The Effect of Handle Friction and Inward or Outward Torque on Maximum Axial Push Force

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Objective: To investigate the relationship among friction, applied torque, and axial push force on cylindrical handles. **Background:** We have earlier demonstrated that participants can exert greater contact force and torque in an "inward" movement of the hand about the long axis of a gripped cylinder (wrist flexion/forearm supination) than they can in an "outward" hand movement. **Method:** Twelve healthy participants exerted anteriorly directed maximum push forces along the long axis of aluminum and rubber handles while applying deliberate inward or outward torques, no torque (straight), and an unspecified (preferred) torque. **Results:** Axial push force was 12% greater for the rubber handle than for the aluminum handle. Participants exerted mean torques of 1.1, 0.3, 2.5, and –2.0 Nm and axial push forces of 94, 85, 75, and 65 N for the preferred, straight, inward, and outward trials, respectively. Left to decide for themselves, participants tended to apply inward torques, which were associated with increased axial push forces. **Conclusion:** Axial push force was limited by hand-handle coupling – not the whole body's push strength. Participants appeared to intuitively know that the application of an inward torque would improve their maximum axial push force. Axial push forces were least when a deliberate torque was requested, probably because high levels of torque exertions interfered with the push. **Application:** A low-friction handle decreases maximum axial push force. It should be anticipated that people will apply inward torque during maximum axial push.

INTRODUCTION

Significance

Many activities in work and daily living entail gripping a cylindrical object about its diameter and applying an axial force to move it from one location to another, to join it to another part, to support the body, or to propel a wheelchair. Friction produced between the hand and the handle is necessary to overcome external forces that tend to push the handle out of the hand. Slippery handles and hands sliding onto the blades of knives can cause many injuries, including lacerations and even amputation of fingers (Malker, 1991).

Hose installation and pipe assembly, which are prevalent in many manufacturing, plumbing, and service jobs, are examples of a task that requires a large axial push force. A hose installation task entails grasping a rubber hose and pushing it onto a flange until the hose is tightly seated on the base of the flange. A survey study by Ebersole and Armstrong (2004) reported that hose installation tasks were consistently rated by workers in an automotive truck assembly plant as the most physically demanding part of their job. Also, it is well known that repeated exertions of high forces may cause fatigue (Byström & Fransson-Hall, 1994; Rohmert, 1973) and pain or injury to a worker (Armstrong et al., 1993; Byström & Kilbom, 1990; National Research Council, 1999; National Research Council & Institute of Medicine, 2001).

Rationale

Previous investigators have studied maximum voluntary isometric push forces and maximum acceptable push forces in a standing posture (Chaffin, Andres, & Garg, 1983; Daams, 1993; Davis & Stubbs, 1977; Peebles & Norris, 2003; Snook & Ciriello, 1991). These studies used handles that produced mechanical interference to prevent the

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hands from slipping, so that the full force of the body could be transferred to the work object (e.g., pushing against a wall). Though helpful in some situations, these data are not appropriate when the magnitude of a push force applied to an axial handle may be limited by friction, as illustrated in Figure 1a.

It has been previously shown, both empirically and by a biomechanical model, that when the hand applies torque about the long axis of a cylindrical object in a power grip, an "inward" torque (i.e., acting in a proximal-to-distal sense with respect to the fingers) resulted in 19% greater normal force on the handle, compared with an "outward" torque (i.e., proximal-to-distal sense with respect to the thumb; Seo, Armstrong, Ashton-Miller, & Chaffin, 2007). As a result, the maximum inward torque was 22% greater than the maximum outward torque. This is because skin friction produced by twisting an object in the direction the fingertips

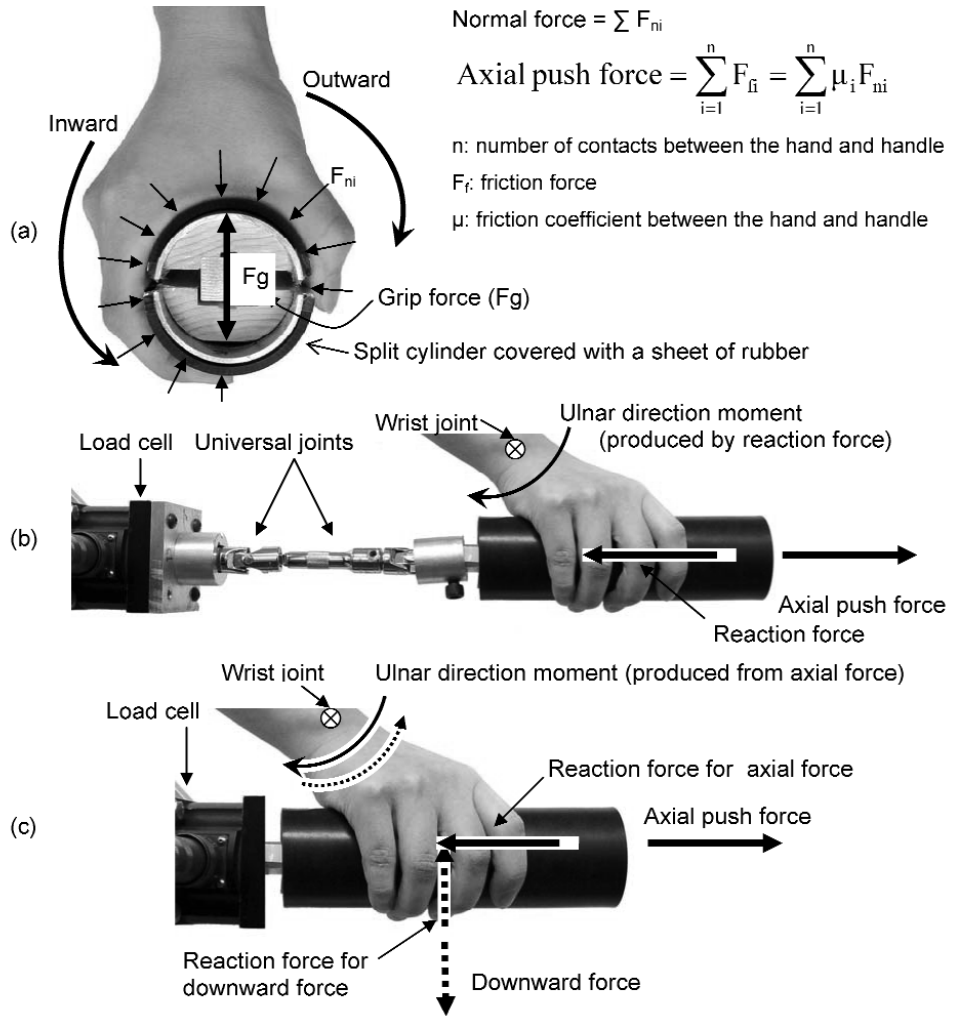

Figure 1. (a) Axial push force can be modeled as a sum of friction forces at the hand-handle contact, where friction force at each hand-handle contact is a product of the friction coefficient and normal force at the contact. The directions of inward and outward torque exertions and illustration of grip force (Fg) and normal force ($\sum F_{ni}$) are shown. (b) The handle was connected to a load cell via universal joints. Axial push force results in reaction force in the opposite direction, which generates a moment about the wrist in the ulnar direction. (c) Moment about the wrist joint is reduced when there is downward force applied by the hand to a fixed handle (segmented lines). The downward force results in an upward reaction force, which generates a moment about the wrist joint in the radial direction. This radially directed moment can alleviate the ulnar-directed moment resulting from the axial force (solid lines).

point causes flexion of the distal phalanges and increases the normal force, and thus torque, as described by the biomechanical model proposed in Seo et al. (2007) and Seo, Armstrong, Chaffin, and Ashton-Miller (2008).

Based on these findings, we hypothesized that the increased grip force when applying an inward torque would result in an increased maximum push force along a cylindrical handle (termed *axial push force*). Conversely, a decreased grip force from an outward torque would result in a decrease in axial push force along the long axis of a cylindrical handle.

We therefore conducted an experiment to test two hypotheses: Hypothesis 1, that maximum axial push force is related to friction, and Hypothesis 2, that maximum axial push force on a cylindrical handle will increase with the simultaneous application of an inward torque.

METHODS

Procedures

The independent variables in this study were handle material (aluminum or rubber) and push method: push with an inward torque, push with an outward torque (see Figure 1a for torque directions), straight push (with no torque), and a participant-selected preferred method. Dependent variables were maximum axial push force, torque, grip force, normal force, and finger flexor muscle activities estimated by using surface electromyography (EMG).

Upon their arrival at the laboratory, participants washed and dried their hands with paper towels to eliminate possible artifacts attributable to contaminants. Finger flexor muscle activities were recorded using surface EMGs. One pair of surface EMG electrodes was placed over the proximal muscle belly fibers of the flexor digitorum profundus (FDP) on the medial side of the forearm, approximately one third the distance on a line from the medial epicondyle to the styloid process of the ulna (Garland & Miles, 1997). The flexor digitorum superficialis (FDS) was located as recommended by Basmajian (1989), except that surface EMG electrodes were placed approximately two thirds the distance on a line from the medial epicondyle to the center of the wrist, to minimize crosstalk from the flexor carpi radialis and flexor carpi ulnaris.

The participants, while standing, grasped a horizontal cylindrical handle with the right hand in a power grip to exert a maximum axial push for 5 s (see Figure 1b). The handle height was adjusted to each participant's standing elbow height. Participants were allowed to freely choose a posture – for example, leaning forward – to maximize the push force (Daams, 1993). Trials were randomized, except that the preferred method was tested at the beginning and at the end of the sequence of trials.

Pushes with deliberate inward or outward torques were performed at a comfortable torque level, and at 30%, 50%, and 80% of each participant's maximum voluntary torque. For a push with a comfortable level of torque, participants were instructed to apply whatever torque they felt was comfortable during their maximum axial push exertion. For pushes with specified torques, participants were instructed to match their torque levels to the 30%, 50%, or 80% of maximum voluntary torque displayed on a computer screen. Additionally, each participant's maximum grip force and maximum inward and outward torque on the handle were measured. Each condition was tested twice, and data were averaged for two repetitions. A 2-min break was given between successive trials.

Apparatus

Grip force was measured using a split cylinder in which two halves of the cylinder are connected by a force gauge (Ayoub & Lo Presti, 1971; Edgren, Radwin, & Irwin, 2004; Grant & Habes, 1993; Grant, Habes, & Steward, 1992; measurement error within 7%). The split cylinder was covered with a pressure-sensitive pad (Tekscan Pressure Measurement System; measurement error within 6%) that recorded normal pressure on each 5.08- × 5.08-mm sensor. The pressure-sensitive pad was calibrated as specified by the manufacturer (Tekscan, Inc). Total normal force was calculated by summing forces on each pressure sensor (see Figure 1a).

The pressure-sensitive pad was covered with a smooth, 3.5-mm-thick rubber sheet or with a smooth, 0.2-mm-thick aluminum sheet. With the pressure-sensitive pad and a sheet of rubber or aluminum wrapping the split cylinder, the tested handle diameters were 57.8 and 51.2 mm for the rubber and aluminum handles, respectively. The handle was connected to a load cell via two universal joints to eliminate lateral forces as defined by Drury (1980). The load cell measured axial push forces and the applied torque about the handle's long axis (measurement error 0.2%).

The EMG instrumentation used surface EMG electrodes (AMBU Neuroline 720 Wet Gel Ag/AgCl) and a preamplifier with gain of 100 and a common mode rejection ratio of 115 dB. The raw signal was converted to real-time root mean square values using a 55-ms time constant. Among all maximum exertions, the highest EMG value was used to normalize other EMG values as a percentage of maximum voluntary contraction. The data were collected at 5 Hz. All data were averaged over 2 s during maximum exertions. The floor on which the participants stood was covered with a coarse rubber mat to provide sufficient foot traction. Throughout the experiment, none of the participants exhibited problems with foot slippage, irrespective of footwear or postures adopted during exertions.

ANOVA was performed using MINITAB® Release 14 to determine whether axial push force was significantly affected by handle material, push method, torque, and gender, with a value of $p = .05$ being considered significant.

Participants

Twelve healthy university students (6 men and 6 women, age 21–35 years, mean age 27.0 ± 4.8 years) participated in the experiment. All participants were right-handed and were free of any upper-extremity disorders. They gave written informed consent prior to testing. Their mean hand length was measured using the method of Garrett (1971) and was found to be 18.4 ± 0.8 cm for men and 16.8 ± 0.9 cm for women. Their mean grip strength, as measured with a Jamar dynamometer with a grip span of 49 mm, was found to be 397 ± 155 N. Male participants' grip strengths ranged from the 14th to the 78th percentile, and female participants' grip strengths ranged from the 1st to the 86th percentile, based on population data from Mathiowetz et al. (1985). Table 1 summarizes the participants' average maximum inward and outward torques, maximum grip forces and normal forces, and FDP and FDS EMGs during maximum grip exertions on the horizontal cylindrical handles.

RESULTS

Mean maximum axial push forces, grip forces, normal forces, torques about the long axis of the handle, and FDP and FDS EMGs are summarized in Table 2 by gender. Maximum axial push force was, on average, 12% greater for the rubber handle than for the aluminum handle (for the preferred and the straight methods, $p < .01$), although grip force and FDP and FDS EMG level did not vary with handle material ($p > .05$). The mean maximum axial push force for men was twice that for women ($p < .01$).

Among all methods, axial push force was greatest for the preferred method, followed by the straight method (Figure 2a). The mean axial push force for the preferred method was 10% greater than that for the straight method ($p < .01$). The FDS and FDP EMGs were not significantly different between the two methods. Greater inward torque was observed for the preferred method (1.1 Nm on average; 17% of maximum voluntary inward

TABLE 1: Torque During Maximum Torque Exertions and Forces and EMG Activity During Maximum Grip Exertions (Mean ± 1 *SD*)

Handle Material	Max. Inward Torque[a] (Nm)	Max. Outward Torque[a] (Nm)	Max. Grip Force (N)	Total Normal Force (N)	FDP During Max. Grip (%)	FDS During Max. Grip (%)
			Men (n = 6)			
Aluminum	6.9 ± 1.3	–5.1 ± 1.2	222 ± 87	567 ± 162	80 ± 16	80 ± 17
Rubber	8.7 ± 2.5	–6.9 ± 1.8	222 ± 91	460 ± 150	89 ± 9	84 ± 16
			Women (n = 6)			
Aluminum	2.8 ± 1.7	–2.3 ± 1.1	94 ± 44	217 ± 131	83 ± 14	86 ± 8
Rubber	3.5 ± 2.1	–2.9 ± 1.7	84 ± 38	155 ± 115	88 ± 10	78 ± 14

Note. Handle diameter = 57.8 and 51.2 mm for the rubber and aluminum handles, respectively. FDP = flexor digitorum profundus, FDS = flexor digitorum superficialis.

[a]Inward and outward torque directions are described in Figure 1a.

TABLE 2: Forces, Torques, and EMG Activity During Maximum Push Exertions by Push Method, Handle Material, and Gender (Mean ± 1 *SD*)

Method	Push Force (N)	Grip Force[a] (N)	Normal Force[b] (N)	Torque (Nm)	FDP (%)	FDS (%)
			Men (*n* = 6): Aluminum Handle			
Preferred	113 ± 19	142 ± 82	328 ± 110	2.1 ± 2.0	63 ± 17	56 ± 14
Straight	107 ± 20	109 ± 51	266 ± 99	0.7 ± 0.5	63 ± 11	58 ± 12
Inward torque						
Comf	99 ± 28	156 ± 73	380 ± 216	3.0 ± 1.5	65 ± 19	62 ± 22
30%	92 ± 29	118 ± 75	298 ± 141	2.3 ± 0.5	58 ± 12	63 ± 10
50%	95 ± 34	151 ± 70	350 ± 200	3.2 ± 0.8	57 ± 13	69 ± 18
80%	78 ± 33	181 ± 54	404 ± 194	4.2 ± 1.3	68 ± 15	70 ± 20
Outward torque						
Comf	84 ± 31	147 ± 42	395 ± 190	–2.5 ± 1.0	72 ± 10	54 ± 11
30%	88 ± 23	124 ± 57	345 ± 112	–1.7 ± 1.2	69 ± 14	48 ± 9
50%	74 ± 27	138 ± 61	364 ± 106	–2.2 ± 0.8	76 ± 17	49 ± 9
80%	83 ± 31	167 ± 65	443 ± 154	–3.0 ± 1.1	82 ± 20	53 ± 12
			Men (*n* = 6): Rubber Handle			
Preferred	136 ± 25	137 ± 65	259 ± 68	1.5 ± 2.3	64 ± 20	56 ± 18
Straight	112 ± 27	115 ± 50	199 ± 69	0.3 ± 0.6	51 ± 11	51 ± 11
Inward torque						
Comf	110 ± 27	160 ± 56	323 ± 157	3.7 ± 2.5	61 ± 15	68 ± 14
30%	94 ± 27	107 ± 22	209 ± 71	2.5 ± 0.7	53 ± 14	59 ± 13
50%	96 ± 35	144 ± 37	267 ± 115	4.1 ± 1.3	60 ± 15	68 ± 17
80%	97 ± 27	220 ± 55	400 ± 177	6.0 ± 2.0	70 ± 17	75 ± 16
Outward torque						
Comf	92 ± 24	180 ± 46	239 ± 73	–3.5 ± 1.6	71 ± 9	48 ± 6
30%	95 ± 22	125 ± 44	176 ± 48	–2.1 ± 0.7	62 ± 13	48 ± 8
50%	91 ± 32	155 ± 59	216 ± 55	–2.9 ± 1.2	69 ± 12	49 ± 7
80%	74 ± 28	229 ± 78	270 ± 58	–4.4 ± 1.6	79 ± 18	53 ± 5
			Women (*n* = 6): Aluminum Handle			
Preferred	62 ± 22	55 ± 21	142 ± 84	0.5 ± 0.4	60 ± 13	70 ± 12
Straight	57 ± 25	51 ± 19	138 ± 85	0.2 ± 0.2	70 ± 13	70 ± 6
Inward torque						
Comf	53 ± 24	67 ± 29	157 ± 94	1.3 ± 0.7	67 ± 14	71 ± 12
30%	49 ± 27	54 ± 25	137 ± 81	0.9 ± 0.6	59 ± 8	70 ± 9
50%	51 ± 27	66 ± 31	151 ± 93	1.3 ± 0.8	59 ± 9	71 ± 13
80%	50 ± 28	81 ± 29	165 ± 107	1.6 ± 1.0	65 ± 10	77 ± 10
Outward torque						
Comf	44 ± 20	51 ± 16	146 ± 74	–1.1 ± 0.6	71 ± 13	66 ± 8
30%	44 ± 27	35 ± 14	107 ± 70	–0.6 ± 0.4	65 ± 17	63 ± 9
50%	46 ± 27	41 ± 19	137 ± 80	–1.0 ± 0.6	74 ± 17	63 ± 12
80%	43 ± 20	60 ± 29	178 ± 117	–1.4 ± 0.9	84 ± 12	67 ± 11
			Women (*n* = 6): Rubber Handle			
Preferred	65 ± 29	42 ± 18	93 ± 64	0.5 ± 1.1	63 ± 18	64 ± 22
Straight	61 ± 32	38 ± 32	100 ± 121	0.1 ± 0.1	65 ± 13	70 ± 19
Inward torque						
Comf	59 ± 27	53 ± 42	114 ± 120	1.5 ± 1.0	64 ± 16	75 ± 19
30%	61 ± 32	36 ± 16	87 ± 68	1.1 ± 0.7	60 ± 13	72 ± 20
50%	59 ± 28	51 ± 28	112 ± 111	1.6 ± 0.9	63 ± 15	74 ± 18
80%	57 ± 29	64 ± 30	122 ± 120	2.2 ± 1.2	67 ± 17	75 ± 17
Outward torque						
Comf	50 ± 24	67 ± 40	97 ± 82	–1.6 ± 0.9	79 ± 15	68 ± 16
30%	48 ± 26	45 ± 26	62 ± 50	–0.9 ± 0.7	57 ± 11	63 ± 18
50%	47 ± 24	57 ± 39	72 ± 47	–1.4 ± 0.6	66 ± 15	65 ± 18
80%	43 ± 21	68 ± 49	93 ± 79	–1.9 ± 1.1	74 ± 14	67 ± 17

Note. Handle diameters = 57.8 and 51.2 mm for the rubber and aluminum handles, respectively. Push methods were preferred push, straight push, and push with an inward or outward torque at a comfortable (Comf) level or at 30%, 50%, and 80% of the maximum torque level. FDP = flexor digitorum profundus, FDS = flexor digitorum superficialis.

[a]Grip force was measured with a split cylinder with the force gauge's major axis aligned to the forearm (see Figure 1a). [b]Normal force is the total normal contact force between the hand and the cylindrical handle. Normal force was measured with a pressure-sensitive pad wrapped around the cylindrical handle (see Figure 1a).

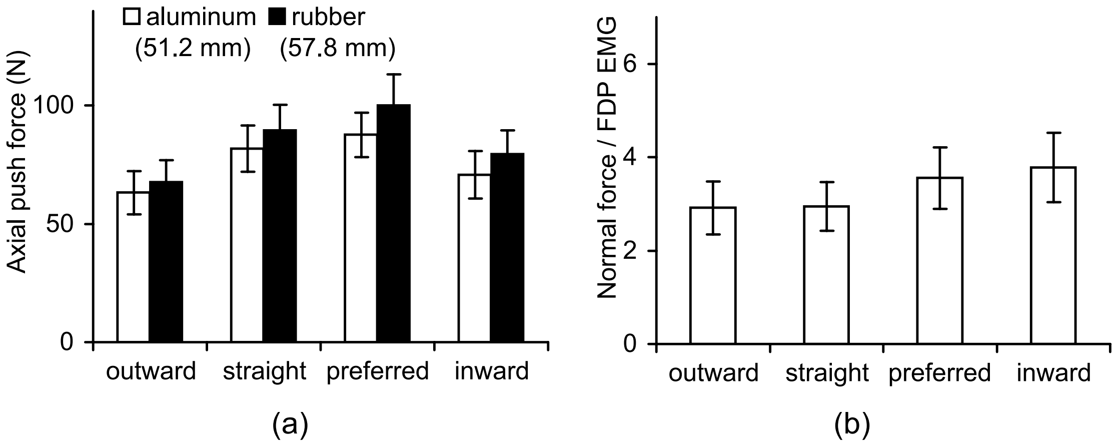

Figure 2. (a) Maximum axial push force for four push methods and two handle materials (Mean ± *SE*). The preferred method was associated with an inward torque that was 17% of the maximum value. (b) The efficiency of normal force generation as the ratio of normal force to flexor digitorum profundus (FDP) EMG for the four push methods (mean ± *SE*). Outward: push with a deliberate outward torque; straight: the straight method with no torque as possible; preferred: the preferred method; inward: push with a deliberate inward torque. Pushes with 30%, 50%, 80%, and comfortable inward and outward torques are pooled. Data are pooled from 6 men and 6 women.

torque) than for the straight method (0.3 Nm on average; 5% of maximum voluntary inward torque; $p < .01$). The "efficiency" in normal force generation, which was accessed by examining the normal force for a given FDP EMG (DeVries, 1968), was greater for the preferred method than for the straight method ($p < .05$; Figure 2b). For the preferred and the straight methods combined, high normal force and grip force were associated with high inward torque ($p < .01$) and high axial push force ($p < .01$).

The magnitude of inward torque for the preferred method was not significantly different between the beginning and the end of the experimental trials ($p > .05$). Some inward torque was observed for 85% of all straight push and preferred push trials. Even when participants were instructed to exert axial push forces in the absence of torque (the straight method), participants produced inward torque that was greater than 0 Nm ($p < .01$).

Axial push force decreased with deliberate inward or outward torque, as compared with the straight method (Table 2; Figure 2a). Axial push forces for the straight method were not different from those with a comfortable inward torque ($p > .05$); however, pushing while also applying 30%, 50%, or 80% inward torque resulted in 15% less axial push force than that for the straight method ($p < .05$). For pushes with 30%, 50%, and 80% inward torque, axial push force did not vary significantly with the magnitude of inward torque ($p > .05$ for both handle materials). Among the four methods, axial push force was least with deliberate outward torque ($p < .01$; Figure 2a). For pushes with 30%, 50%, 80%, and comfortable outward torque, axial push force decreased with increasing outward torque ($p < .01$ for both handle materials).

When the participants were instructed to specifically produce inward or outward torque while pushing, FDS and FDP EMGs, normal forces, and grip forces were greater than those for the straight method ($p < .05$; Table 2). The efficiency in normal force generation was worse for the pushes with deliberate outward torque, and better for the pushes with deliberate inward torque, as compared with the straight method ($p < .05$; Figure 2b). Despite the increases in normal forces, grip forces, and FDS and FDP EMGs, axial push force did not increase for the pushes with deliberate torque, compared with the straight method.

From a modeling standpoint, axial push force was predicted by multiplying the normal force and static friction coefficient, as described in Figure 1a, for the preferred method. The average static friction coefficient between the hand and the handle has been estimated to be 0.33 for aluminum (Buchholz, Frederick, & Armstrong, 1988) and 0.77 for rubber (Bobjer, 2004). Predicted axial push forces were not significantly different from the measured axial push forces ($p > .05$) for the aluminum handle (see Figure 3). For the rubber handle, predicted axial push forces were, on average, 35% greater than measured axial push forces ($p < .01$).

DISCUSSION

Hypothesis 1: Effect of Handle Friction on Axial Push Force

The data support the hypothesis that axial push force is related to handle friction: Axial push force was 12% greater for the high-friction rubber handle than for the low-friction aluminum handle ($p < .01$), even though grip force and FDP and FDS EMG were not different between the two handle materials ($p > .05$, for the preferred and the straight methods). This suggests that the weakest link in the chain is the friction between the hand and handle.

Maximum whole-body push force can be limited by slippage between the hand and a work object. As compared with previous studies, which measured push force in the absence of friction constraints, the present study, with hand-handle friction, resulted in less push force. In this study, in which friction was a limiting factor, the highest axial push force was 179 N for a man, which is 38% to 51% of male maximum push forces seen in previous studies where friction was not a limiting factor, as reported by Chaffin et al. (1983), Daams (1993), and Peebles and Norris (2003). Similarly, the highest axial push force measured for a woman in this study, 152 N, was about 36% to 70% of reported female maximum push forces with no friction constraints by Chaffin et al. (1983), Daams (1993), and Peebles and Norris (2003).

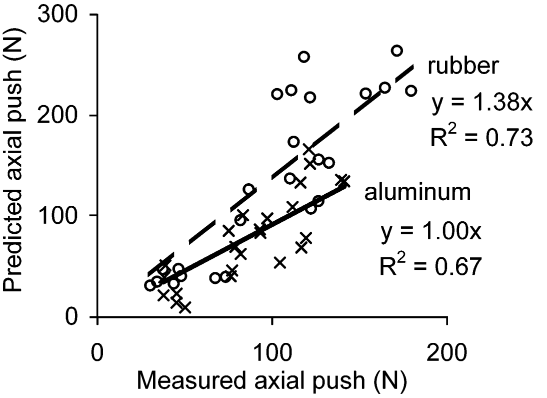

Figure 3. Comparison between measured and predicted axial push force for the rubber handle (empty circles, segmented line) and aluminum handle (cross, solid line).

None of the axial push forces measured in this study exceeded the maximum "acceptable" push forces recommended by Davis and Stubbs (1977) and Snook and Ciriello (1991), in which friction was not a limiting factor. The highest axial push force in this study under high-friction conditions was about 41% to 61% less than the maximum acceptable push force established by Davis and Stubbs (1977) and Snook and Ciriello (1991), for both genders.

Note that the push posture in the present study was similar to that in these previous studies (Chaffin et al., 1983; Daams, 1993), wherein a freely adopted posture was used, usually with one foot placed in front of the other foot and the torso leaned in the direction of push, with the handle at about elbow height. No slipping between the shoes and the floor was observed throughout the experiment. This suggests that handle friction limits axial push force, if wrist strength is not a limiting factor. It also indicates that the current standards for pushing overestimate the abilities of the population for cylindrical axial handles.

Because the static friction coefficient for rubber (0.77) was approximately twice that for aluminum (0.33), twice greater axial push force was expected for the rubber handle than for the aluminum handle from the axial push model in Figure 1a. The difference in measured axial push force between the rubber and aluminum handles turned out to be only 12%.

Two reasons may exist for the small difference. First, it may be because different handle diameters were used for the two handles. The diameters for the rubber and aluminum handles were 57.8 and 51.2 mm, respectively, in this study. Previous studies have shown that maximum grip force decreases with increasing handle diameter for handle diameters greater than 38 mm (Ayoub & Lo Presti, 1971; Edgren et al., 2004; Grant et al., 1992). For example, in the study by Edgren et al. (2004), as a handle diameter increased 25% from 50.8 to 63.5 mm, average maximum grip force decreased 14% from 228 to 197 N. Similarly, in the present study, as the handle diameter increased 13% from 51.2 (aluminum handle) to 57.8 mm (rubber handle), maximum grip force decreased 5% and maximum normal force decreased 20%. Thus, decreased grip force and normal force attributable to a greater handle diameter could have reduced maximum axial push force for the rubber handle.

Second, maximum axial push force may also be limited by wrist strength. Pushing in the axial direction of the handle results in reaction force from the handle to the hand in the opposite direction (see Figure 1b). This reaction force generates a moment about the wrist joint in the ulnar direction, which then requires radial deviators' activity to stabilize the wrist. According to Delp, Grierson, and Buchanan (1996), average men can produce approximately 147 N with their radial deviators. This is only 8% greater than the average axial push force observed for men with the high-friction rubber handle in this study (Table 2). Thus, axial push force exertions may have been limited not only by handle friction but also by wrist abduction strength. This is probably why measured axial push force for the rubber handle was less than predicted (Figure 3). When the wrist becomes more deviated in the ulnar direction when pushing, however, the passive force of the wrist will increase, and the wrist may not be a limiting factor for axial push.

Grieshaber (2007) measured axial push force for a fixed handle (with no universal joints and a handle diameter of 60 mm) and reported about a twofold higher axial push force than was found in this study. This may be because participants could apply downward force on a fixed handle. First, with a downward force exertion, normal force on the handle comes not only from the gripping activity but also from the downward force exertion. The increased normal force can result in increased axial push force.

Second, a downward force can result in a decreased moment about the wrist, as shown in Equation 1. A downward force results in a reaction force upward, which generates a moment about the wrist in the radial direction (see Figure 1c). This is an opposite moment from that generated by the reaction force from pushing (ulnar direction). Thus, the two moments from the two reaction forces will counterbalance, reducing a resultant moment about the wrist joint and relieving loads on the wrist deviators. For example, if moment arms for the two reaction forces are equal, a downward force equivalent to 20% of axial push force can reduce the moment about the wrist by 20%.

$$\text{Moment about the wrist} = \sum \text{reaction force} \times \text{moment arm} = (\text{reaction force for axial push} \times \text{moment arm}) - (\text{reaction force for downward force} \times \text{moment arm}) \quad (1)$$

Hypothesis 2: Effect of Torque on Axial Push Force

The data for the straight and preferred methods support the hypothesis that inward torque will result in increased axial push force. It was observed that participants preferred to use about 17% of maximum inward torque during axial pushing (1.1 Nm on average; Table 2). The amount of inward torque participants preferred to use while pushing with their preferred method was significantly greater than 0 Nm ($p < .01$).

Even though FDP and FDS EMGs did not vary with inward torque level, grip force and normal force were positively correlated with the inward torque and axial push force ($p < .01$). Therefore, it appears that during pushing with the preferred method, inward torque helped participants increase grip forces and normal forces, and thus increase axial push force, without more effort from the finger flexor muscles. It agrees with our previous finding that friction force toward the proximal end of the fingertip causes flexion of the distal phalanges and increases the normal force on the fingertip (Seo et al., 2007, 2008).

Axial push force was the least with a deliberate outward torque (only 70% of axial push force for the preferred method; see Figure 2a), and it decreased 12% as the outward torque level increased from 30% to 80% (Table 2), which also supports the hypothesis. Contrary to the prediction, however, axial push force with a deliberate inward torque was 12% less than that for the straight method ($p < .01$, inward torque level pooled), even though the normal force and the ratio of normal force to FDP EMG increased 25% and 27% with deliberate inward torque, respectively (Table 2; Figure 2b).

This may be because the instruction imposed an extra torque task in addition to pushing. Also, participants may have perceived the instructed push method with the deliberate inward or outward torque requirements as unnatural, which in turn may have lowered their push force. This is similar to what Daams (1993) reported: that standardized postures were perceived by many participants as unnatural and uncomfortable, and the forces measured in such a posture were often less than those exerted in a free, unrestricted posture. Therefore, it appears that even though voluntary inward torque results in increased axial push force, instructed inward torque may not necessarily improve axial push force.

LIMITATIONS AND FUTURE WORK

The experimental design in this study did not separate the effect of the handle friction from the effect of the handle diameter, as they both changed at the same time. Future studies should eliminate this confounder. In addition, the handle diameter used in this study was greater than the "optimal" handle diameter that results in the highest grip force: 38 mm according to Ayoub and Lo Presti (1971) and Edgren et al. (2004). Thus, use of handles with diameters close to 38 mm can result in higher axial push forces than those reported in this study. In this study we used large handle diameters because it would have been difficult to wrap the pressure pad around a small-diameter cylinder. Future studies may evaluate the effect of handle diameter.

Maximum grip forces measured in this study were 17% and 43% lower than those reported by Edgren et al. (2004) for men and women, respectively. This may be because axial pushing on a horizontal handle at elbow height required wrist ulnar deviation, and ulnar deviation has been shown to reduce grip strength by approximately 30% (Lamoreaux & Hoffer, 1995; O'Driscoll et al., 1992). Also, the average grip strength of the female participants in this study was only in the 23rd percentile, based on normative data by Mathiowetz et al. (1985). Thus, the average female axial push force may be higher than reported herein.

The inward or outward torque levels required in this experiment (30%, 50%, and 80% of maximum torque) may have been higher than the torque that people can comfortably generate and match while pushing maximally at the same time. In fact, the torque level participants preferred to use (for the preferred method) was only 17% of their maximum inward torque. Thus, instructing participants to generate high inward or outward torque on top of maximum push force exertion may have resulted in decreased push force.

Participants freely chose a posture in this study, under one constraint: that the handle was located at elbow height. In reality, however, the handle may be located above the head or at ankle height, which may lead participants to adopt a different posture that makes it difficult to apply inward torque. It will be useful to examine the effects of different handle locations and constraints on body posture on torque, normal force, and thus axial push force.

The data reported here were collected from participants with little labor work experience. Thus the data may be useful for consideration in product design for the general population. In workplaces such as assembly plants, where workers have more experience, greater torques may be observed than reported here. Also, when a given task requires a small axial push force, then people may not necessarily apply inward torque. Future studies may investigate the effect of individual experience and required level of efforts on push methods.

CONCLUSIONS

1. Axial push forces can be limited by low handle friction: Axial push forces increased 12% for the high-friction rubber handle, compared with those for the low-friction aluminum handle. Comparison with previous studies suggests that the limiting factors for axial push force were wrist strength and the friction between the hand and handle. Literatures that report push force in the absence of friction constraints seem to significantly overestimate people's axial push capabilities. Use of a high-friction handle may improve the axial push force that can be produced on a handle by a worker of a given strength.

2. Inward torque should be assumed for highest axial push forces and will be obtained when participants are free to select their own push method. During pushing in a preferred way, participants chose to use inward torque of 1.1 Nm (17% of maximum inward torque). The self-chosen inward torque appeared to help increase grip force and normal force on the handle, and thus increase axial push force by 10%, without increasing FDP and FDS muscle activities. Work objects or consumer products should be designed so that workers or users can use inward torque during axial pushing.

3. Tasks that require deliberate twisting in either direction, but particularly in an outward direction while pushing, can result in decreased axial push force.

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