The Effect of Bracing Availability on Force-Exertion Capability in One-Hand Isometric Pulling Tasks

Monica L.H. Jones, Matthew P. Reed, Don B. Chaffin
Human Motion Simulation Laboratory, University of Michigan
Ann Arbor, MI 48109

In activities of daily living and industrial tasks people encounter obstructions in their environment that kinematically limit the postures that they can achieve. These obstructions can also provide an opportunity for additional support such as bracing with the hand, thigh or other body part. The reaction forces acting at hand or body coupling, which are in addition to those acting at the feet and task hand, may support some percentage of body weight, allow modification to postural behavior strategies, or provide the ability to generate oppositional forces relative to the task force. The effects of kinematic constraints and associated bracing opportunities on isometric hand force were quantified in a motion-capture study of 25 men and women with a range of body size. The objective of this work was to quantify the effect of bracing availability on force-exertion capability. Analyses of one-hand maximal pulling tasks demonstrated that the additional force reaction surfaces enable participants to exert more force at the task hand, by 31% on average, but these values were greatly affected by the location and utility of the constraint and the specified force direction.

INTRODUCTION

Accurate representation of task postures is essential for assessment of worker capabilities (Chaffin & Erig, 1991) given that the risk of injury is greatly increased when job strength requirements approach worker capabilities (Chaffin, *et al.*, 1978). Biomechanical analyses of tasks with hand or body bracing are difficult to analyze because they are statically indeterminate. That is, even after accounting for the primary hand force and body weight effects, the forces at the bracing hand and other externally braced contact points cannot be easily determined from the posture and task force requirements.

Early work by Gaughran and Dempster (1956) measured maximal push and pull exertions in various seated postures and performed a mechanical analysis of the force system (subject, seat and force handle) to explain the differences in push/pull strengths across postures. Dempster (1958) conducted a similar analysis of two-handed standing, seated and braced pulls using free body diagrams. Both studies revealed that the magnitude of the push/pull force one can exert is related to the relative magnitudes of the gravitational and horizontal force couples acting on the system. Kroemer (1974) also concluded that maximal push and pull exertions are dependent upon the amount of reaction force available. Analysis confirmed that force exertion depends on posture that is optimized for position of body weight, muscle activation, available support and the subsequent chain of force vectors from a supported surface through the body to the point of force application (Kroemer, 1974; Rancourt and Hogan, 2001). Pheasant et al. (1982) required subjects to exert force in all directions in the sagittal plane under prescribed foot placement, force hand height and the presence of bracing wall or ceiling. Force exertion capability was found to be dependent upon the task handle location, foot placement and the direction of the exertion. Bracing against the constraint surface substantially increased the push and pull exertion magnitudes by enabling subjects to generate oppositional forces against the bracing surface (Pheasant et al., 1982).

This paper presents an investigation of one-hand, isometric, maximal force-exertions, obstructed by a structure located between the participant and task handle, with a range of bracing opportunities.

METHODS

Participants

Data were gathered from twenty-five men and women, all right-hand dominant and with no history of musculoskeletal disorders or functional mobility impairments. Table 1 lists summary attributes for the participants. All participants were young (median age 21 years) and relatively thin (median body mass index 23.6 kg/m^2). Participant whole-body strength capabilities were characterized by standardized arm, torso and leg lift strength tests (Stobbe, 1982).

	n	Age [yrs]	Stature [cm]	BMI [kg/m^2]
Females	12	20.3 (0.9)	163.9 (6.3)	24.7(2.4)
Males	13	21.4 (1.2)	178.4 (9.0)	23.8(4.0)

Table 1: Mean (standard deviation) of participant descriptors.

Laboratory Set-up

Reconfigurable force platforms captured ground reaction forces for each trial condition (Figure 1). Task forces were exerted on a cylindrical, rigid bar in a horizontal orientation, 470-mm long and 35-mm diameter task handle instrumented with a six-axis load cell (JR3, Woodland, CA). The handle was covered with 5-mm thick foam rubber that provided a high-friction grip. An adjustable bracing structure included a vertical planar surface at thigh height and a handrail at hip height, and a force feedback display was positioned at eye height. All aspects of the structure were reconfigurable in order to fit the task handle location relative to the obstruction and the placement of the bracing opportunities. Analog force data was acquired at each reactive surface by 6-DOF analog load cells (AMTI, Watertown, MA) and whole-body motions and postures were captured using an 8-camera Qualysis Proreflex 240-MCU passive optical motion tracking system.

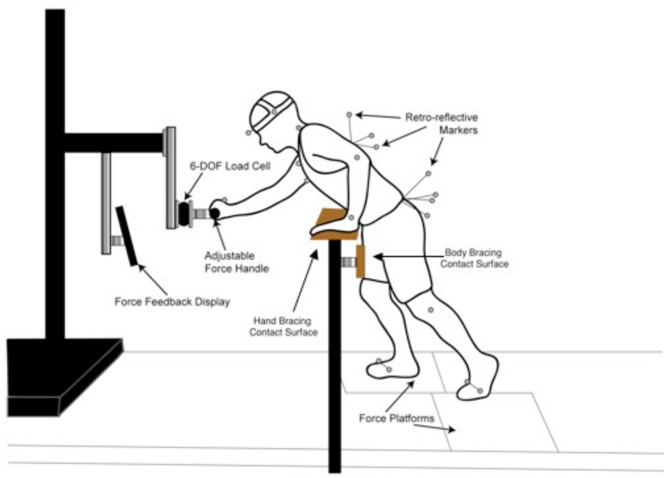

Figure 1: Laboratory configuration with visual force feedback display, 6-DOF load cells at task handle and bracing obstructions, and reconfigurable force platforms for measuring forces and moments at the hand and feet respectively.

Hand force feedback was presented visually to the subject allowing subjects to achieve and maintain requested hand forces. Custom software was developed in LabVIEW (National Instruments, Austin, TX). The display indicates the desired force magnitude and direction, and the participant's current force magnitude on the desired axis (Hoffman, 2008). Forces on axes other than the requested axis were not displayed.

Data Collection

Thirty-two retro-reflective markers were placed on each participant. Marker locations were sampled at 60 Hz and synchronized with the analog signals from the five independent load cells, sampled at 600 Hz. Video and static photos of the terminal postures were taken of each trial and synchronized with the kinematic and analog data. In addition, anthropometric and strength measures were obtained from each participant. Manually digitized body landmark data from each trial were used to create a linkage representation of the human body in the terminal posture (Reed et al., 1999, Hoffman 2008).

Test Conditions

The current analysis compares one-hand isometric pulling tasks at pelvis height that were kinematically constrained by a structure, while being presented with varying levels of bracing opportunities. For all trials, participants were required to exert 100% of maximal capability. Adjustability of the bracing structure ensured that all test conditions were normalized to an individual participant's anthropometry. Pull exertions were performed at a pelvis task handle height (59% of stature) and the horizontal position was scaled to a close location (34% of stature). The bracing handrail was configured to hip height (59% of stature) and body-thigh bracing surface was located at mid-thigh height (54% of stature).

Participants performed a series of practice trials in the assigned direction. During the practice trials participants were encouraged to explore different postural strategies. A minimum of one practice trial was conducted for each level of bracing availability and was repeated until the participant indicated that they were comfortable with their posture. Practice trials served as an opportunity for participants to identify their preferred postures and to gain familiarity with the force feedback display.

In each trial, participants pulled with maximum force with their right hand on the task handle. Trials were 6 seconds in duration, in which a three-second ramp-up preceded a three second maintenance of the maximal force level.

All exertions were performed on a painted wood platform with a coefficient of friction (CoF) of approximately 0.75. All participants wore their own shoes and thus the available friction at the shoe-floor interface may have been different across subjects.

Four bracing conditions were evaluated.

1. No contact with the structure permitted.
2. Hand bracing permitted, no contact with thigh structure.
3. Thigh bracing permitted, no hand bracing.
4. Both thigh and hand bracing permitted.

All test conditions were presented randomly. To minimize the effects of fatigue, rest breaks were provided to participants between trials. Strength testing measures taken pre- and post-test conditions did not reveal any significant fatigue.

Analysis

Forces are positive upward and forward, and the angle of the resultant force direction relative to forward is defined positive upward. Analysis of variance (ANOVA) was used to explore statistical trends in the data and to determine if force magnitude and/or direction exerted at the bracing surfaces yielded effective force-exertion tactics. Post-hoc comparison for all pairs used Tukey-Kramer HSD. An alpha level of 0.05 was used for all mean comparisons and analysis of variance. Linear regression was also used to determine if bracing availability is a significant predictor of force-exertion capability and pulling postures. All linear trends selected presented here are highly significant ($p < 0.001$). All analyses were conducted using the JMP statistical software package (SAS, Cary, NC). For the current analysis, forces measures were presented as both resultant magnitudes and normalized by body weight.

RESULTS

Analysis of the resultant task forces exerted during pulling tasks at pelvis height revealed that the availability of bracing increased force-exertion capability. The No Bracing condition was the only level of bracing that yielded a significantly different task hand force ($p < 0.0001$). Mean comparisons between those conditions with bracing availability, Hand Only, Thigh Only and Hand & Thigh were not significant (Figure 2). However, the effect of bracing availability afforded men an increase of 100 N additional resultant task hand force as compared to women, on average.

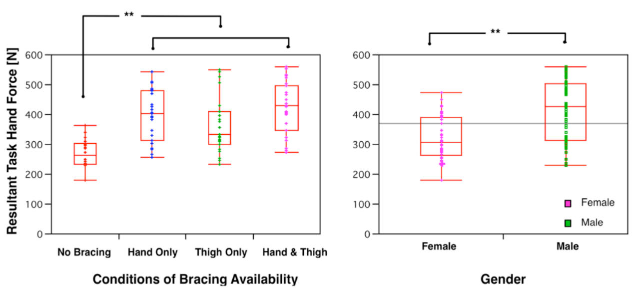

Figure 2: Resultant task hand force magnitude during one-handed pull task as a function of bracing availability. Mean difference of 100 N between men and women across bracing conditions was also significant (** indicates a significantly different pairs of means ($\alpha = 0.05$; $p<0.0001$)).

Figure 3 shows that resultant hand force can be predicted as a function of bracing hand and thigh body forces. A significant relationship was observed between task hand force and bracing hand (R^2 for linear regression is 0.70). When pulling backward an increase in opposing bracing hand force was observed with an increase in task hand force. This is consistent with the hypothesis that bracing affords joint load distribution strategies that yield increased force-exertion capability.

Compensatory force generated at body-bracing surface (R^2 for linear regression is 0.53) was also a significant predictor of force-exertion capability (Figure 3). Increase in horizontal force at the thigh was correlated with an increase in force-exertion capability at the task hand. This strategy acts to re-distribute loads across the body and extend reach capability by expanding the range of postures that are in static equilibrium.

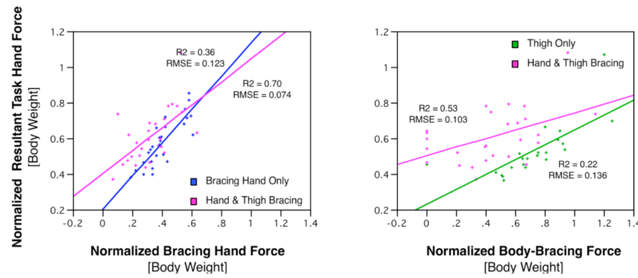

Figure 3: Task hand force normalized to body weight significantly predicted by normalized bracing hand and thigh forces.

Participants were asked to pull backward but were not instructed how to perform the exertion. Three general posture categories were characterized by the base-of-support (BoS) was used to categorize a posture as being *open*, *closed* or *neutral*. A posture in which the ipsilateral foot was aligned with task hand and the BoS rotated to the left with respect to the task hand was defined as *open*. A *closed* posture corresponded to the contralateral foot aligned with the task hand and BOS rotated to the right. *Neutral* BoS required both feet to be aligned towards the task hand (Figure 5). The probabilities of either 'open' or 'neutral' BoS strategies were approximately equal and independent of the availability of bracing (Table 2). The preference for an 'open' base of support (i.e. rotating towards the left) is to reduce the low-back rotational moment. Both 'open' and 'neutral' strategies also enabled participants to generate an opposing horizontal force by recruiting body bracing at the thigh. This force-generation tactic evokes additional forces and moments to re-distribute joint loading subsequently increasing balance and stability and force-exertion capability.

Bracing Availability	**Closed**	**Neutral**	**Open**
No Bracing	0.04	0.54	0.42
Hand Only	0.10	0.45	0.45
Thigh Only	0.04	0.52	0.44
Hand & Thigh	0.10	0.55	0.35

Table 2: Frequencies of base-of-support (BoS) strategies within bracing levels.

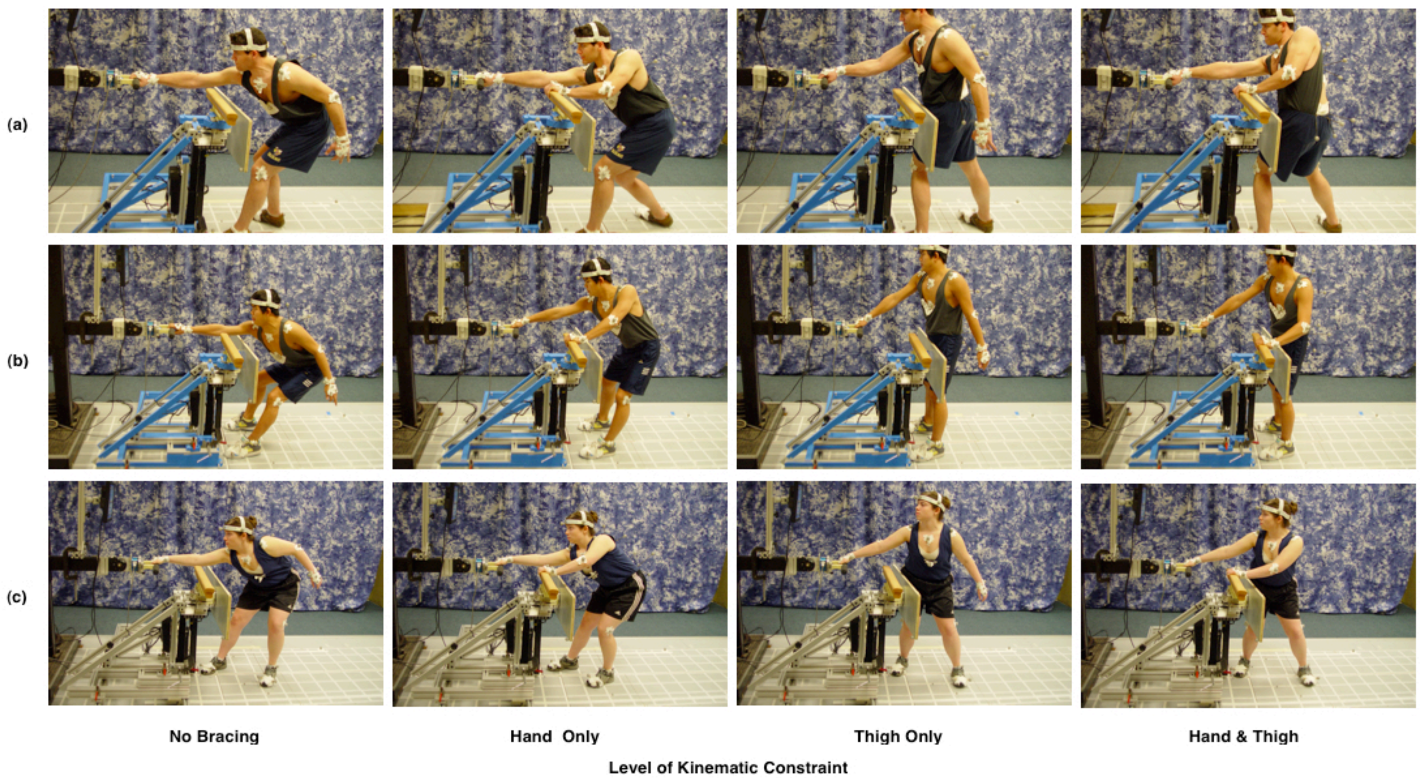

Figure 4: Representative postures of the base-of-support strategies used: a) closed, b) neutral, and c) open orientations.

Across all levels of bracing availability, pull exertions resulted in substantial off-axis forces. Variation in the direction of the resultant hand force vector (zero corresponds to a horizontal force), with the bracing availability levels indicates a significant amount of off-axis force (Figure 5). During the No Bracing condition, in which the kinematic constraint imposed an obstruction to the participant without affording the opportunity to generate compensatory reactive forces and moments, the pull force has a downward component (negative force direction) (mean = -8.7 deg). Participants lowered their center of mass by adopted a squatting posture or forward flexion moment about the lumbar spine (Figure 4). The corresponding downward orientation for the task hand force vector is indicative of a postural strategy to align the task shoulder with the horizontal task hand force vector (Figure 5).

There was limited vertical orientation of the task hand force vector during the Bracing only condition (mean = 3 deg). The horizontal orientation of the task force direction for the Bracing only condition is correlated to the oppositional force generated at the bracing hand (Figure 5). Subsequently, test conditions in which bracing was prohibited or that only the bracing hand surface was afforded to the participant were characterized by a squatting posture in which body weight is recruited to increase force-exertion capability (Figure 4). This tactic aligned the task shoulder with the task hand that resulted in primarily horizontal task hand force component.

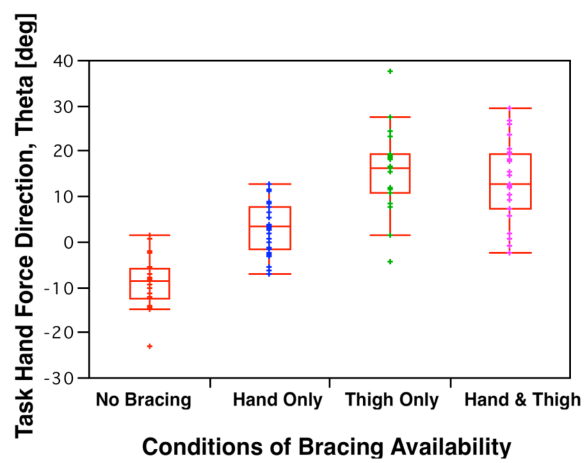

Figure 5: Direction of resultant task hand force vector with respect to horizontal (+ upward) during one-hand pull exertions as a function of kinematic constraint level. All mean pair wise comparisons are significant ($p < 0.001$) with the exception of the Thigh Only and Hand & Thigh conditions as denoted by the bracket.

As subsequent bracing opportunities were made available in the Thigh Only and Hand & Thigh conditions, participants tended to exert an upward force in addition to the required horizontal force (mean = 15.8 deg & 14 deg respectively). This trend appears consistent across all BoS strategies. The change in the vertical component of the task hand force as a function of a postural strategy can be significantly predicted based upon the availability compensatory forces at the horizontal, body-bracing surface (Figure 5). As depicted in Figure 4, the task shoulder tended to be above the handle and the vertical component indicates that the resultant task hand force was oriented closer to the shoulder that the horizontal vector would be. Upward task hand force increase the vertical ground reaction force at the feet, allowing higher horizontal forces to be generated at the thigh surface and within limits of the floor friction.

DISCUSSION

Analysis of laboratory data has found that maximum isometric one-hand pulling force magnitudes and directions were significantly affected by a structure that imposed a kinematic constraint. When permitted to do so, subjects braced with their hands and thighs in ways that increased force-exertion capability and altered the force direction.

In all task exertions the environmental obstruction constrained the postures. Pulling forces that are performed in the absence of such bracing surface availability are derived from body weight and ground reaction force only. Force-exertion capability was therefore limited by the body mass location relative to the base of support, and alignment of the task shoulder height location with the task force vector.

Bracing provides additional reaction forces and moments, beyond those available at the feet. Bracing forces allow postural strategies that increase hand force exertion without increasing the loading at limiting joints. Oppositional forces generated at both the contralateral hand and body-bracing surface facilitated an extension of the effective base of support beyond the feet. Corresponding postural tactics adopted by way of bracing availability afforded alternative strategies to maintain postural equilibrium. This trend was consistent across both the *open* and *neutral* BoS strategies.

Biomechanical analyses of supported or externally braced tasks are difficult to conduct without additional information on reaction force distribution to overcome the indeterminacy of the static force/moment balance equations. Current biomechanical models are ineffective in predicting force-exertion postures with bracing or accounting for compensatory forces generated at additional points of contact beyond the hands and feet. Quantification of force-exertion strategies is imperative to accurate analysis of whole-body postures, loads and strengths with bracing availability.

The current analysis is limited to a qualitative posture classification of the postural strategies. Further quantification of the kinematic biomechanical variables underway will assist in defining the underlying biomechanical principles that can predict key postural elements in relation to kimematic constraints. Lack of diversity in the participant pool and the limited test condition also restricts this analysis.

REFERENCES

Chaffin, D. B., Andres, R. O., and A. Garg. (1983). "Volitional Postures during Maximal Push/Pull Exertions in the Sagittal Plane," *Human Factors* 25(5):541-550.

Chaffin, D. B., and M. Erig, (1991). "Three-Dimensional Biomechanical Static Strength Prediction Model Sensitivity to Postural and Anthropometric Inaccuracies," *IIE Transactions* **23**(3):215-227.

Chaffin, D.B., Herrin, G. D., and W. M. Keyserling. (1978). "Pre-employment Strength Testing – Updated Position," *Journal of Occupational & Environmental Medicine* **20**(6):403- 408.

Dempster, W. (1958). Analysis of two-handed pulls using free body diagrams. *Journal of Applied Physiology* **13**(3): 469-480.

Gaughran, G. R. L., and W. T. Dempster. (1956). "Force analysis of horizontal two-handed pushes and pulls in the sagittal plane," *Human Biology* **28**(1):67-92.

Hoffman, S.G. (2008). Whole-Body Postures during Standing Hand-Force Exertions: Development of a 3D Biomechanical Posture Prediction Model. Ph.D. dissertation, University of Michigan, Ann Arbor, Michigan, U.S.A.

Kroemer, K.H.E. (1974). Horizontal push and pull forces: exertable when standing in working positions on various surfaces. *Applied Ergonomics* **5**(2): 94-102.

Pheasant, S., Grieve, D., Rubin, T. and Thompson, S. (1982). Vector representations of human strength in whole body exertion. *Applied Ergonomics* **13**(2): 139-144.

Rancourt, D. and Hogan, N. (2001). Dynamics of Pushing. *Journal of Motor Behavior* **33** (4): 351-362.

Reed, M. P., Faraway, J., Chaffin, D. B., and Martin, B. J. (2006). The HUMOSIM framework: A new approach to human motion simulation for ergonomic analysis. Technical Report 2006-01-2365, SAE International, Warrendale, PA.

Stobbe, T.J. (1982). The development of a practical strength testing program for industry. PhD thesis, The University of Michigan, Ann Arbor, MI.