bracing by the lower-extremities, are strongly influenced by the task configuration variables. Over the range studied, exertion handle height has the stronger effect on brace hand force and fore-aft task handle location effects thigh bracing.

Among the task configuration variables, the fore-aft position of the task handle was one of the most important determinants of task hand and thigh bracing forces for nominal backward and upward tasks and across FGSs. As a result, the task hand force exertion capability is reduced, direction of task hand force vectors were more closely associated for nominal forward and backward tasks, and thigh force generation increased for tasks in which the thigh force opposes the task hand force.

Vertical handle height did not affect task hand force generation capability. This result differs from unconstrained tasks, in that obstructed tasks provide bracing affordances, which enable compensatory forces and moments, that mitigate the effect of task handle height observed in unconstrained exertions (Haslegrave et al., 1997; 1997; Hoffman, 2008; 2010). Nominal task and brace hand force vectors were observed to have significant directional changes across the nominal backward, forward and upward task forces as a result of the vertical task handle position.

Leg strength, stature, strength and other combinations of subject characteristics predictors were found to be significant predictors for task hand force and direction in task configurations and FGSs in which subjects were not afforded the opportunity to use the bracing surfaces, most importantly at the thigh bracing surfaces. Moreover, worker variables affected task hand force and direction prediction within task configurations that did not impose a high degree of kinematic constraint on the subject. For example, during NB and HB backward exertion trials for which subjects were observed to adopt a squatting posture, thereby shifting their centre of mass to the generate a moment utilizing body weight to increase task hand exertion capability. A similar postural modifications (increase base of support and lower centre of mass) for forward tasks, when bracing forces exerted at the thigh support would not be effective in increasing task exertion capability.

Prediction of bracing forces, both at the contralateral hand and thigh, were highly correlated with task hand force exertion capability. Increasing task hand force levels were associated with an increase in bracing hand and thigh forces, most often for subjects adopting the HB and TB FGSs respectively. It is noteworthy that the direction of the hand bracing force vector was not strongly predicted. Average effects of the regressors on brace hand force direction are somewhat misleading in that subtle changes to the brace force vector orientation are indicative of brace shoulder location. This effect will be considered with respect to the biomechanical implications of the brace hand force vector in Chapter Eight. Further investigated of the correlation between task and contralateral hand force vectors are an opportunity for future research.

A limitation of this analysis is a need for the requested force, a model input, to be translated into a fraction of strength in order to be able to use the model as currently derived. An additional concern is the segmentation of the models into 50% or maximal task hand force level. Modeling the actual on-axis task hand force as the force-level predictor, to essentially derive a continuous predictor that merges across maximal and sub-maximal force levels would address this issues. Actual task hand force requirements are measures that are readily available to an ergonomist.

Bracing force relationships with task hand force exertion capability and force-generation strategies are observed to be consistent with the classification-based approach to force-generation strategies presented in Chapter Four and modeled in Chapter Five. The findings of this chapter further substantiate the categorization of bracing forces with respect to their contribution to task hand force generation. These results will also provide quantitative input to the development of biomechanical models to analyze and simulate these tasks (Chapter Eight).

Application

Knowledge of the relationship between task configuration, subject and task hand force can be used to within the context of existing ergonomic analysis tools, including biomechanical simulation of kinematically constrained tasks. The following guidelines provide practitioners methods to account for the effects of brace hand and body-bracing forces on task-exertion capability:

- Task configuration requirements, 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.
- As the degree of kinematic constraint increases, fore-aft position of task requirement, task-exertion capability will decrease, and contralateral hand

and body-bracing force generation will increase during nominal backward and upward tasks.

- Bracing forces, exerted at the contralateral hand and thigh, increase with increased task hand force levels across all multinomial classifications of FGS, force directions and magnitudes.

6.6. Conclusions

This study provides a detailed quantitative description of task hand force and bracing forces as a function of task configuration and task hand force magnitude and direction for a wide range of task conditions observed in industry. These results provide ergonomists a means to accurately predict task hand, brace hand and body-bracing forces for force-exertion tasks in which the obstruction imposes a kinematic constraint and provides an opportunity to generate such forces.

6.7. References

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