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Biomechanical analysis for handle stability during maximum push and pull exertions

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This study investigated the effect of handle stability on maximum push/pull force. It was hypothesised 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 an 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 USA, Canada and the UK (Hoozemans *et al.* 1998). Repeated 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 analysing 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 (Davis and Stubbs 1977, Grieve and Pheasant 1981, Fothergill *et al.* 1992, Kumar 1995, Kumar *et al.* 1995, Das and Wang 2004, 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 stable and unstable handles. Specifically, the present paper proposes a viewpoint that people exploit the handle stability and apply forces not only in push/

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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-D 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 ($M_{external}$):

$$M_{external} = -F_{z, reaction} \cdot d_y + F_{y, reaction} \cdot d_z$$

$$= F_z \cdot d_y - F_y \cdot d_z \quad (1)$$

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 ($M_{wrist\ extension\ strength}$) and wrist flexion strength ($M_{wrist\ flexion\ strength}$):

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

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/

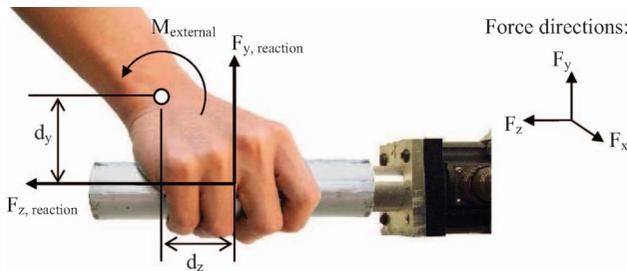


Figure 1. A typical posture for push/pull exertions. Reaction forces ($F_{z, reaction}$ and $F_{y, reaction}$) from push/pull force (F_z) and vertical force (F_y) exertions generate an external moment about the wrist joint ($M_{external}$).

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.

$$|Max\ push\ force| = (-F_z)_{max}$$

$$= \frac{M_{wrist\ extension\ strength} - F_y d_z}{d_y} \quad (4)$$

$$Max\ pull\ force = F_{z, max}$$

$$= \frac{M_{wrist\ flexion\ strength} + F_y d_z}{d_y} \quad (5)$$

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

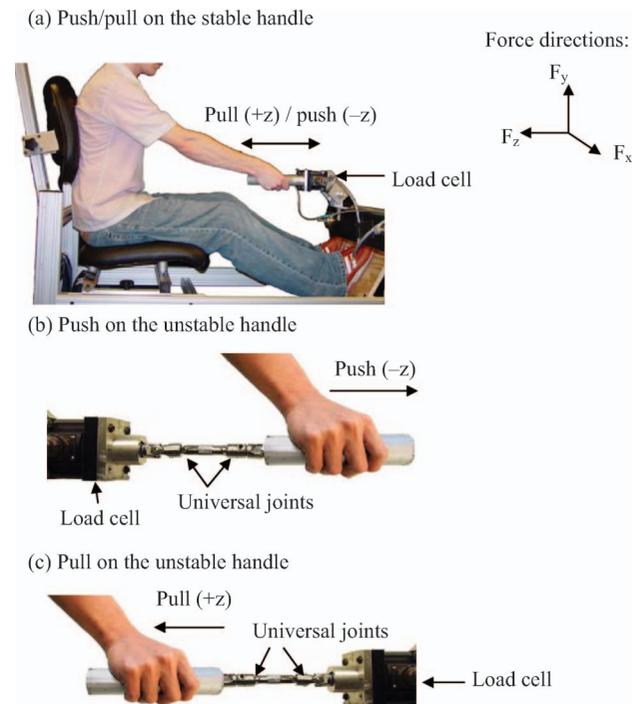


Figure 2. Subjects applied maximum push/pull forces for the stable (a) vs. unstable (b, c) handles. The unstable handle was simulated using universal joints, which prevented subjects from applying forces in the x- and y-directions during push (b) and pull (c). All three-direction forces were measured using a load cell.

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 minimise 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 the 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) (Chengalur *et al.* 2004, Choi *et al.* 2007). 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 hypothesised that: 1) people will apply downward force during push and upward force during pull on a stable handle; 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 2² 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 immobilised (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 consisting 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 handle, 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 handle 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 min prior to testing, to eliminate artefacts due to contaminants (Comaish and Bottoms 1971, Buchholz *et al.* 1988). Subjects were seated on a chair that supported the back and feet to minimise 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 s. 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 2-min 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 six-axis load cell. Data were collected at 5 Hz. All data were averaged over 2 s during maximum push or pull exertions.

2.2. Subjects

Eight healthy subjects (four male, four female, average age 26.3 ± 4.5 years 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 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, one-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 0.025 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 summarised 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) ($p < 0.025$ for all). The one-sample t-tests showed the following: vertical force was not different from zero for push and pull on the unstable handle ($F_y \approx 0$; $p = 0.463$); vertical force was less than zero for push on the stable handle (i.e. downward force; $p < 0.025$); vertical force was greater

Table 1. Mean \pm SE lateral (F_x), vertical (F_y) and push/pull force (F_z) during maximum push/pull exertions for the stable and unstable handles (eight subjects' data pooled).

	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

Note: See Figure 2 for illustration of handle stability conditions and force directions.

than zero for pull on the stable handle (i.e. upward force; $p < 0.025$) (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) ($p < 0.025$ 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, respectively, on the stable handle. 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 1 SE from the mean measured forces for the corresponding conditions.

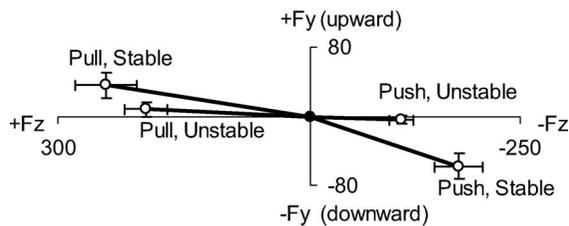


Figure 3. Mean \pm SE maximum pull/push force (positive F_z / negative F_z) and upward/downward forces (positive F_y / negative F_y) for the stable and unstable handles (eight subjects' data pooled).

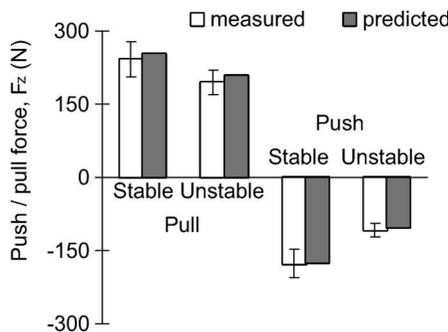


Figure 4. Comparison between measured and predicted push/pull forces (F_z) for the stable and unstable handles. Predicted push/pull forces were calculated using wrist extension/flexion strength and measured vertical force.

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 hypothesised, 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: 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 favourably 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 categorising stabilising muscles and directional force generating muscles (Bober *et al.* 1982, Kornecki 1995, Kornecki *et al.* 2001). The findings of the present study suggest that the reason people could use less muscle effort for stable handles than for unstable handles in the

previous studies (Bober *et al.* 1982, Kornecki 1995, Kornecki *et al.* 2001, Fischer *et al.* 2009) may be because they reduced external moments at the joints, consequently reducing required joint stabilisation efforts by applying forces in directions deviating 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 force in other directions in an 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 vs. 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 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 force 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 (Davis and Stubbs 1977, Keyserling *et al.* 1980, Kumar 1995, Kumar *et al.* 1995, Das and Wang 2004), 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 that the hand could apply to the handle surface by gripping, as previously modelled (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 force 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 analyse 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 the design of a workstation that requires high force exertions to enhance individuals' push/pull capabilities and reduce fatigue and musculoskeletal disorders.

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Conflict of interest

The authors declare no conflict of interest.

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