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Justin G. Young^a, Jia-Hua Lin^b, Chien-Chi Chang^b & Raymond W. McGorry^b

^a Department of Industrial and Manufacturing Engineering, Kettering University, 1700 University Ave, Flint, MI, 48504, USA

^b Center for Physical Ergonomics, Liberty Mutual Research Institute for Safety, 71 Frankland Rd, Hopkinton, MA, 01748, USA

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The natural angle between the hand and handle and the effect of handle orientation on wrist radial/ulnar deviation during maximal push exertions

Justin G. Young^{a*}, Jia-Hua Lin^{b1}, Chien-Chi Chang^{b2} and Raymond W. McGorry^{b3}

^aDepartment of Industrial and Manufacturing Engineering, Kettering University, 1700 University Ave, Flint, MI 48504, USA; ^bCenter for Physical Ergonomics, Liberty Mutual Research Institute for Safety, 71 Frankland Rd, Hopkinton, MA 01748, USA

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The purpose of this experiment was to quantify the natural angle between the hand and a handle, and to investigate three design factors: handle rotation, handle tilt and between-handle width on the natural angle as well as resultant wrist radial/ulnar deviation ('RUD') for pushing tasks. Photographs taken of the right upper limb of 31 participants (14 women and 17 men) performing maximal seated push exertions on different handles were analysed. Natural hand/handle angle and RUD were assessed. It was found that all of the three design factors significantly affected natural handle angle and wrist RUD, but participant gender did not. The natural angle between the hand and the cylindrical handle was $65 \pm 7^\circ$. Wrist deviation was reduced for handles that were rotated 0° (horizontal) and at the narrow width (31 cm). Handles that were tilted forward 15° reduced radial deviation consistently ($12\text{--}13^\circ$) across handle conditions.

Practitioner summary: Manual materials handling (MMH) tasks involving pushing have been related to increased risk of musculoskeletal injury. This study shows that handle orientation influences hand and wrist posture during pushing, and suggests that the design of push handles on carts and other MMH aids can be improved by adjusting their orientation to fit the natural interface between the hand and handle.

Keywords: manual handling; hand tools and interfaces; pushing; posture; equipment design

1. Introduction

Manual materials handling (MMH) tasks involving pushing and pulling exertions have been related to increased risk of musculoskeletal injury, specifically in the shoulder and lower back (Hoozemans et al. 1998, 2002). Because MMH tasks require the transmission of large forces to work objects via the hand/handle interface, it is important to assess how handle design influences usability, posture and physical capacity (Mack, Haslegrave, and Gray 1995; Devereux, Buckle, and Haisman 1998; Jung, Haight, and Freivalds 2005). Accordingly, many studies have measured pushing exertions for various handle design factors such as height (Lee et al. 1991; Snook and Ciriello 1991; Kumar 1995; Al-Eisawi et al. 1999; Lee, Hoozemans, and van Dieën 2011), size and shape (Cochran and Riley 1986), stability (Seo and Armstrong 2009), frictional properties (Seo, Armstrong, and Young 2010) and orientation (Okunribido and Haslegrave 1999, 2003, 2008; Seo, Armstrong, and Young 2010). While these studies confirm that handle design factors affect body posture and the capacity to create push force, they do not specifically address hand posture and how changes at the hand/handle interface manifest these effects.

In order to transmit push forces to the work object, a stable coupling between the hand and handle is generally established by gripping the handle and pushing with the palm. Since the palm is asymmetrical (due to difference in digit lengths and the presence of the thumb and thenar tissues), the long axis of handles that are grasped in a power grip are not naturally oriented perpendicularly to the metacarpal bones. Instead, the handle is angled or tilted by the tissues between the thumb and index finger. The degree to which a grasped cylindrical handle is oriented with respect to the hand is defined here as the 'natural hand/handle angle' of the hand/handle coupling (Figure 1(a)). The natural hand/handle angle should not be confused with the posture of the wrist (i.e. radial/ulnar deviation (RUD) angles; Figure 1(b)).

The natural angle of a grasped handle has been described or reported by very few sources (Kroemer, Kroemer, and Kroemer-Elbert 1994; Hsu and Chen 1999) and there is little or no explanation of how the angle was measured or determined. Nonetheless, researchers have proposed designs of grasped tools such as knives, pliers, screwdrivers and files that incorporate tilted handles which theoretically adjust for the natural hand/handle angle and allow the wrist to remain in neutral postures during use (Armstrong et al. 1982; Kroemer, Kroemer, and Kroemer-Elbert 1994; Hsu and Chen, 1999). There are no studies, to the authors' knowledge, reporting the natural hand/handle angle for exertions other than gripping; however, many operator handles where push forces are commonly exerted have been angled or tilted to increase the comfort of the operator (such as the handlebars on bicycles and motorcycles). In addition, studies of pushing exertions show that

*Corresponding author. Email: jyoung@kettering.edu

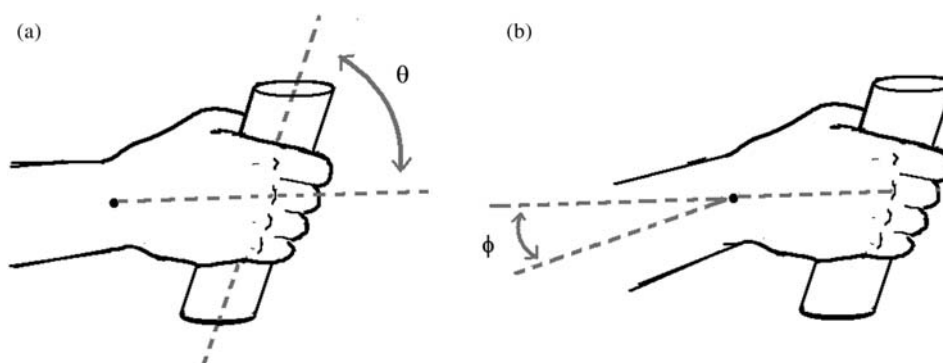


Figure 1. (a) Natural hand/handle angle is defined as the angle between the third metacarpal bone in the hand and the long axis of the grasped cylinder; (b) wrist radial/ulnar deviation is defined as the angle between the long axis of the forearm and the third metacarpal bone in the hand.

tilting handles affects wrist posture and push capacity (Okunribido and Haslegrave, 2008), and that neutral wrist postures correspond to greater strength (Al-Eisawi, Kerk, and Congleton 1994; Roman-Liu and Tokarski 2005). Despite this evidence, tilted handles have been largely absent in MMH aids such as hand trucks, trolleys and pushcarts.

It is our hypothesis that tilting push handles according to the natural hand/handle angle will allow for more neutral wrist postures. The aims of this experiment are to test this hypothesis by: (1) determining the natural angle between the hand and a handle; and (2) investigating the effects of handle rotation, tilt and between-handle width on the natural angle as well as the resultant wrist RUD for bi-manual pushing exertions.

2. Methods

To achieve the aims of this study, wrist and hand posture information collected in a larger study of push strength (Lin, McGorry, and Chang 2012) were analysed. In that experiment, participants performed seated, bi-manual maximal forward pushing exertions on two symmetrical handles. The two handles were adjustable so that different handle orientations and widths could be presented to the participant. Participants were instructed to push on the handles in various orientations while following the Caldwell strength-testing protocol, which consisted of a one-second strength build-up followed by a three-second maximum exertion (Caldwell et al. 1974). Verbal encouragement was provided to the participant by the experimenter during each trial (i.e. 'ramp up ... hold ... hold ... hold ... relax'). In the middle of the three-second maximal exertion period, a digital photograph of the participant's right forearm and hand was acquired. Hand and wrist posture was determined from these photographs and is presented here.

2.1 Participants

Thirty-one healthy adults without any existing musculoskeletal or other health conditions that prohibited them from performing regular daily activities participated in this study. Participants (14 females and 17 males) were between 19 and 64 years of age. Their average (SD) age, body mass and height were 38.5 (13.2) years, 69.4 (18.6) kg and 166.0 (5.6) cm, respectively for the females; and 34.8 (14.5) years, 77.5 (16.0) kg and 175.4 (9.1) cm, respectively for the males. Participants' hand length (measured according to Garrett, 1971) varied from 16.0 cm to 21.5 cm, with an average length of 18.8 (1.4) cm. Two participants were left-hand dominant. Prior to the start of the study, participants provided informed consent which was approved by the research facility's Institutional Review Board.

2.2 Apparatus and set-up

Participants performed maximal push exertions while seated. Seat height was adjusted and set so that when seated the participant's popliteal region of the knee was clear of the seat's front edge, the lower extremities were unsupported and feet were clear of the ground. The seat's backrest was modified, so that support was provided only approximately as high as the iliac crests. In front of the seated participant, two 4.0-cm diameter aluminium handles, whose surfaces were textured by sandblasting to minimize hand slipping, were mounted to a rigid, height-adjustable crossbar. The crossbar height was adjusted and set so that when the participant grasped the handles, the forearms were parallel to the ground and the elbows were flexed at 115° (Figure 2(a)). Participants began each trial in this initial posture, but were unconstrained during the maximal push exertions. This assured the relative seat arrangement and starting posture for each participant was consistent throughout the study.

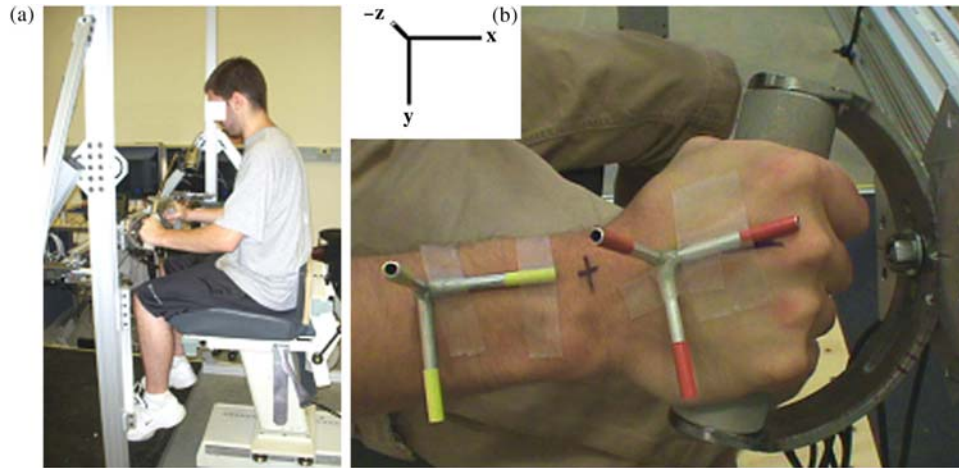


Figure 2. (a) Participants performed bi-manual, seated push exertions on various handles; (b) a camera, mounted onto the handle base structure, captured photographs of the right hand during push exertions. In this example, the handle was at 45° rotation and 15° tilt.

A camera (Sony Handycam® DCR-SR82) was mounted on a rigid fixture that was attached to the base of the right-handle structure. The camera's optical axis (line of sight) was orthogonal to the long axis of the handle and the target push direction (forward) at the centre of the handle. The rigid fixture allowed the same camera view to be taken on the handle at any handle rotation or position along the crossbar. Two triad markers were affixed to the upper limb, one on the back of the hand and one on the forearm, which indicated orthogonal directions along and normal to the surface of the forearm and hand (Figure 2(b)). The x -axis of the forearm marker was oriented along the long axis of the forearm and in the direction of the centre of the wrist, while the x -axis of the hand marker was oriented along the third metacarpal bone of the hand.

Handle orientation was adjustable in two dimensions to allow different handle rotation (axis aligned with the direction of push) and tilt (axis perpendicular to the direction of push) configurations. In addition, the width between right and left handles could be adjusted to present spacing that was either within an average female's shoulder breadth or outside an average male's shoulder breadth. Three handle rotations (0° horizontal, 45° and 90° vertical), two between-handle widths (narrow 31.0 cm and wide 48.6 cm) and two handle tilts (0° and 15°) were randomly presented, and their effects on maximal forward pushing exertions were investigated (Figure 3). There were two repetitions of each treatment, with a minimum two-minute rest afforded between trials.

2.3 Posture calculation

Wrist and hand posture is calculated by comparing the angular directions of the orthogonal axes of the marker triads (either the x - or the y -axes) between the forearm and hand markers (see Figure 2). Extension of the wrist rotates the hand marker triad about the marker triad's y -axis, inclining the hand marker triad's x -axis with respect to the RUD plane. When the forearm is rotated with respect to the fixed camera plane (rotation about forearm x -axis), any wrist extension will be interpreted as RUD if the marker's x -axes are used to calculate RUD angle. Therefore, the marker's y -axes instead are used to calculate RUD angle and reduce the theoretical two-dimensional projection error.

2.3.1 Wrist RUD

Wrist RUD is defined here as the angle between the third metacarpal bone in the hand (from wrist to middle knuckle) and the long axis of the forearm. For this study, radial deviation is a negative angle and ulnar deviation is a positive angle. RUD was calculated by comparing the y -axis of forearm and hand marker triads (Figure 4(a)).

2.3.2 Natural hand/handle angle

Natural handle angle is defined here as the angle between the third metacarpal bone in the hand (from wrist to middle knuckle) and the long axis of the cylindrical handle. The natural handle angle can be calculated by comparing the direction of the hand marker triad's y -axis to the perpendicular of the handle's long axis (Figure 4(b)).

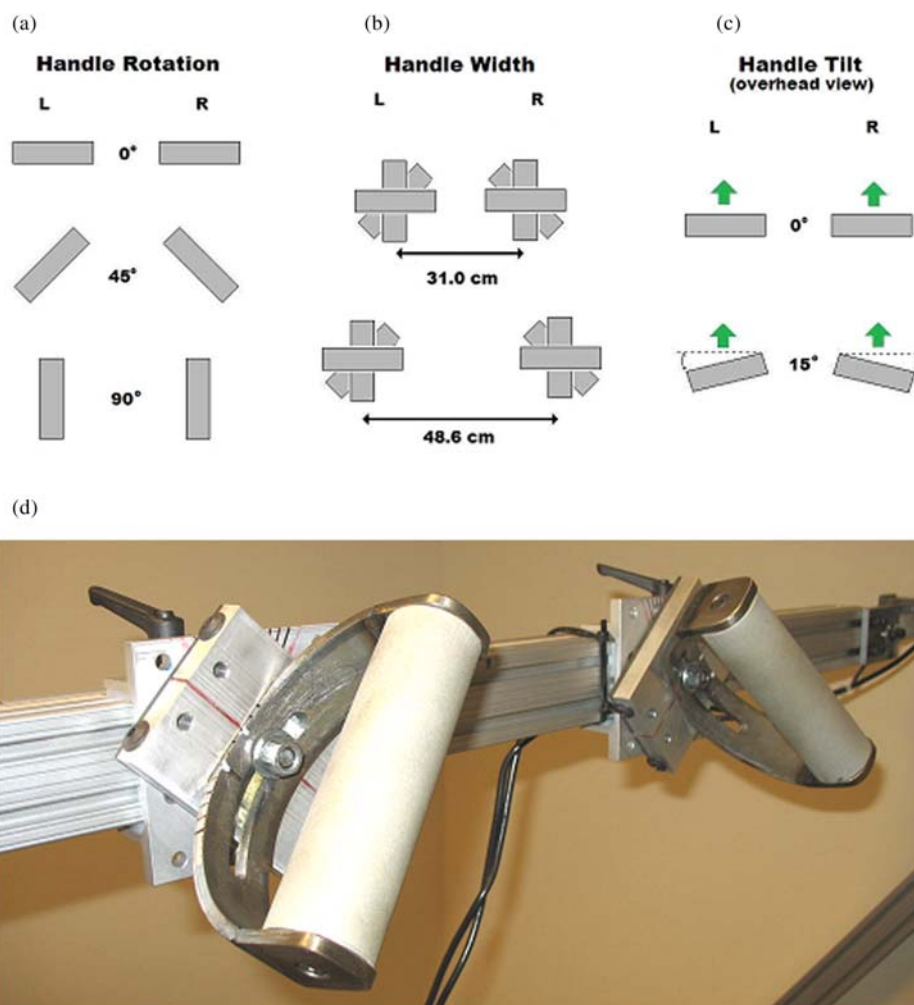


Figure 3. Push handle conditions: (a) three rotations in the anatomical coronal plane shown from the point of view of the operator; (b) two widths shown from the point of view of the operator; and (c) two tilt levels, either perpendicular to push or rotated towards the thumb, shown for just one rotation in an overhead view. Right (R) and left (L) handles are shown. Push direction is into the page for operator views (a) and (b) and toward the top of the page (as indicated by arrows) for the overhead view (c); (d) shows the actual test handles at 45° rotation, 15° tilt, and narrow width.

2.4 Camera-based calculation validation protocol

Since photographs represent a two-dimensional projection of the actual three-dimensional marker triad positions, 'perspective' or 'parallax' error is introduced by the camera lens when the optical axis is not precisely orthogonal to the local wrist 'RUD' plane (Paul and Douwes 1993; Lau and Armstrong 2011). The camera placement was chosen to minimise this perspective error; however, participant posture during push exertions was not constrained. This means that if participants rotated their forearm with respect to the fixed handle axis during push exertions, the wrist RUD plane would become misaligned with the fixed camera plane and error can be introduced.

For a subset ($n = 20$) of participants, a validation experiment was performed that compared angles calculated by the above-described methods with those measured by a MotionStar Wireless electromagnetic motion-tracking system (Ascension Technology, Inc., Burlington, VT, USA). Electromagnetic motion-tracking system cannot be used around large metal objects, so the validation experiment was performed prior to the main experiment in a separate room. Two marker triads and two motion-tracking 'birds' were placed on the forearm and back of the hand in similar positions as in the main experiment. Participants were then asked to keep their forearm stationary while tightly gripping a 4.0-cm diameter acrylic cylindrical rod. The experimenter then manually altered the rod's orientation so that the participant's wrist moved through the full range of motion (flexion/extension and RUD) while synchronised photographs and joint angles were recorded. Wrist RUD angles were then calculated from the photographs using the above-described method and compared with those

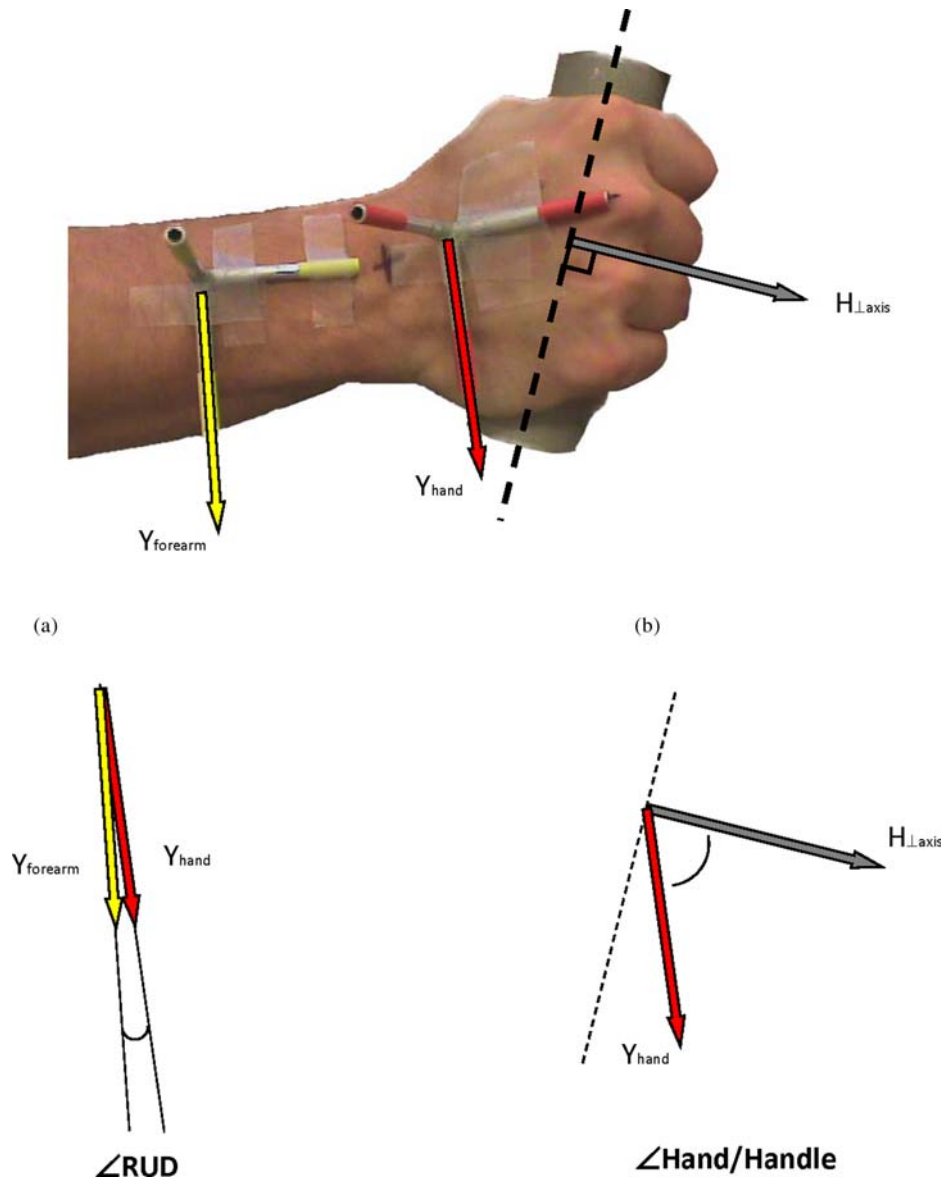


Figure 4. (a) Radial/ulnar deviation can be calculated as the angle between the forearm (y_{forearm}) and hand (y_{hand}) marker triads using the marker triad y-axes; (b) the natural hand/handle angle is calculated as the angle between the perpendicular to long axis of the grasped handle ($y_{\perp \text{axis}}$) and the y-axis of the hand marker triad (y_{hand}).

recorded by the motion-tracking system. The resulting mean error in RUD angle between the two methods was $\pm 3^\circ$ with a variance of 7° . Pearson correlation between measurement methods was 0.97.

2.5 Design and statistical analysis

A $3 \times 2 \times 2$ full factorial study design testing push force for handle rotation, tilt and between-handle width was employed. There were two repetitions of each treatment, yielding 24 photographs per participant. RUD and natural handle angles were calculated from the 744 photographs. Repeated measures ANOVA analysis was performed for the fixed effects of gender, handle rotation, handle tilt and between-handle width, as well as their interactions on calculated angles. Participant was nested within gender and was treated as a random effect. Post hoc multiple comparisons (Bonferroni) were performed for significant effects. Statistical analysis was performed using SPSS[®] v. 17 (Chicago, IL, USA) linear mixed model module. A p -value of 0.05 was considered significant for all statistical tests.

Table 1. Repeated measures ANOVA for main effects and interactions.

Effect	Natural hand/handle angle		Wrist deviation	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Rotation	7.827	0.000	872.286	0.000
Tilt	43.554	0.000	716.895	0.000
Width	62.373	0.000	299.844	0.000
Gender	0.231	0.632	0.458	0.502
Rotation × gender	7.117	0.001	49.085	0.000
Tilt × gender	6.607	0.010	4.734	0.030
Width × gender	0.053	0.819	0.009	0.925
Rotation × width	1.774	0.170	19.166	0.000
Rotation × tilt	0.539	0.584	0.461	0.631
Tilt × width	1.458	0.228	1.600	0.206

Note: $p < 0.05$ is significant.

3. Results

3.1 Natural hand/handle angle

Average (SD) natural angle over all trials was 65(7) degrees. Analysis of variance (Table 1) shows that the main effects of handle rotation, handle tilt and between-handle width were significant, but gender was not. There were two significant two-way interactions: the interaction between handle rotation and gender, and the interaction between handle tilt and gender. In both the cases, observed natural angle was affected less for males by the handle factor than for females.

Post hoc results indicate that natural angle was significantly greater for 90° handle rotation (neutral forearm) than for the 0° handle rotation ($p < 0.001$), but natural angle for the 45° rotation was not different from either of the other rotations ($p = 0.119 - 0.172$). Mean (SD) natural angle for handle rotations 0°, 45° and 90° was 65(6), 65(7) and 66(7) degrees, respectively. Natural angle was significantly greater for handle angle of 0° than for handle tilt of 15° ($p < 0.001$). Natural angle for handle tilt of 0° and 15° was 66(7) and 64(7) degrees, respectively. Natural angle was significantly greater for wide handles than for narrow handles ($p < 0.001$). Natural angle for narrow- and wide-handle spacing was 64(7) and 66(7) degrees, respectively.

3.2 Wrist deviation

Analysis of variance (Table 1) shows that the main effects of handle rotation, handle tilt and handle width ($F = 299.4$, $p < 0.001$) were significant, but gender was not significant. There were three significant two-way interactions. The interaction between handle rotation and between-handle width was significant: the effect of handle width was smaller in the 90° handle rotation than for other rotations. The interaction between handle rotation and gender was significant: the effect of handle rotation was greater for males than for females. The interaction between handle tilt and gender was significant: the effect of handle tilt was slightly greater for males than for females. Mean values for wrist deviation for different handle conditions are plotted in Figure 5.

Post hoc results indicate that the wrist was significantly more radial deviated for 90° handle rotation (neutral forearm) than for 45° handle rotation ($p < 0.001$), which, in turn, was significantly more radial deviated than 0° handle rotation ($p < 0.001$). Mean (SD) RUD for handle rotations 0°, 45° and 90° was 4(15), -8(13) and -20(13), respectively. The wrist was significantly more radial deviated for handle tilt angle of 0° than for handle tilt angle of 15° ($p < 0.001$). Mean (SD) RUD for handle tilt of 0° and 15° was -14(16) and -1(16), respectively. The wrist was significantly more radial deviated for wide handles than for narrow handles ($p < 0.001$). Mean (SD) RUD for the narrow- and wide-handle widths was -4(17) and -12(16), respectively.

4 Discussion

4.1 Natural hand/handle angle

Results show that the natural hand/handle angle when performing push tasks was approximately 65°. This result is slightly lower than the 67° reported by Hsu and Chen (1999) for grasping and 'about 70°' suggested by Kroemer, Kroemer, and Kroemer-Elbert (1994). The difference may be due to the functional task being performed (maximum voluntary push vs. voluntary gripping). An applied load on the handle may cause the natural angle to change due to tissue deformation and functional advantage, so it is reasonable to assume that there will be differences for push, gripping or pulling tasks. In

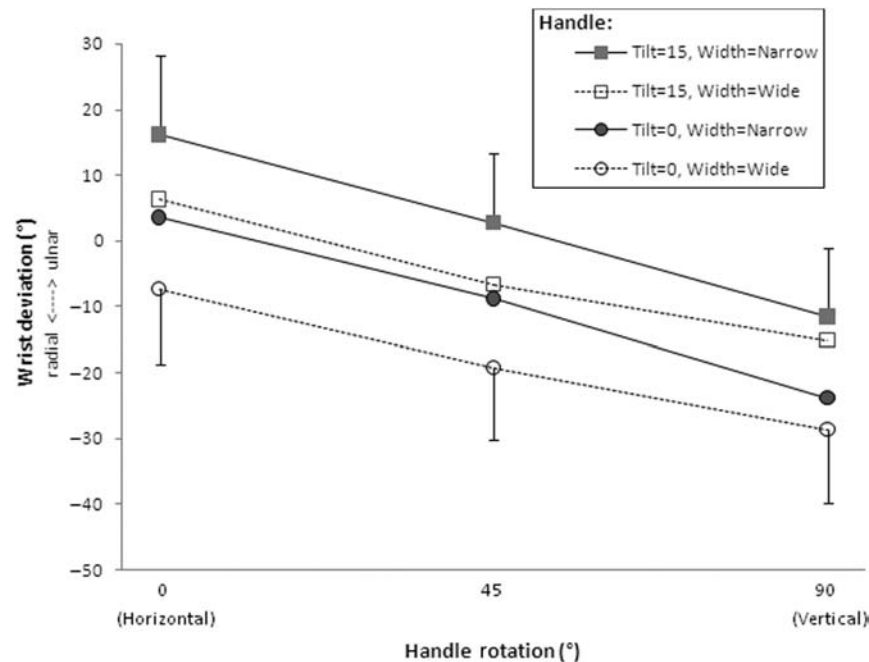


Figure 5. Mean wrist radial/ulnar deviation for different handle rotations, tilts and between-handle widths. Gender is pooled.

addition, previous studies define the natural angle with respect to the forearm, which can alter results if the wrist is deviated. Defining the natural angle with respect to the third metacarpal bone isolates the natural angle of hand/handle push coupling from wrist deviations.

Analysis of variance showed significant main effects due to handle rotation, tilt and width but not gender. This suggests that natural handle angle is independent of hand size and is more generally due to the anatomical shape of the hand, palmar tissues and bones. Pushing does not require a concurrent grip force (finger flexion) as the handle can be stabilised between the first and second metacarpal bones (thumb and index finger) and by tissues in the thenar and hypothenar regions. Therefore, the natural handle angle may be less influenced by the length of the fingers in push tasks than in gripping or pulling tasks.

Because of the anatomical asymmetry of the hand, the push force that is applied to the handle through the tissues of the hand may be distributed unevenly. When the handle is orthogonal (perpendicular) to the forearm and push direction, a higher concentration of force would be expected in the thenar/thumb area (Aldien et al. 2005). The average natural angle was 2° greater for non-tilted handles than for handles tilted forward 15°. This change was likely associated with a greater tissue deformation in the thenar region due to increased pressure on the non-tilted handles. This change may be even greater for handles of smaller diameter, because the same force would result in a greater localised pressure on a smaller contact area than for the current handles.

It should be noted that differences in natural handle angle are fairly small between treatments when compared to possible calculation error introduced by two-dimensional marker triad rotation artefacts ($\pm 3^\circ$). While it is likely that extreme change in handle rotation, tilt and width will affect natural handle angle, it is uncertain that these effects are practically significant over the small ranges tested in this study.

4.2 Wrist deviation

4.2.1 Effect of handle rotation and between-handle width

For the initial testing posture described in the methods, rotation of the handles should affect forearm rotation (from pronated to neutral) but not necessarily wrist posture. However, our results show that rotation significantly affected RUD and that the wrist became more radial deviated as the handle moved from 0° to 90°. The change in deviation was consistent over the handle rotations tested, with a mean change of -12° from rotation 0° to 45° and -12° from rotation 45° to 90°. Since changes in the natural hand/handle angle are small across handle orientations compared to changes in wrist deviation, changes in RUD are likely not due to hand posture, but rather due to changes in upper-limb posture during push exertions; a conclusion supported by previous studies (Okunribido and Haslegrave 2003, 2008).

Consistent postural changes in the upper limb should have different effects on wrist posture due to the rotation of the forearm. For example, a hypothetical postural change where the torso flexes slightly and the shoulder abducts the upper arm during the push task will cause the forearm to rotate in the transverse body plane and affect the wrist differently depending on handle orientation. For 0° (horizontal) handle rotations, the forearms are generally pronated with the palms facing the floor, so this postural change should mainly affect wrist RUD and not wrist flexion/extension. For 90° (vertical) handle rotations, the forearms are generally neutral with the palms facing inward to the midline of the body, so this postural change should mainly affect wrist flexion/extension rather than wrist RUD.

The influence of upper-limb posture is reflected in the significant effect of handle width, which shows that handles at wider distances caused greater radial deviation of the wrist than narrow-distanced handles. The two levels of handle width chosen in the experiment were based on the mean of the population biacromial breadth. The narrow-handle width (31.0 cm) was slightly smaller than the women population's mean breadth of 36.6 cm, while the wide-handle width (48.6 cm) was slightly larger than the men's mean breadth of 41.1 cm (McDowell, Fryar, and Orgen 2009). As described in the previous paragraph, it would therefore be expected that for the 0° handle rotations (horizontal handles), wrists would be ulnar deviated more for the narrow-handle width than for the wide-handle width. However, the width of the handles should affect RUD less for handle rotations where the forearm is not pronated or supinated. Results confirm this as the interaction between rotation and width was significant and the effect of width was reduced for 90° (vertical) handle rotations. Average change in RUD between narrow and wide handles were -10°, -10° and -4° for 0°, 45° and 90° handle rotations, respectively.

The interaction of handle rotation and gender shows that the effect of rotation was greater for males than for females. The mean change in RUD was -15° from rotations 0° to 45° and -15 from rotations 45° to 90° for males, and -10° from rotations 0° to 45° and -9° from rotations 45° to 90° for females. This could be due to differences in anthropometry or overall strength between males and females, or that females tend to adjust their upper-limb posture to attenuate wrist posture changes.

4.2.2 Effect of handle tilt

It was expected that tilting the handles by 15° should affect wrist postures similarly in all cases by a difference of approximately 15°. Results confirm that handle tilt affected RUD, and because interactions with other handle factors were not significant, the effect was similar across both rotations (difference of 13°, 12° and 13° for 0°, 45° and 90° rotations, respectively) and between-handle widths (difference of 12° and 13° for narrow and wide handles, respectively). These differences were slightly smaller than 15° and correspond to the changes in the natural angle between handle tilt conditions.

If it is assumed that maximal push strength occurs when forearm is in line with the push force and the wrist is in neutral posture, a 65° natural hand/handle angle would therefore correspond to a 25° natural handle tilt. In this study, handles of 0° and 15° were tested, so we would expect the wrist to be radial deviated by 25° and 10° on average for each handle tilt conditions, respectively. For 90° rotated handles (the forearm was neutral and RUD was less susceptible to upper-limb postural changes), radial deviation was 26° and 13° for 0° and 15° tilted handles, confirming the hypotheses. However in other handle rotations, the RUD would be more influenced by upper-limb posture. These results show that for pushing tasks while in pronated forearm postures, upper-limb posture likely decreased radial deviation.

4.3 Limitations

While general results for natural hand/handle angle and the effects of handle tilt and orientation on wrist RUD are convincing, this study is limited by the photographic method used to quantify joint angles. Observation of worker posture in person or by photographic/video analysis is common practice, and analysis of this method has received much attention (Paul and Douwes 1993; Juul-Kristensen et al. 2001; Lowe 2004; Lau and Armstrong 2011). During a validation experiment, the photographic method employed here had a mean error of $\pm 3^\circ$ and a variance of 7° . Differences in natural hand/handle angle across handle conditions (at most 2°) were small compared to this error, so it is difficult to make conclusions regarding specific effects. However, for wrist RUD, differences in mean angles are generally large compared to the photographic error (e.g. a difference of over 35° was observed between tilted, narrow, horizontal handles and the non-tilted, wide, vertical-oriented handles). Therefore, there may be small inaccuracies in the reported RUD values, but overall conclusions about the effects of handle parameters should be robust.

Another limitation is that wrist angle is dependent on both the hand/handle interface angle and the position of the forearm. In the experimental set-up, the seating system was adjusted so that when the participant grasped the handles, the forearms were parallel to the ground and the elbows were flexed at 115° . While the hands were fixed on the handles as prescribed by the protocol, the participant was free to alter their torso and upper-limb posture by leaning forward, abducting/adducting the shoulder or flexing/extending the elbow during the push exertion. As discussed above, these

postural changes would affect the relative orientation of the handle with respect to the torso, so it is difficult to extrapolate specifically how handle orientation may affect wrist posture in other body positions (such as standing). Furthermore, only the right hand and arm was analysed. There may be slight differences in posture between right and left arms due to differences in strength and hand dominance. Future studies employing a more sophisticated recording system that permits measurement of detailed body and upper-limb kinematics can improve the understanding of the effects of hand/handle interface on push posture and capacity.

Finally, the postures observed here were for seated maximum horizontal push exertions observed in a laboratory setting. While this is not a typical MMH situation, the handles that the subjects pushed on were in orientations found commonly on equipment and the focus of the analysis was the hand/handle interface and the wrist. The implications therefore should be relevant to many situations regardless of work pace, acceleration, weight of tools, etc. – as long as the task is pushing on a handle that is grasped in a power-grip posture. Even so, these results should be considered in conjunction with the larger body of literature about pushing exertions and are not necessarily applicable to other tasks, such as pulling exertions.

5. Conclusions

This research shows that wrist deviation posture during maximal pushing exertions was dependent on handle configuration. However, the natural angle between the hand and the handle was similar across the different handle configurations tested. These results suggest that the natural hand/handle angle is caused by anatomical asymmetry of the hand and that corresponding wrist posture is affected by this natural angle, in conjunction with handle orientation and upper-limb posture.

For ergonomists evaluating push tasks, it is important to consider how the handle interface affects both the capacity to produce force and the resulting postural demand. These findings are useful for designers who wish to understand naturally adopted hand and wrist postures and incorporate them into designs for the pushing hand/handle interface. Handles tilted forward at angles corresponding to the natural hand/handle angle ($\sim 25^\circ$) will tend to reduce radial deviation of the wrist. Therefore, handles that are typically straight and perpendicular to the push direction (i.e. pushcarts and hospital beds) could be tilted to account for the natural hand/handle angle and thus promote neutral wrist posture. However, as the wrist is part of a kinematic chain, operator's upper-arm posture and torso position must also be considered as well as the task and force requirements. Appropriate handle tilt angles to promote neutral wrist posture must be adjusted to account for the commonly adopted elbow position and forearm rotation for that specific piece of equipment. Furthermore, natural hand posture is likely different for pulling than for pushing tasks, so suitable tilt angle designs for dual task MMH handles (those used for both pushing and pulling) require further investigation.

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Notes

1. Email: jia-hua.lin@libertymutual.com
2. Email: Chien-chi.Chang@libertymutual.com
3. Email: raymond.mcgorry@libertymutual.com

References

- Al-Eisawi, K. W., C. J. Kerk, and J. J. Congleton. 1994. "Limitations of Wrist Strength to Manual Exertion Capability in 2D Biomechanical Modeling." *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*, 559–563. Santa Monica, CA: Human Factors and Ergonomics Society.
- Al-Eisawi, K. W., C. J. Kerk, J. J. Congleton, A. A. Amendola, O. C. Jenkins, and W. G. Gaines. 1999. "The Effect of Handle Height and Cart Load on the Initial Hand Forces in Cart Pushing and Pulling." *Ergonomics* 42 (8): 1099–1113.
- Aldien, Y., D. Welcome, S. Rakheja, R. Dong, and P. -E. Boileau. 2005. "Contact Pressure Distribution at Hand–Handle Interface: Role of Hand Forces and Handle Size." *International Journal of Industrial Ergonomics* 35: 267–286.
- Armstrong, T. J., J. A. Foulke, B. S. Joseph, and S. A. Goldstein. 1982. "Investigation of Cumulative Trauma Disorders in a Poultry Processing Plant." *American Industrial Hygiene Association Journal* 43: 103–116.
- Caldwell, L. S., D. B. Chaffin, F. N. Dukes-Dobos, K. H. E. Kroemer, L. L. Laubach, S. H. Snook, and D. E. Wasserman. 1974. "A Proposed Standard Procedure for Static Muscle Strength Testing." *American Industrial Hygiene Association Journal* 35: 201–206.
- Cochran, D. J., and M. W. Riley. 1986. "The Effects of Handle Shape and Size on Exerted Forces." *Human Factors* 28 (3): 253–265.
- Devereux, J., P. Buckle, and M. Haisman. 1998. "The Evaluation of a Hand–Handle Interface Tool (HHIT) for Reducing Musculoskeletal Discomfort Associated With Manual Handling of Gas Cylinders." *International Journal of Industrial Ergonomics* 21 (1): 23–34.
- Garrett, J. W. 1971. "The Adult Human Hand: Some Anthropometric and Biomechanical Considerations." *Human Factors* 13: 117–131.

- Hoozemans, M. J., A. J. van der Beek, M. H. Frings-Dresen, L. H. van der Woude, and F. J. H. van Dijk. 2002. "Low-Back and Shoulder Complaints Among Workers With Pushing and Pulling Tasks." *Scandinavian Journal of Work, Environment and Health* 28 (5): 293–303.
- Hoozemans, M. J., A. J. van der Beek, M. H. Frings-Dresen, F. J. H. van Dijk, and L. H. van der Woude. 1998. "Pushing and Pulling in Relation to Musculoskeletal Disorders: A Review of Risk Factors." *Ergonomics* 41 (6): 757–781.
- Hsu, S. -H., and Y. -H. Chen. 1999. "Evaluation of Bent-Handled Files." *International Journal of Industrial Ergonomics* 25: 1–10.
- Jung, M. C., J. M. Haight, and A. Freivalds. 2005. "Pushing and Pulling Carts and Two-Wheeled Hand Trucks." *International Journal of Industrial Ergonomics* 35 (1): 79–89.
- Juul-Kristensen, B., G. A. Hansson, N. Fallentin, J. H. Andersen, and C. Ekdahl. 2001. "Assessment of Work Postures and Movements Using a Video-Based Observation Method and Direct Technical Measurements." *Applied Ergonomics* 32: 517–524.
- Kroemer, K. H. E., H. B. Kroemer, and K. E. Kroemer-Elbert. 1994. *Ergonomics: How to Design for Ease and Efficiency*. Englewood Cliffs, NJ: Prentice Hall.
- 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.
- Lau, M. H., and T. J. Armstrong. 2011. "The Effect of Viewing Angle on Wrist Posture Estimation From Photographic Images Using Novice Raters." *Applied Ergonomics* 2: 634–643.
- Lee, K. S., D. B. Chaffin, G. D. Herrin, and A. M. Waiker. 1991. "Effect of Handle Height on Lower-Back Loading in Cart Pushing and Pulling." *Applied Ergonomics* 22 (2): 117–123.
- Lee, Y. -J., M. J. Hoozemans, and J. H. van Dieën. 2011. "Handle Height and Expectation of Cart Movement Affect the Control of Trunk Motion at Movement Onset in Cart Pushing." *Ergonomics* 54 (10): 971–982.
- Lin, J. -H., R. W. McGorry, and C. -C. Chang. 2012. "Effects of Handle Orientation and Between-Handle Distance on Push Strength." *Applied Ergonomics* 43: 664–670.
- Lowe, B. D. 2004. "Accuracy and Validity of Observational Estimates of Wrist and Forearm Posture." *Ergonomics* 47: 527–554.
- Mack, K., C. M. Haslegrave, and M. I. Gray. 1995. "Usability of Manual Handling Aids for Transporting Materials." *Applied Ergonomics* 26 (5): 353–364.
- McDowell, M. A., C. D. Fryar, and C. L. Ogden. 2009. "Anthropometric Reference Data for Children and Adults: United States, 1988–1994." National Center for Health Statistics. *Vital and Health Statistics*, Series 11, no. 249.
- Okunribido, O. O., and C. M. Haslegrave. 1999. "Effect of Handle Design for Cylinder Trolley." *Applied Ergonomics* 30: 407–419.
- Okunribido, O. O., and C. M. Haslegrave. 2003. "Postures Adopted When Using a Two-Wheeled Cylinder Trolley." *Applied Ergonomics* 34 (2): 339–353.
- Okunribido, O. O., and C. M. Haslegrave. 2008. "Ready Steady Push: A Study of the Role of Arm Posture in Manual Exertions." *Ergonomics* 51 (2): 192–216.
- Paul, J. A., and M. Douwes. 1993. "Two-Dimensional Photographic Posture Recording and Description: A Validation Study." *Applied Ergonomics* 24 (2): 83–90.
- Roman-Liu, D., and T. Tokarski. 2005. "Upper Limb Strength in Relation to Upper Limb Posture." *International Journal of Industrial Ergonomics* 35: 19–31.
- Seo, N. J., and T. J. Armstrong. 2009. "Biomechanical Analysis for Handle Stability During Maximum Push and Pull Exertions." *Ergonomics* 52 (12): 1568–1575.
- Seo, N. J., T. J. Armstrong, and J. G. Young. 2010. "Effects of Handle Orientation, Gloves, Handle Friction and Elbow Posture on Maximum Horizontal Pull and Push Forces." *Ergonomics* 53 (1): 92–101.
- Snook, S. H., and V. M. Ciriello. 1991. "The Design of Manual Handling Tasks: Revised Tables of Maximum Acceptable Weights and Forces." *Ergonomics* 34 (9): 1197–1213.