Published in final edited form as:
Ergonomics. 2009 December ; 52(12): 1568–1575. doi:10.1080/00140130903287999.

Biomechanical analysis for handle stability during maximum push and pull exertions

Na Jin Seo, PhD,
Department of Industrial Engineering, University of Wisconsin-Milwaukee, 3200 N. Cramer St., Milwaukee, WI, 53211

Thomas J. Armstrong, PhD
Department of Industrial and Operations Engineering, University of Michigan, 1205 Beal Ave, Ann Arbor, MI 48109

Abstract

This study investigated the effect of handle stability on maximum push/pull force. It was hypothesized that people apply force in directions deviated from the pure push/pull direction to generate a moment that assists producing greater push/pull force when the handle position is fixed (stable) compared to when it is not fixed (unstable). Eight healthy subjects performed maximum push and pull exertions on a stable and an unstable handle in a seated posture, while maximum push/pull force, vertical force, and lateral force were recorded. For the unstable handle, vertical and lateral forces were not different from zero during push and pull. For the stable handle, subjects intuitively applied significant downward force during push and significant upward force during pull exertions. As predicted from biomechanical analysis, this downward and upward force was found to be significantly associated with increased push and pull force, respectively, for the stable handle compared to the unstable handle.

Keywords

stability; handle; push; pull; grip

1. INTRODUCTION

1.1 Significance

The purpose of this paper is to investigate the effect of handle stability on maximum push/pull force using biomechanical analysis. Push/pull activities are frequently performed to move an object from one location to another, to join it to another part, to support the body, or to propel a wheelchair. With increasing number of lifting tasks replaced by pushing and pulling tasks in workplaces, pushing and pulling tasks contribute to 20% of all industrial back injuries in the United States, Canada and the U.K. (Hoozemans et al., 1998). Repeated

corresponding author: Phone: 414-229-6190, Fax: 414-229-6958, seon@uwm.edu.

CONFLICT OF INTEREST STATEMENT
The authors declare no conflict of interest.

forceful push/pull exertions lead to fatigue and musculoskeletal disorders including cumulative trauma disorders for workers installing hoses during automotive assembly (Ebersole and Armstrong, 2004) and manual wheelchair users (Richter et al., 2006, Dubowsky et al., 2008). In addition, an individual's limited push/pull capability can pose safety risks in situations such as climbing a ladder (Christensen and Cooper, 2005).

Thus, an understanding of push/pull force exertions in relation to handle features is important for analyzing causes of hand injury as well as for designing grip objects to prevent overexertion and repetitive stress injury. Many studies have been undertaken to examine handle design factors associated with individuals' push/pull forces. These factors include handle shape (Fothergill et al., 1992), handle orientation (Okunribido and Haslegrave, 2008), hand-handle friction (Seo et al., 2008b), location of the handle from the body (Fothergill et al., 1992, Kumar et al., 1995, Kumar, 1995, Das and Wang, 2004, Davis and Stubbs, 1977, Grieve and Pheasant, 1981, Chow and Dickerson, 2009), obstruction around the handle (Grieshaber, 2007), push method such as simultaneously applying torque during push (Seo et al., 2008b), and handle stability (Bober et al., 1982, Kornecki et al., 2001, Fischer et al., 2009). The present study focuses on handle stability.

1.2 Handle Stability

Previous studies focused on the effect of handle stability on upper extremity muscle activities during push (Bober et al., 1982, Kornecki et al., 2001, Fischer et al., 2009). The present study examined how people apply forces in three dimensions during push and pull on a stable and unstable handles. Specifically, the present paper proposes a viewpoint that people exploit the handle stability and apply forces not only in push/pull directions but also in other directions to reduce external moments at the joints of the arm. This argument is derived from biomechanical analysis as shown below and is applicable to both push and pull exertions.

Figure 1 shows a typical push/pull posture in two dimensions. Push and pull forces are defined as the force in the anterior-posterior horizontal axis (z-axis) in this paper, as opposed to the resultant force (vector sum of all 3-dimensional forces). Exertion of push/pull force (F_z) and vertical force (F_y) produces reaction forces to the hand in the opposite directions with the same amounts of forces ($F_{y,\ reaction}$, $F_{z,\ reaction}$). These reaction forces, in turn, produce an external moment at the wrist joint about the x-axis ($M_{external}$):

$$
\begin{aligned}
M_{external} &= -F_{z,\ reaction} \cdot d_y + F_{y,\ reaction} \cdot d_z \\
&= F_z \cdot d_y - F_y \cdot d_z
\end{aligned}
\quad (1)
$$

where d_y is the perpendicular distance between F_z and the wrist joint, and d_z is the perpendicular distance between F_y and the wrist joint. This external moment should be resisted by the internal moment generated by muscles crossing the wrist ($M_{internal}$) in an isometric condition:

$$M_{internal} + M_{external} = 0 \quad (2)$$

Wrist internal moment about the x-axis is bounded by wrist extension strength $\left(M_{wrist\ extension\ strength}\right)$ and wrist flexion strength $\left(M_{wrist\ flexion\ strength}\right)$:

$$-M_{wrist\ flexion\ strength} \le M_{internal} \le M_{wrist\ extension\ strength} \quad (3)$$

Wrist flexion/extension strength as opposed to wrist adduction/abduction strength was considered as being responsible for generating internal moments about the x-axis for the following reason. During push/pull exertions, the thenar area of the hand makes a firm contact with the handle, resulting in the forearm and wrist pronation, in which case, x-axis moments are generated by the wrist flexor and extensor muscles. Even when the forearm was half-pronated at 45°, most wrist extensor muscles are still located above the horizontal plane through the wrist joint, and most wrist flexor muscles are below the horizontal plane passing through the wrist joint (Brand and Hollister, 1993, Gonzalez et al., 1997).

From Equations 1, 2 and 3, maximum push/pull force can be expressed as follows.

$$|\text{Max push force}| = (-F_z)_{max} = \frac{M_{wrist\ extension\ strength} - F_y d_z}{d_y} \quad (4)$$

$$\text{Max pull force} = F_{z,\ max} = \frac{M_{wrist\ flexion\ strength} + F_y d_z}{d_y} \quad (5)$$

If a handle position is constrained to prevent any movement and rotations (i.e., stable handle, shown in Figure 1 and Figure 2a), then by pulling up or pressing down the handle, it is possible to adjust the vertical force (F_y) to increase push/pull force for a given wrist strength (Equations 4 and 5). Specifically, maximum push force can increase by simultaneously applying downward force (negative F_y) as described in Equation 4. Likewise, maximum pull force can increase by simultaneously applying upward force (positive F_y) as described in Equation 5.

If a handle position is not constrained (i.e., unstable handle, shown in Figure 2b, c), the handle can move up, down, or to the side as a person applies upward force (positive F_y), downward force (negative F_y), or forces to the side ($\pm F_x$), respectively. To maintain the handle's position during push/pull exertions, the person should minimize forces in these directions, resulting in the following:

$$F_x \approx 0 \text{ and } F_y \approx 0 \text{ for an unstable handle} \quad (6)$$

Based on Equations 4 and 6, it can be seen that inability to apply forces in directions other than push/pull direction (especially in the vertical direction) will result in reduced push force. Likewise, inability to apply forces in other directions (especially in the vertical direction) will result in reduced pull force based on Equations 5 and 6.

The same biomechanical analysis can be performed about the elbow and shoulder joints. Similar conclusions can be obtained: Application of vertical force can increase maximum push/pull force limited by the elbow and shoulder flexion/extension strength. In the posture examined in this study (Figure 2), it was postulated that maximum push/pull force is limited by the wrist strength rather than by the elbow or shoulder strength, given the joint strengths for the wrist (Seo et al., 2008a), elbow (Holzbaur et al., 2007) and shoulder (Murray et al., 1985) and the moment arms for each joint (vertical distance, d_y, from the handle to each joint) (Choi et al., 2007, Chengalur et al., 2004). Thus, the present paper focused on the wrist strength and how maximum push/pull force is related to wrist strength as described in Equations 4 and 5. However, it is to be noted that the elbow or the shoulder could be the limiting joint depending on the posture used during push and pull exertions (Daams, 1992, Al-Eisawi et al., 1994).

In summary, biomechanical analysis suggests that additional push/pull force can be exerted without exceeding the strength capacity of the wrist by applying F_y for a stable handle. Therefore, it was hypothesized that 1) people will apply downward force during push and upward force during pull on a stable handle, and 2) this downward or upward force is related to increased maximum push or pull force for a stable handle compared to an unstable handle, respectively.

2. METHODS

2.1 Procedure

A 2^2 factorial experiment was conducted to test this hypothesis. The independent variables were handle stability (stable vs. unstable as shown in Figure 2a–c) and direction of force exertions (push vs. pull). The dependent variables were maximum push/pull force, vertical force, and lateral force. The stable handle was simulated by fixing the handle to the force transducer such that the handle was immobilized (Figure 2a). The unstable handle was simulated using two universal joints at the attachment of the handle to the transducer (Figure 2b,c). Under this arrangement, the handle was free to move in all three axes within the spherical space limited by the lengths of the linkage consisted of the universal joints. This restricted subjects from pressing down or pulling up the handle, or pushing/pulling the handle to the side.

Note that previously, handle stability has been examined only for push, with the handle instability provided in front of the hand via joints (“inverted pendulum” type of instability) (Bober et al., 1982, Kornecki et al., 2001, Fischer et al., 2009). For this type of unstable handles, the handle can buckle at the joint unless push force is in line with the joint. To prevent buckling, greater muscle efforts were observed for the upper extremity muscles. The present study investigated unstable handles by introducing the handle instability via joints behind the hand for push, and in front of the hand for pull (“regular pendulum” type of instability; see Figure 2). Forces applied in directions other than the push or pull direction on this type of unstable handles may result in changes in the handle location, but not buckling.

Subjects washed their hands with soap, rinsed with water, and dried with paper towels 10 minutes prior to testing, to eliminate artifacts due to contaminants (Buchholz et al., 1988, Comaish and Bottoms, 1971). Subjects were seated on a chair that supported the back and feet to minimize the effect of balance/slip (Figure 2a). The handle height was adjusted to each subject's elbow height when the arm was resting vertically on the side of the body. The horizontal distance from the handle to the subject was adjusted to allow subjects to maintain an extended elbow posture as shown in Figure 2a.

Subjects were instructed to grasp a cylindrical handle with the right hand in a power grip and perform maximum push/pull exertions for 5 seconds. The cylindrical handle's long axis was parallel to the push/pull direction. No instructions regarding vertical or lateral force (F_y, F_x) were given to subjects. Each condition was tested twice. Conditions were randomly presented to subjects. A two-minute break was given between consecutive trials.

The cylindrical handle had a smooth aluminium surface, and its diameter was 38.1 mm. All forces (F_x, F_y, F_z) were measured using a 6-axis load cell. Data were collected at 5 Hz. All data were averaged over 2 seconds during maximum push or pull exertions.

2.2 Subjects

Eight healthy subjects (4 male, 4 female, average age = 26.3 ± 4.5 yrs ranging from 23 to 37) participated in the experiment. Their grip strength ranged from 8th to 77th percentile for males, and 8th to 73rd percentile for females. The protocol for the experiments was approved by the University of Michigan Institutional Review Board. Subjects gave written informed consent prior to testing.

2.3 Data Analysis

First, repeated measures analysis of variance (ANOVA) was performed to determine if vertical force (F_y) was significantly affected by the handle stability, force direction (push vs. pull), and the interaction between the two. A significant main effect of handle stability would mean that vertical force changes depending on whether the handle is stable or unstable. A significant interaction effect between the handle stability and force direction would mean that the change in the vertical force differs depending on whether it is a push exertion or a pull exertion (e.g., the vertical force increases to the upward direction for pull, whereas it increases to the downward direction for push). The same analysis was performed for lateral force (F_x).

To double check if the vertical force direction is consistent with the hypothesis, 1-sample t-tests were performed to compare vertical forces to zero for each group (push on a stable handle, pull on a stable handle, push or pull on an unstable handle). More specifically, it was tested to see if vertical force for pushing on the stable handle is less than zero (negative F_y), if vertical force for pulling on the stable handle is greater than zero (positive F_y), and if vertical force for the unstable handle was different from zero.

Then, another repeated measures ANOVA was performed to determine if the magnitude of push/pull force ($|F_z|$) was significantly affected by the amount of vertical force ($|F_y|$) and force direction (push vs. pull). If $|F_z|$ changes significantly with $|F_y|$, it would mean that push/pull force is significantly affected by vertical force generation. Since two major statistical analyses were performed, a *p*-value of .025 was considered significant after Bonferroni correction.

In addition to the two main hypothesis tests, prediction of maximum push and pull forces was attempted using Equations 4 and 5. The predicted maximum push force was calculated by plugging the wrist extension strength, d_y, d_z, and F_y into Equation 4. Wrist extension strength measured during maximum grip (Seo et al., 2008a), 6.0 N·m, was used as an input in this calculation. The moment arms values of 59 and 75 mm for d_y and d_z, respectively, were adopted from a previous study (Choi et al., 2007). Vertical force (F_y) was set to zero for the unstable handle. For the stable handle, vertical force measured using the load cell was used as an input in this calculation. Likewise, maximum pull force was predicted based on Equation 5 using wrist flexion strength of 12.2 N·m (Seo et al., 2008a), the same moment arm values (d_y, d_z), and zero and measured vertical force for the unstable and stable handles, respectively.

3. RESULTS

Mean maximum push/pull force, vertical force, and lateral force measured for the stable and unstable handles are summarized in Table 1. Mean maximum pull force was 53% greater than push in absolute values ($|F_z|$) (Table 1). The magnitude of maximum push/pull force ($|F_z|$) for the stable handle was, on average, 38% greater than that for the unstable handle (Figure 3; Table 1).

Repeated measures ANOVA showed that vertical force (F_y) was significantly affected by handle stability and the interaction between handle stability and force direction (pull vs. push) (p<.025 for all). The 1-sample t-tests showed the following: Vertical force was not different from zero for push and pull on the unstable handle ($F_y \approx 0$; p=.463). Vertical force was less than zero for push on the stable handle (i.e., downward force; p<.025). Vertical force was greater than zero for pull on the stable handle (i.e., upward force; p<.025) (see Figure 3). Lateral force (F_x) was not significantly affected by stability, direction nor their interaction.

Repeated measures ANOVA for the push/pull force showed that the magnitude of push/pull force ($|F_z|$) was significantly affected by the magnitude of vertical force ($|F_y|$) and force direction (push vs. pull) (p<.025 for both). More specifically, $|F_z|$ increased with increasing $|F_y|$. These relationships are depicted in Figure 3: Vertical force (F_y) is close to zero for push/pull on the unstable handle. Significant upward force (positive F_y) and downward force (negative F_y) were observed for pull and push on the stable handle, respectively. These upward and downward forces were associated with increased magnitude of pull and push forces ($|F_z|$), respectively, as shown in Figure 3.

The measured push/pull forces for the stable and unstable handles are compared with the predicted forces in Figure 4. Prediction showed the same trend with the measured forces that the push/pull forces were greater for the stable than for the unstable handle. The predicted push/pull forces for the stable and unstable handles were within one standard error from the mean measured forces for the corresponding conditions.

4. DISCUSSION

4.1 Handle stability

The present paper proposes a viewpoint that during push/pull exertions, people apply forces not only in the push/pull direction but also in other directions to increase their push/pull force if forces applied in other directions can reduce external moments applied at the joints of the arm. On the other hand, inability to generate forces in other directions due to handle instability may limit individuals' push/pull capability. More specifically, in the posture examined in this study, it was hypothesized based on Equations 4 and 5 that 1) people will apply downward force during push and apply upward force during pull on a stable handle, and 2) this downward or upward force is related to increased maximum push or pull force for a stable handle compared to an unstable handle, respectively.

Both hypotheses were supported by the empirical data obtained in this study (Table 1; Figure 3). When the handle position was unstable, subjects could apply little forces in the medial-lateral and vertical directions during push or pull. When the handle position was fixed, allowing subjects to exert forces in all directions (i.e., stable handle), the subjects indeed applied downward and upward forces during push and pull, respectively, although no instruction regarding the vertical and medial-lateral force was given to the subjects.

These downward and upward forces could generate a moment about the x-axis at the wrist in the opposite direction from the moment generated by the reaction force from push and pull. As a result, the total external moment at the wrist joint could be reduced, decreasing the required muscle efforts to counterbalance the external moment or affording to produce greater push/pull forces (as reflected in Equations 4 and 5). Empirically, these downward and upward forces were indeed associated with increased push and pull forces (z-direction forces), respectively (Figure 3). Push/pull forces were greater when the subjects pulled up or pushed down (for the stable handle) than when they could not (for the unstable handle). In addition, predictions performed using Equations 4 and 5 agreed favorably with measured push/pull forces (Figure 4).

This study provides a biomechanical basis for explaining decreased push/pull force for unstable handles. Previously, the effect of handle stability has been examined as a motor control issue by categorizing stabilizing muscles and directional force generating muscles (Bober et al., 1982, Kornecki et al., 2001, Kornecki, 1995). The findings of the present study suggests that the reason people could use less muscle efforts for stable handles than for unstable handles in the previous studies (Bober et al., 1982, Kornecki et al., 2001, Fischer et al., 2009, Kornecki, 1995) may be because they reduced external moments at the joints, consequently reducing required joint stabilization efforts, by applying forces in directions deviated from the pure push direction. It agrees with the previous studies that a stable handle provides persons with leverage. The leverage appears to be the ability to apply forces in other direction in effort to lessen external moments about the wrist joint that will assist push/pull force exertions.

Subjects intuitively knew that applying force in deviated directions could improve their push and pull force magnitudes, which is consistent with a previous study by Grieve and Pheasant (1981). The present study differs from the previous study in that the present paper predicted which direction force would be beneficial from joint biomechanical analysis in Equations 4 and 5, whereas the previous study empirically measured individuals' maximum force capability in all directions in the sagittal plane (Pheasant and Grieve, 1981). In addition, this paper assumes that maximum push/pull force is achieved when force is applied in the direction that has the greatest push/pull-direction component force, as opposed to considering component forces in all possible directions as in Grieve and Pheasant (1981). The present study is in line with the discussion in the previous study (Pheasant and Grieve, 1981) that the reason force capacity is bigger in one direction versus other directions may be related to the external moment at the body joints that muscles would have to work to resist in order to maintain the posture.

The finding in the present study is sensitive to the posture adopted during push/pull exertions. If different postures are used during push/pull exertions on the stable handle, people may apply forces in different directions (Grieve and Pheasant, 1981). For example, if a push/pull exertion is performed for a handle at the shoulder height, with the upper arm abducted 90° and flexed 45° and with the elbow flexed at 90°, the biomechanical analysis shows that push and pull force may increase by applying forces in the negative and positive x-direction, respectively, rather than applying force in the y-direction. Thus the specific finding in this paper that vertical force was related to maximum push/pull force may be applicable only to the particular posture examined in this study. Separate analyses may be required for different postures used during push/pull exertions.

4.2 Comparison with previous studies

Maximum push/pull forces measured in this study were not significantly different from those previously reported for the stable handle (Grieshaber, 2007, Okunribido and Haslegrave, 2008) and for an unstable handle (Seo et al., 2008b) under the same handle orientation. Consistent with previous studies (Keyserling et al., 1980, Das and Wang, 2004, Davis and Stubbs, 1977, Kumar, 1995, Kumar et al., 1995), average maximum pull force was 53% greater than push force (Table 1). Equations 4 and 5 suggest that pull force is related to wrist flexion strength and push force is related to wrist extension strength. Therefore, greater wrist flexion strength than extension strength may be responsible for greater maximum pull force than push observed for the unstable handle in the posture examined in the present study. For the stable handle, with forces in other directions (for example, in the y-direction) reducing external moments for the wrist, the push strength may have been limited by other joint strength such as the elbow and shoulder strength. For pull, forces in the z- and y-directions could have resulted in the arm under the tensile load, in which case the pull strength is limited by the torso extension or whole-body pull strength.

4.3 Future studies

Maximum push/pull force is limited by the weakest link in the chain which often includes the hand and the wrist. The present study focused on the wrist moment; however, push/pull force can also be limited by normal force the hand could apply to the handle surface by gripping, as previously modeled (Seo et al., 2008b). Force generation deviated from the pure push/pull direction may not only affect wrist external joint moments, but also increase normal force on the handle surface. Thus, vertical force observed in this study may have contributed to increased push/pull force not only in terms of wrist joint moment, but also by increasing normal force. Future studies may measure normal force on the handle surface and gauge the effect of increase in normal force on push/pull force for the stable handle compared to the unstable handle.

5. Conclusions

This study investigated the effect of handle stability on maximum push/pull force using biomechanical analysis and empirical data. The unstable handle prevented subjects from applying forces in directions other than the push/pull direction. When the stable handle was presented, the subjects intuitively applied downward force during maximum push exertions and upward force during maximum pull exertions for the stable handle. As predicted from the biomechanical analysis (Equations 4 and 5), this downward and upward force was significantly associated with increased maximum push and pull force, respectively, for the stable handle compared to the unstable handle. It appears that deviation of the force exertion direction from the pure push-pull direction could reduce the external moment applied to the joints of the arm, resulting in increased force capability. In other words, inability to generate forces in other directions due to handle instability resulted in decreased maximum push/pull force.

The present study demonstrated that joint biomechanics can be used to analyze and predict the effect of handle stability on push/pull exertions which has previously been examined in a motor control paradigm. The finding can be applied to design of workstation that requires high force exertions to enhance individuals’ push/pull capabilities and reduce fatigue and musculoskeletal disorders.

Acknowledgements

The authors would like to thank Justin G. Young and Kathryn L. Dannecker for their assistance in acquisition of data. This project was funded by a NIOSH pilot grant.

REFERENCES

AL-EISAWI KW, KERK CJ & CONGLETON JJ (1994) Limitations of wrist strength to manual exertion capability in 2D biomechanical modeling. Human Factors and Ergonomics Society.

BOBER T, KORNECKI S, LEHR RP JR. & ZAWADZKI J (1982) Biomechanical analysis of human arm stabilization during force production. J Biomech, 15, 825–30. [PubMed: 7161284]

BRAND PW & HOLLISTER A (1993) Clinical mechanics of the hand, Mosby Elsevier Health Science.

BUCHHOLZ B, FREDERICK LJ & ARMSTRONG TJ (1988) An investigation of human palmar skin friction and the effects of materials, pinch force and moisture. Ergonomics, 31, 317–25. [PubMed: 3383835]

CHENGALUR SN, RODGERS SH & BERNARD TE (2004) Kodak's Ergonomic Design for People at Work. New York, John Wiley & Sons, Inc.

CHOI J, GRIESHABER DC & ARMSTRONG TJ (2007) Estimation of Grasp Envelope Using a 3-Dimensional Kinematic Model of the Hand.

CHOW AY & DICKERSON CR (2009) Shoulder strength of females while sitting and standing as a function of hand location and force direction. Appl Ergon, 40, 303–8. [PubMed: 19162258]

CHRISTENSEN T & COOPER N (2005) Attacking Ladder Falls-One Rung at a Time. Occupational Hazards, 67, 39.

COMAISH S & BOTTOMS E (1971) The skin and friction: deviations from Amonton's laws, and the effects of hydration and lubrication. Br J Dermatol, 84, 37–43. [PubMed: 5573184]

DAAMS BJ (1992) Comparison of moments exerted round one or more joints in the arm. Contemporary ergonomics, 1992: proceedings of the Ergonomics Society's 1992 Annual Conference, 36th, 104–109.

DAS B & WANG Y (2004) Isometric pull-push strengths in workspace: 1. Strength profiles. Int J Occup Saf Ergon, 10, 43–58. [PubMed: 15028193]

DAVIS PR & STUBBS DA (1977) Safe levels of manual forces for young males (2). Appl Ergon, 8, 219–28. [PubMed: 15677246]

DUBOWSKY SR, RASMUSSEN J, SISTO SA & LANGRANA NA (2008) Validation of a musculoskeletal model of wheelchair propulsion and its application to minimizing shoulder joint forces. J Biomech, 41, 2981–8. [PubMed: 18804763]

EBERSOLE ML & ARMSTRONG TJ (2004) An analysis of task-based worker self-assessments of force Human Factors and Ergonomics Society 48th Annual Meeting. New Orleans, LA.

FISCHER SL, WELLS RP & DICKERSON CR (2009) The effect of added degrees of freedom and handle type on upper limb muscle activity during simulated hand tool use. Ergonomics, 52, 25–35. [PubMed: 19308817]

FOTHERGILL DM, GRIEVE DW & PHEASANT ST (1992) The influence of some handle designs and handle height on the strength of the horizontal pulling action. Ergonomics, 35, 203–212.

GONZALEZ RV, BUCHANAN TS & DELP SL (1997) How muscle architecture and moment arms affect wrist flexion-extension moments. J Biomech, 30, 705–12. [PubMed: 9239550]

GRIESHABER DC (2007) Use of a biomechanical model of the hand to evaluate physical task requirements Department of Industrial and Operations Engineering. Ann Arbor, University of Michigan.

GRIEVE DW & PHEASANT ST (1981) Naturally preferred directions for the exertion of maximal manual forces. Ergonomics, 24, 685–93. [PubMed: 7318819]

HOLZBAUR KR, DELP SL, GOLD GE & MURRAY WM (2007) Moment-generating capacity of upper limb muscles in healthy adults. J Biomech, 40, 2442–9. [PubMed: 17250841]

HOOZEMANS MJ, VAN DER BEEK AJ, FRINGS-DRESEN MH, VAN DIJK FJ & VAN DER WOUDE LH (1998) Pushing and pulling in relation to musculoskeletal disorders: a review of risk factors. Ergonomics, 41, 757–81. [PubMed: 9629062]

KEYSERLING WM, HERRIN GD & CHAFFIN DB (1980) Isometric strength testing as a means of controlling medical incidents on strenuous jobs. J Occup Med, 22, 332–6. [PubMed: 7381613]

KORNECKI S (1995) Biomechanical Consequences of Hand's Action on Unstable Handle. Int J Occup Saf Ergon, 1, 199–207. [PubMed: 10603552]

KORNECKI S, KEBEL A & SIEMIENSKI A (2001) Muscular co-operation during joint stabilisation, as reflected by EMG. Eur J Appl Physiol, 84, 453–61. [PubMed: 11417435]

KUMAR S (1995) Upper body push-pull strength of normal young adults in sagittal plane at three heights. International Journal of Industrial Ergonomics, 15, 427–436.

KUMAR S, NARAYAN Y & BACCHUS C (1995) Symmetric and asymmetric two-handed pull-push strength of young adults. Hum Factors, 37, 854–65. [PubMed: 8851781]

MURRAY MP, GORE DR, GARDNER GM & MOLLINGER LA (1985) Shoulder motion and muscle strength of normal men and women in two age groups. Clin Orthop Relat Res, 268–73.

OKUNRIBIDO OO & HASLEGRAVE CM (2008) Ready steady push--a study of the role of arm posture in manual exertions. Ergonomics, 51, 192–216. [PubMed: 17852368]

PHEASANT ST & GRIEVE DW (1981) The principal features of maximal exertion in the sagittal plane. Ergonomics, 24, 327–38. [PubMed: 7262058]

RICHTER WM, RODRIGUEZ R, WOODS KR, KARPINSKI AP & AXELSON PW (2006) Reduced finger and wrist flexor activity during propulsion with a new flexible handrim. Arch Phys Med Rehabil, 87, 1643–7. [PubMed: 17141646]

SEO NJ, ARMSTRONG TJ, ASHTON-MILLER JA & CHAFFIN DB (2008a) Wrist strength is dependent on simultaneous power grip intensity. Ergonomics, 51, 1594–605. [PubMed: 18803097]

SEO NJ, ARMSTRONG TJ, CHAFFIN DB & ASHTON-MILLER JA (2008b) The effect of handle friction and inward or outward torque on maximum axial push force. Hum Factors, 50, 227–36. [PubMed: 18516834]

Author Manuscript

Author Manuscript

Author Manuscript

Statement of Relevance

Stabilizing the handle position could increase individuals' push/pull capacity by 38%, compared to when the handle position was not stabilized. The finding can be applied to design of workstation that requires high force exertions to reduce fatigue during push/pull exertions and thus prevent musculoskeletal disorders.

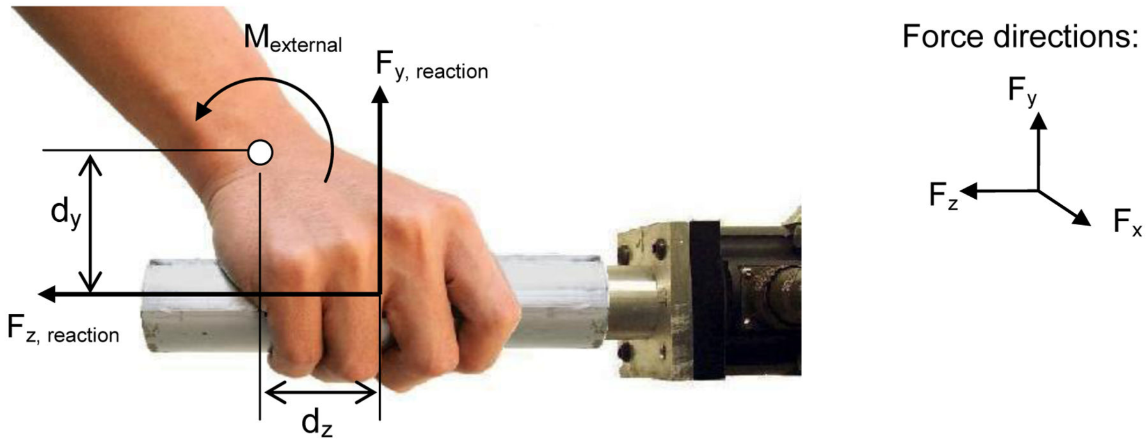

Figure 1.

A typical posture for push/pull exertions. Reaction forces ($F_{z,\ reaction}$ and $F_{y,\ reaction}$) from push/pull force (Fz) and vertical force (Fy) exertions generate an external moment about the wrist joint (Mexternal).

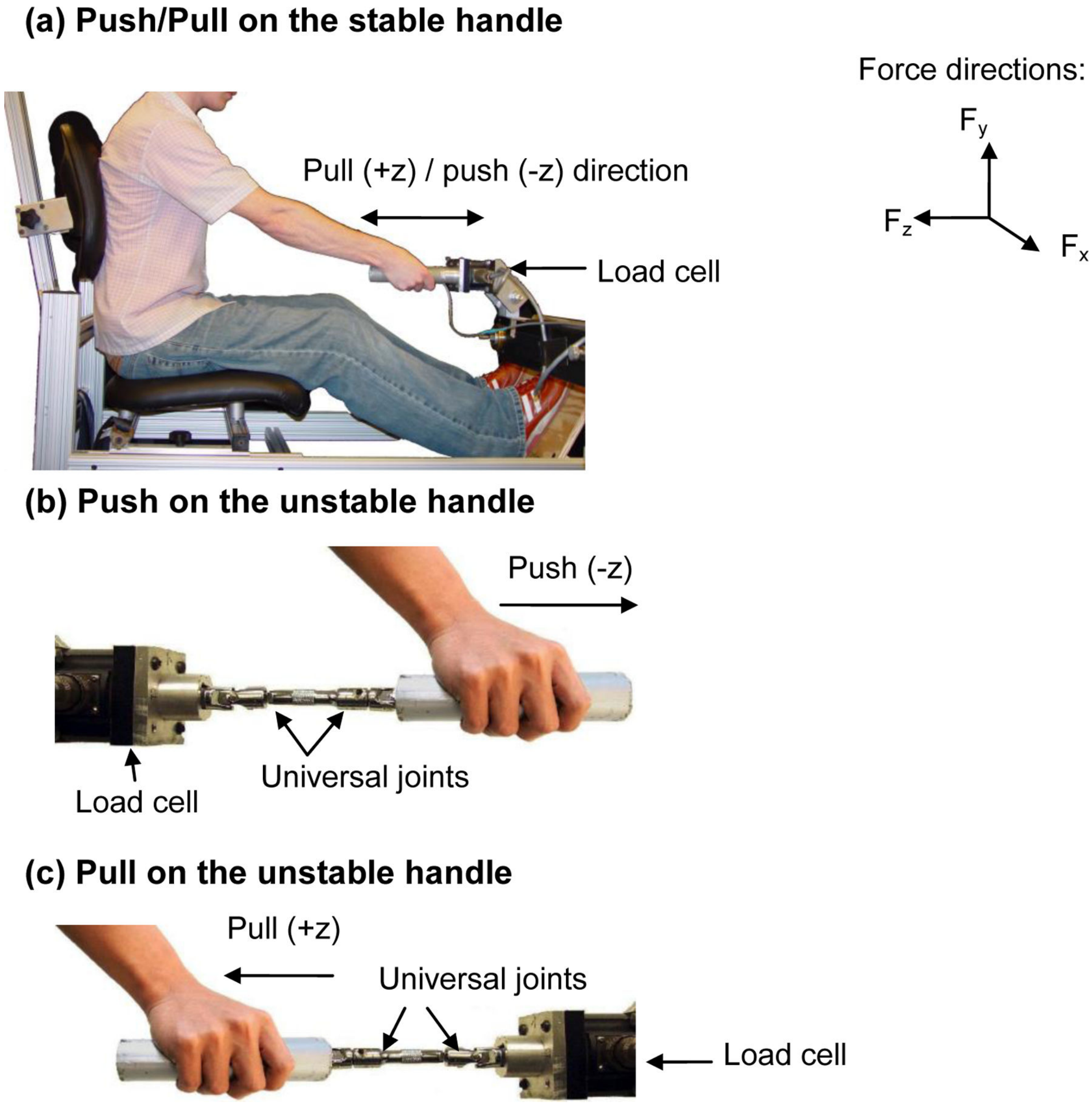

Figure 2.

Subjects applied maximum push/pull forces for the stable (a) vs. unstable handles (b, c). The unstable handle was simulated using universal joints which prevented subjects from applying forces in the x- and y-directions during push (b) and pull (c). All three-direction forces were measured using a load cell.

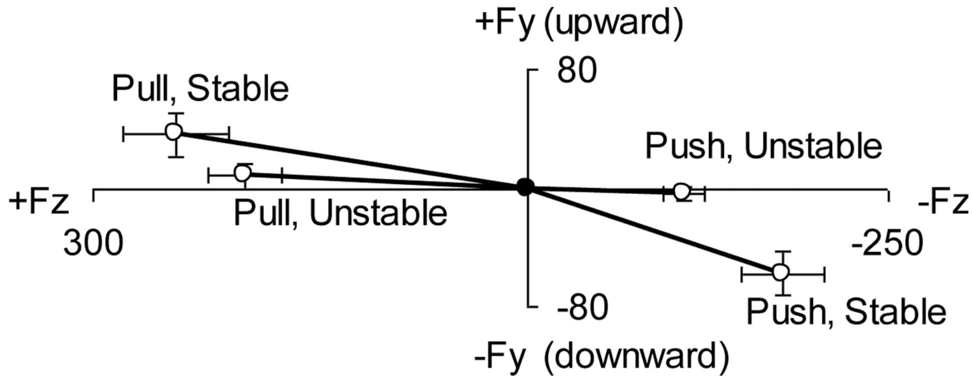

Figure 3.

Mean ± SE maximum pull/push force (positive Fz/ negative Fz) and upward/downward forces (positive Fy/ negative Fy) for the stable and unstable handles (8 subjects' data pooled)

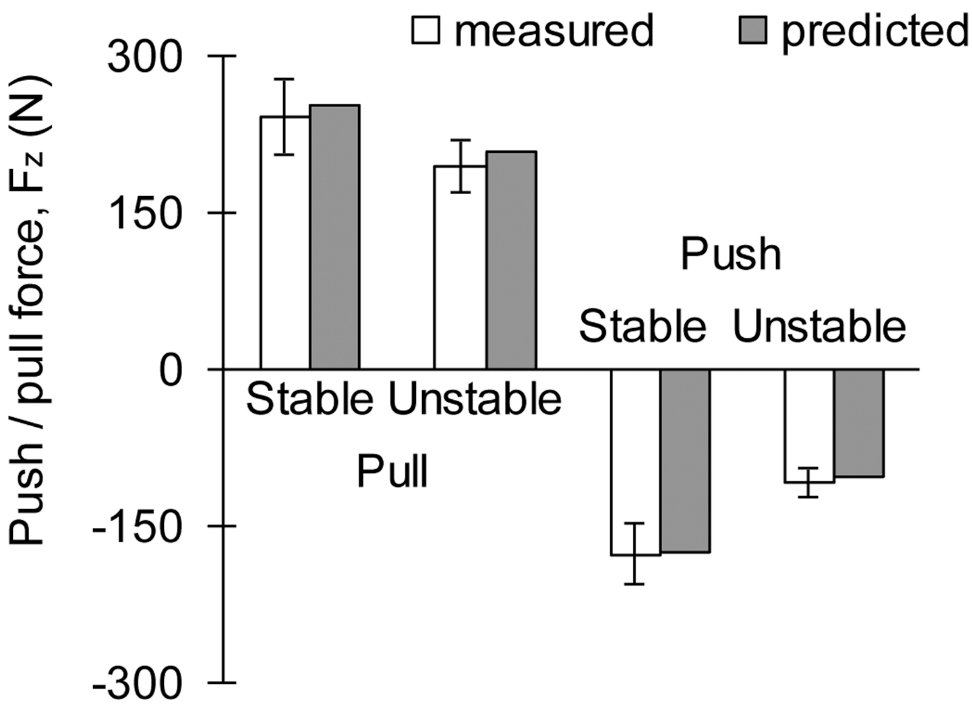

Figure 4.

Comparison between measured and predicted push/pull forces (Fz) for the stable and unstable handles. Predicted push/pull forces were calculated using wrist extension/flexion strength and measured vertical force.

Table 1.

Mean ± SE lateral (Fx), vertical (Fy), and push/pull force (Fz) during maximum push/pull exertions for the stable and unstable handles (8 subjects' data pooled; See Figure 2 for illustration of handle stability conditions and force directions)

	Stability	F_x (N)	F_y (N)	F_z (N)
Push	Stable	−1±13	−58±14	−177±29
	Unstable	11±4	−4±5	−109±14
Pull	Stable	−16±9	36±14	243±36
	Unstable	0±1	8±3	195±25