Effect of elliptic handle shape on grasping strategies, grip force distribution, and twisting ability

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A generic torque model for various handle shapes has been developed and evaluated using experimental data. Twelve subjects performed maximum isometric torques using circular and elliptic cylinders in medium and large sizes (circular: $r = 25.4$, 38.1 mm; elliptic: semi-major/minor axes = 30.9/19.3, 47.1/27.8 mm) finished with aluminium and rubber, in two opposite directions. Torque, grip force distribution, and finger position were recorded. Maximum torques were 25%, 7%, and 31% greater for the elliptic, large-size, and rubber-finished cylinders than for the circular, medium-size, and aluminium-finished cylinders, respectively. Greater torque for the elliptic cylinders was associated with 58% greater normal force that the subjects could generate for the elliptic than circular cylinders. The model suggests that greater torques for the large-size and rubber cylinders are related to long moment arms and greater frictional coupling at the hand–cylinder interface, respectively. Subjects positioned their hands differently depending on torque direction to maximise their normal force and torque generation.

Statement of Relevance: Desirable handle features for torque generation may be different from those for grip only. Design of handles per advantageous handle features (e.g., shape, size, and surface) may help increase people's torque strength and contribute to increased physical capacity of people.

Keywords: friction; torque direction; normal force distribution; moment arm

1. Introduction

Knowledge on how handle features affect the way people squeeze and twist a work object with their hand is essential to improve the design of handles and reduce acute and chronic hand injuries (Kong *et al.* 2007, Kuo *et al.* 2009). Previously, investigators have shown that maximum torque capacity is affected by the diameter of cylinder handles (Pheasant and O'Neill 1975, Adams and Peterson 1988, Imrhan and Loo 1988, Crawford *et al.* 2002), handle material (Nagashima and Konz 1986), handle surface texture (Pheasant and O'Neill 1975), handle surface area (Crawford *et al.* 2002), a person's grip strength (Imrhan and Loo 1988, Crawford *et al.* 2002), and the direction to which torque is applied (Seo *et al.* 2008b). In the present study, the effect of handle shape on a person's maximum torque capacity was examined.

A generic isometric torque model has been developed as an extension of the previous torque model (Seo *et al.* 2007) to account for different handle shapes (Figure 1). For circular cylinder handles, torque about the long axis of the handle is produced by friction force applied on the surface of the handle with a moment arm equal to the radius, while normal force is needed to support friction force generation so that the hand

does not slip on the handle during torque exertion (Pheasant and O'Neill 1975, Seo *et al.* 2007, 2008b). For cylindrical handles with non-circular cross sections, however, both friction force and normal force can directly contribute to torque generation. Figure 1 illustrates that contact force $(\vec{f}_{resultant})$ can be resolved into normal (f_n) and friction force (f_f) components, both of which contribute to torque generation as depicted in Equation (1).

$$T = \int_0^{2\pi} \vec{r} \times \vec{f}_{resultant}\, d\theta = \int_0^{2\pi} \{r(f_f \cos\alpha + f_n \sin\alpha)\}d\theta \tag{1}$$

where T is the torque about the centre of rotation, f_n is the normal force applied by the hand at a point on the handle surface, f_f is the friction force applied by the hand at that point, $\vec{r}$ is a vector (magnitude $= r$) from the centre of the handle cross section to normal force application point, θ is the angle about the handle centre, and α is the angle between $\vec{r}$ and f_n. Both r and α are the functions of the handle shape and θ (Figure 1).

Previously, we presented experimental results evaluating an earlier torque model for circular cylinders (Seo *et al.* 2007, 2008b). In the present article,
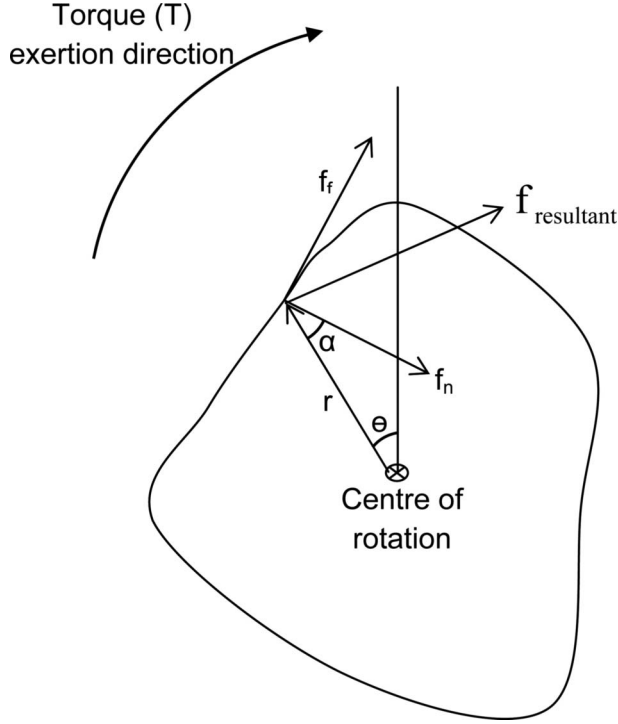
Figure 1. A cross-sectional area of a generic cylinder handle for torque (T) generation. A contact force ($\vec{f}_{resultant}$) can be resolved into a normal force (f_n) and friction force (f_f). Not only friction force but also normal force applied to the handle surface by the hand can contribute to torque generation about the centre of the handle. The extent of each force's contribution to torque is dependent on the moment arm ($r \cos \alpha$ for friction force, $r \sin \alpha$ for normal force; $0 \leq \theta \leq 2\pi$; see Equation (1)).

we present experimental results to evaluate this generic torque model for elliptic cylinders. The generic model (Equation (1)) can be simplified for elliptic cylinders as shown below, assuming people generate maximum allowable friction force at all points of the handle to maximise torque.

$$f_f = \mu f_n \qquad (2)$$

$$r = \frac{ab}{\sqrt{a^2 \sin^2 \theta + b^2 \cos^2 \theta}} \qquad (3)$$

$$\alpha = a \cos \left(\frac{br \cos^2 \theta \pm a \sin \theta \sqrt{a^2 - r^2 \cos^2 \theta}}{\sqrt{a^4 - (a^2 - b^2)r^2 \cos^2 \theta}} \right)$$
$$(+ \text{ for } \theta = 0 - 180°, - \text{ for } \theta = 180 - 360°) \qquad (4)$$

$$T = \int_0^{2\pi} \{rf_n(\mu \cos \alpha \pm \sin \alpha)\} d\theta$$
$$(+ \text{ for } \theta = 0 - 90°, 180 - 270°,$$
$$- \text{ for } \theta = 90 - 180°, 270 - 360°) \qquad (5)$$

where μ is the coefficient of friction between the hand and handle, and a and b are the lengths of the semi-major and semi-minor axes of the ellipse (cross-sectional area of the elliptic cylinder), respectively (Figure 2).

On the basis of this elliptic cylinder model (Equation (5)), effects of cylinder shapes, sizes, and friction on torque can be predicted by examining the ratio of maximum possible torque (output) to a given total normal force (input). The ratios for a few selected cylinder shape, size, and friction conditions are summarised in Table 1a, assuming uniform normal force distribution along the handle circumference. The ratios predict greater torque for large-size than medium-size handles, and greater torque for a high-friction than low-friction condition. Under the assumption of uniform normal force distribution, the ratios are smaller for the elliptic than circular cylinders, indicating that elliptic cylinders' elongated cross section does not necessarily provide increased overall moment arm. However, concentrating normal force close to the semi-major axis to utilise long moment arms in that handle region may help torque generation.

The aim of this study was to evaluate the model proposed in Equation (5) by testing the following hypotheses. First, a person's maximum torque is greater for circular, high-friction, and large-size cylinders than for elliptic, low-friction, and medium-size cylinders, respectively (on the basis of the prediction in Table 1a). Second, people concentrate their grip force close to the semi-major axis to maximise torque for elliptic cylinders.

2. Method

To test the proposed hypotheses, maximum torque and normal force applied to the handle during torque generation were compared for circular vs. elliptic, low- vs. high-friction, and medium- vs. large-size cylinders. To gauge how deviation from the uniform normal force distribution assumption is related to increased torque output per grip normal force, the ratios of torque to normal force experimentally observed were compared with those predicted by the model (Table 1a). Torque exertions in two directions were tested to examine how people applied normal force differently depending on the torque direction. The two torque directions tested were outward (clockwise direction when the right hand's power grip of a vertical cylinder is viewed from the top) and inward (counterclockwise, towards the direction the fingers point) directions. In addition, hand positions relative to the handle were recorded to examine how people positioned their hand differently depending on the handle size and torque direction.
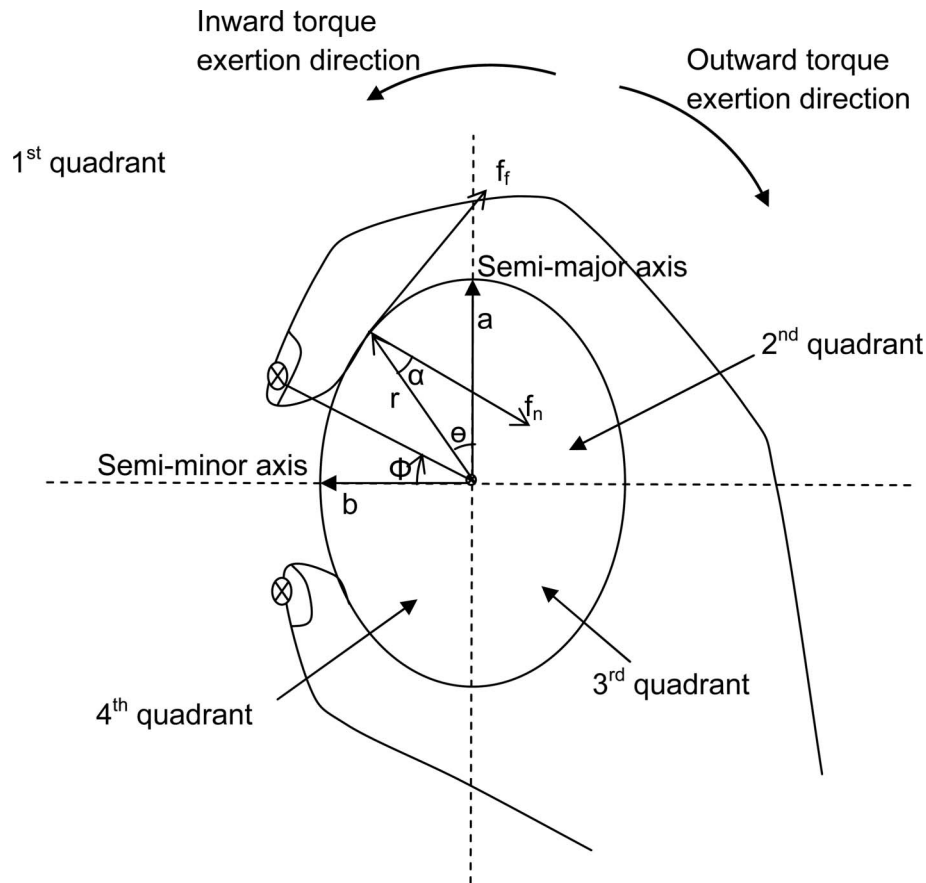
Figure 2. An elliptic cylinder handle grasped by the hand viewed from the top of the handle. Both normal force (f_n) and friction force (f_f which can be up to μf_n, where μ is the coefficient of friction between the hand and handle) contribute to torque generation, via moment arms ($r\cos\alpha$ for friction force, f_f; $r\sin\alpha$ for normal force, f_n). The elliptic cross-sectional area with a semi-major axis length of a and semi-minor axis length of b can be divided into four quadrants to examine force distribution along the handle circumference. Fingertips' angular locations from the semi-minor axis (φ) were found for the thumb tip and the middle fingertip, separately. The finger shown on the top represents the middle finger.

Table 1. The ratio of maximum torque (output) to a given total normal force (input) for different handle surfaces, sizes and shapes (mm) predicted by the model (a) and observed during the experiment (b).

			Estimated torque to total normal force ratio (mm)	
	Handle surface	Handle size	Circular cylinder handle	Elliptic cylinder handle
(a) Model prediction	Aluminium $\mu = 0.85$	Medium	21.6	19.4
		Large	32.4	28.3
	Rubber $\mu = 1.43$	Medium	36.3	32.7
		Large	54.5	47.6
(b) Empirical observation	Aluminium $\mu = 0.85$	Medium	17.6	12.9
		Large	26.9	23.9
	Rubber $\mu = 1.43$	Medium	27.9	19.1
		Large	39.2	34.5

Note: The model prediction was performed using Equation (5), assuming a uniform normal force distribution along the handle circumference (i.e. constant f_n = total normal force/2π in Figure 2) and the coefficient of friction of 0.85 between the aluminium and the hand skin and of 1.43 between the rubber and the hand skin (Seo *et al.* 2009) to examine the combined effects of friction, handle shape (circular vs. elliptic) and handle size (medium size with the circumference of 160 mm vs. large size with the circumference of 239 mm) on torque generation.

2.1. Procedure

Six healthy individuals (3 female and 3 male college students, 23–34 years of age) grasped a vertical cylinder with the right hand in power grip with the elbow flexed approximately at 90°. Subjects were instructed to apply maximum isometric torque

exertions about the long axis of a cylinder for 5 s, while (i) torque, (ii) normal force applied to the cylinder by the hand, and (iii) the hand position on the cylinder were recorded. Subjects decided for themselves where on the cylinder to position their fingers. Subjects did not have training/practice trials. Subjects did not receive feedback on their torque output. Subjects were naïve about the study hypotheses.

Torque was recorded using a six-axis load cell to which the cylinder was connected via universal joints. The universal joints minimise lateral force (Drury 1980) by subjects. Normal force was recorded using a 0.15-mm thick sheet of pressure sensors (Tekscan, Inc., South Boston, MA) that was placed on the cylinder surface and measured normal force on each 5.08×5.08 mm^2 sensor. The thumb and the middle finger's tip locations relative to elliptic cylinders during torque exertions were recorded using infrared emitting markers (OptoTrak Certus, NDI, Waterloo, ON).

A full factorial experiment with four independent variables of handle cross section (circular vs. elliptic), size (circumference $= 160$ mm vs. 239 mm), surface (aluminium vs. rubber), and torque direction (inward vs. outward, verbally instructed to subjects) was conducted. The circular cross sections had radii of 25.4 and 38.1 mm for the medium- and large-size, respectively. The elliptic cross sections' semi-major and minor axes were 30.9 and 19.3 mm, respectively, for the medium-size, and 47.1 and 27.8 mm, respectively, for the large-size. To change the cylinder surface, a thin smooth sheet of aluminium (0.2-mm thick) and rubber (2-mm thick) was placed on the top of the pressure sensors. The independent variables were presented to subjects in a random order. Each condition was tested twice. All data were collected at 30 Hz. A minimum of 2 min of break was given between consecutive exertions to minimise muscle fatigue (Caldwell *et al*. 1974). All participants gave written informed consent before the experiment.

2.2. Analysis

For each torque trial, torque, normal force, and finger position data were averaged over a 2-s window during which the mean isometric torque was the highest. As primary analysis, two analyses of variance (ANOVA) were performed to determine if handle shape, size, surface, torque direction, and their second-order interactions (shape × size, shape × surface, shape × direction, size × surface, size × direction, and sur-face × direction) significantly affected maximum tor-que and total normal force, separately. Total normal force was determined as the sum of all normal forces recorded on the pressure sensors covering the cylinder surface. A significance level of 0.05 was used.

As secondary analysis, normal force distribution across the four quadrants of elliptic cylinders (Figure 2) was examined. Specifically, another ANOVA was performed to determine if the sum of normal forces on each quadrant significantly varied for handle size, surface, torque direction, quadrant (first, second, third, and fourth), and their second-order interactions, only for elliptic cylinders. In addition, subjects' chosen hand position during torque exertion on the elliptic cylinders was examined. The middle fingertip and thumb tip locations were projected to a cross section of the elliptic cylinder and expressed as the angle from the semi-minor axis of the cross-sectional area about the ellipse centre (denoted by φ in Figure 2). Multivariate ANOVA was performed to determine if the thumb and middle finger' angular locations (φ) significantly varied for handle size, surface, torque direction, and their second-order interactions, only for elliptic cylinders. Lastly, the ratios of measured torque to measured normal force ratios were computed for each torque trial. The empirically observed torque to normal force ratios were compared with those predicted by the model.

3. Results

3.1. Maximum torque

Maximum torque significantly varied for handle shape, size, and surface (Figure 3). Mean maximum torque was, on average, 25% greater for the elliptic cylinders than for the circular cylinders ($p < 0.01$, Figure 3a), 7% greater for the large-size than for the medium-size cylinders ($p = 0.04$, Figure 3b), and 31% greater for the rubber- than for the aluminium-finished cylinders ($p < 0.01$, Figure 3c). Maximum torque did not significantly vary for torque direction and any second-order interactions ($p > 0.05$). An interaction between shape and size was seen ($p = 0.06$, Figure 3b).

3.2. Normal force

Total normal force subjects applied during torque exertion significantly varied for handle shape, size, surface (Figure 4), torque direction, and the interaction between shape and size ($p < 0.05$). Other second-order interactions were not found to be significant ($p > 0.05$). Mean total normal force was 58% greater for the elliptic than for circular cylinders ($p < 0.01$, Figure 4a), 54% greater for the medium-size than for the large-size cylinders ($p < 0.01$, Figure 4b), 11% greater for the inward than for the outward torque generation ($p < 0.01$), and 12% greater for the aluminium- than for the rubber-finished cylinders ($p < 0.01$, Figure 4c). Increase in total normal force for the elliptic cylinder compared with the circular cylinder
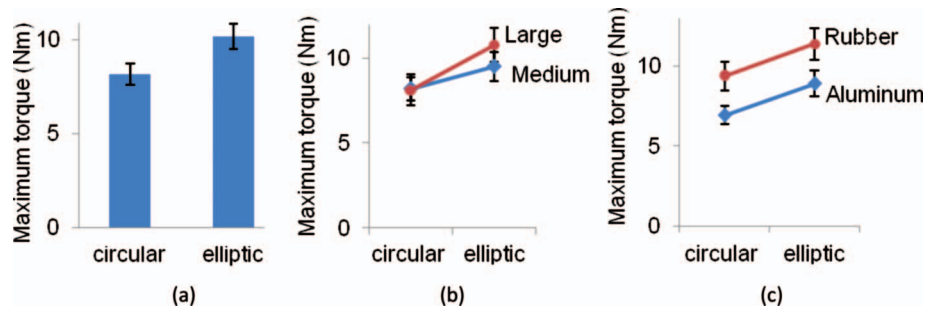
Figure 3.   Maximum torque a person could produce on a handle significantly varied for the handle shape (circular vs. elliptic cylinder handle, a), handle size (cross-sectional circumference of 160 mm vs. 239 mm or medium vs. large, b), and handle surface (aluminium finished vs. rubber finished, c). For each figure, all other conditions including subject and torque direction were pooled.
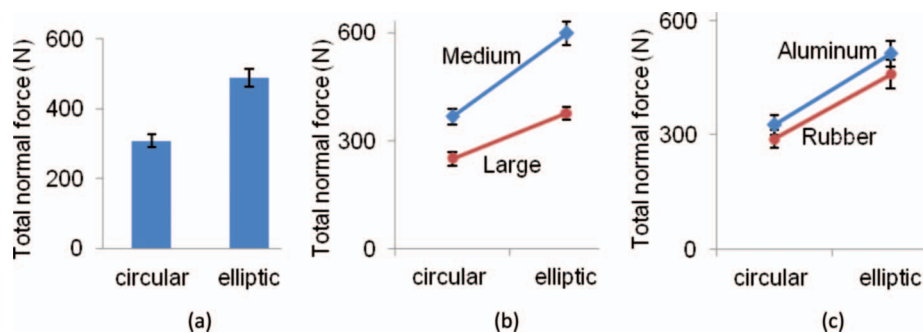

Figure 4.   Total normal force a person applied to a handle during torque exertion significantly varied for the handle shape (circular vs. elliptic cylinder handle, a), handle size (cross-sectional circumference of 160 mm vs. 239 mm or medium vs. large, b), and handle surface (aluminium finished vs. rubber finished, c). For each figure, all other conditions including subject and torque direction were pooled.

was greater for the medium-size (63%) than for the large-size cylinders (51%; $p < 0.01$, Figure 4b).

Normal force in each quadrant during torque exertions on elliptic cylinders significantly varied for handle size, surface, torque direction, quadrant, and interactions between handle size and quadrant and between torque direction and quadrant ($p < 0.05$; Figure 5). Other interactions were not found to be significant ($p > 0.05$). The third quadrant (where the palm and thenar eminence contact the cylinder) had high normal force concentration relative to other quadrants for the medium-size cylinder, but not for the large-size cylinder (Figures 5a and 6a and b). During inward torque generation, normal forces were concentrated on the second (by the phalanges) and fourth quadrants (by the thumb/thenar eminence; Figure 6a-top). For outward torque, normal forces were concentrated on the third quadrant by the thenar eminence (Figures 5b and 6a-bottom). Normal force for all quadrants was, on average, 12% greater for the aluminium- than for the rubber-finished elliptic cylinders (Figure 5c), as expected from the finding that the total normal force was 12% greater for the

aluminium- than for the rubber-finished cylinders (Figure 4c).

3.3.   Fingertip location

Mean fingertip angular location on elliptic cylinders (φ) was $-32°$ for the thumb tip and $43°$ for the middle fingertip. The subjects significantly varied the thumb tip and middle fingertip's locations on the handles (φ) depending on torque direction and handle size ($p < 0.05$; Figure 7), but not depending on other factors ($p > 0.05$). The middle fingertip was further away from the semi-minor axis and the thumb tip was closer to the semi-minor axis during inward torque generation, compared with the outward torque (Figure 7a). The middle finger and thumb tips became further away from the semi-minor axis when grasping a large-size cylinder, compared with a medium-size cylinder (Figure 7b).

3.4.   Ratio of torque to total normal force

To facilitate the comparison with the model prediction (Table 1a), the ratios of measured maximum torque to
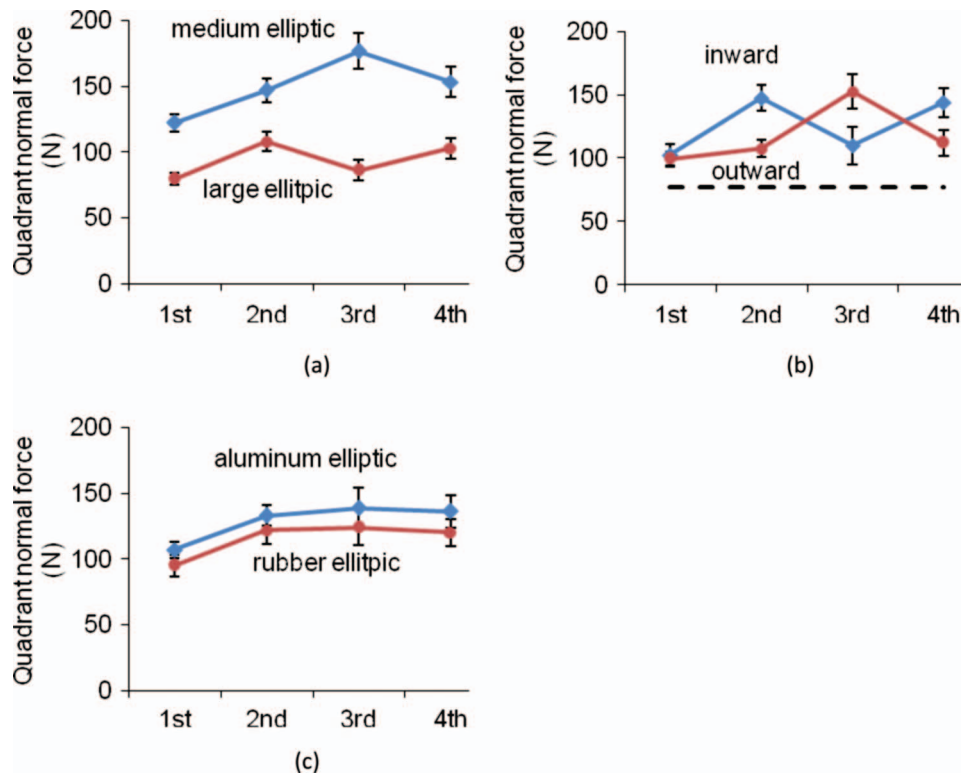
Figure 5. Normal force in a quadrant observed during torque exertion on elliptic cylinder handles significantly varied for the interaction between handle size and quadrant (a) and for the interaction between torque direction and quadrant (b). Normal force in each quadrant was, on average, 12% greater for the aluminium- than rubber-finished elliptic cylinders (c). The quadrant forces on elliptic cylinder handles were, in general, higher than the average quadrant force on circular cylinder handles (total normal force divided by 4) denoted by the segmented line in b. Only elliptic cylinder handle data are shown. For each figure, all other conditions not specified were pooled.

measured total normal force were computed and summarised in Table 1b. As for the handle shape effect, the ratio of measured torque to measured total normal force was, on average, 19% less for the elliptic than the circular cylinders (Table 1b). As for the size effect, the empirically observed ratio of torque to total normal force was, on average, 61% greater for the large-size than for medium-size cylinders. As for the surface effect, the empirically observed ratio was, on average, 48% greater for the rubber-finished than the aluminium-finished cylinders. These trends for the shape, size, and surface were similar with the model predictions. The empirically observed ratios were, on average, 26% lower than the predicted ratios.

4. Discussion

The present study demonstrated that handle features and intended direction of motion significantly affected the way subjects gripped and generated torque. Specifically, maximum torque was greater for the elliptic, large-size, and rubber-finished cylinders than for the circular, medium-size, and aluminium-finished

cylinders, respectively (Figure 3). Greater torque for the elliptic cylinders was associated with greater total normal force that the subjects could generate for the elliptic than the circular cylinders. Greater torque for the large-size cylinders appears due to greater moment arms provided for the large- than the medium-size cylinders. Greater torque for the rubber-finished cylinders appears due to greater coefficient of friction available for the rubber- than the aluminium-finished cylinders. Subjects concentrated the hand normal force close to the semi-major axis during torque generation on the elliptic cylinders (Figure 6). Biomechanical descriptions and ergonomic implications for each handle feature are discussed below.

4.1. Handle shape

Mean maximum torque was 25% greater for the elliptic than the circular cylinders (Figure 3a). Greater maximum torque for the elliptic than the circular cylinders was associated with 58% greater total normal force that subjects could apply for the elliptic than the circular cylinders (Figure 4a), rather than with
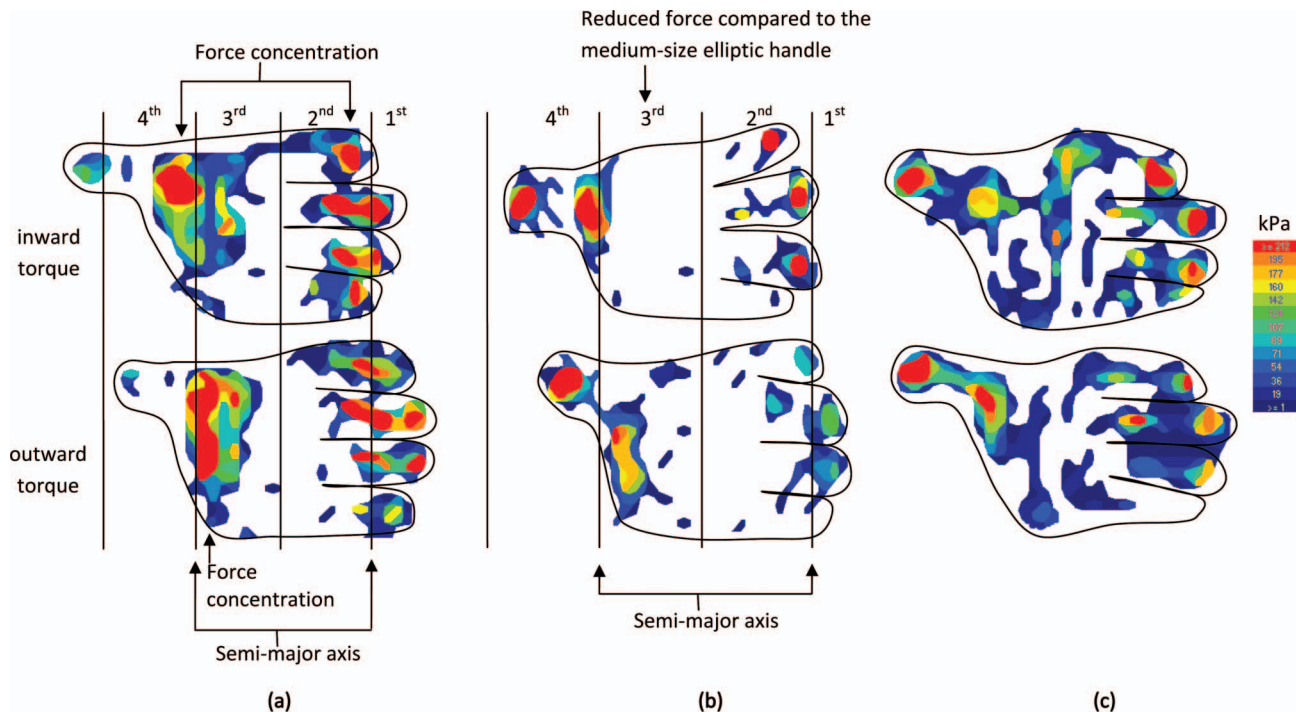
Figure 6. Sample force distribution on the hand across four quadrants (first–fourth) for one subject during the inward (top) and outward (bottom) torque direction for the medium-size elliptic cylinder handle (a), the large-size elliptic cylinder handle (b) and the medium-size circular cylinder handle (c). Outlines of the hands are estimated to illustrate the locations of forces on the hand. Rubber surface only.

the changes in the torque to normal force ratio (Table 1b). It was anticipated that subjects would concentrate the hand force close to the semi-major axis to utilise the long moment arms around the semi-major axis, increase the torque output per given total normal force, and maximise torque for elliptic cylinders. Subjects adjusted their hand position and concentrated the force close to the semi-major axis (Figure 6). However, empirically observed ratios of torque to normal force were not greater for the elliptic than the circular cylinders (Table 1b).

The way that subjects could apply 58% greater normal force across quadrants (Figure 5b) for the elliptic than for the circular cylinders is postulated as follows. First, the hand grip postures for the elliptic cylinders could have allowed the biomechanical parameters such as the long finger flexor muscle length and moment arms to be closer to optimum for grip force production, compared with those for the circular cylinders (Amis 1987, O'Driscoll *et al*. 1992, Kamper *et al*. 2006). Varying finger postures could result in 60% changes in maximum joint moments (Kamper *et al*. 2006). Second, the subjects could have generated greater total normal force for the elliptic than the circular cylinders, by wedging the elliptic cylinders between the finger joints and the palm to secure the handle position in the space, and by counterbalancing large forces from the distal and middle phalanges with the reaction force on the thumb/thenar eminence on the opposite quadrant (Figure 6a). For circular cylinders, forces that people could generate using the fingers were limited by the availability of sufficient reaction force by the palm (Seo *et al*. 2007, Enders and Seo 2011).

Another reason for greater total normal force observed for the elliptic than for the circular cylinders could be that elliptic cylinders allow not only friction force but also normal force to directly contribute to torque generation (Equation (1)), encouraging normal force generation. In contrast, torque about the circular cylinders is produced by the friction forces, while normal force prevents hand slippage on the handle during torque generation. Performing two tasks simultaneously (gripping to generate normal force and twisting to generate torque) may reduce a person's force capacity as evidenced by the reduction in maximum push force when torque generation is simultaneously required (Seo *et al*. 2008a), reduction in digit strength when multiple fingers are working simultaneously (Ohtsuki 1981b), and reduction in hand grip strength when the contralateral hand is simultaneously gripping (Ohtsuki 1981a).

4.2. Handle size

Large-size handles resulted in 13% greater mean maximum torque compared with the medium-size handles for the elliptic cylinders (Figure 3b), likely due to the increased overall moment arms as computed by the model (Table 1a). With 53% increase in *a* and 44% increase in *b*, the model computes, on average, 48% increase in *r* (Equation (3)) and 11% increase in α (Equation (4)). These increases in *r* and α lead to 48% and 1% increase in torque, respectively (Equation (5)). Overall, the model predicts 48% increase in maximum torque for the large- than the medium-size handles, assuming a constant normal force for both handle sizes. Experimentally observed maximum torque increased only 13% for the large- than the medium-size handles (as opposed to 48% increase in the model prediction), probably because increase in the moment arm (48%) was cancelled out by the decrease in total normal force (35%).

Mean total normal force was 35% less for the large-size handles than for the medium-size handles for both shapes (Figure 4b). Decreased total normal force with increased handle size is probably due to the changes in the finger posture leading to (i) lengthened long finger flexor muscle (exceeding the optimal length) reducing muscle force output (accounting for less than 9% changes in grip force output; Amis 1987, O'Driscoll *et al.* 1992, Kamper *et al.* 2006), (ii) reduced muscle moment arm (Peebles and Norris 2003, Greig and Wells 2004, Kong *et al.* 2004, Kamper *et al.* 2006, Lee *et al.* 2008), and (iii) difficulty in strategically placing the fingertips and thenar eminence for max-imising the reaction force (Seo *et al.* 2007). For example, with the large separation between the thumb and middle finger tips for the large-size cylinders (Figure 7b), the four fingers were barely on the first quadrant (Figure 6b-bottom), reducing the reaction force on the thenar eminence on the third quadrant (Figure 5a). Despite this reduction in total normal force, the advantage in the moment arm (as predicted in Table 1a) resulted in greater maximum torque for the large-size than for the medium-size handles. On a similar note, the handle whose size allows maximum grip force such as 38-mm-diameter circular cylindrical handles (Ayoub and Presti 1971, Grant *et al.* 1992, Hall 1997, Edgren *et al.* 2004) may not provide maximum torque due to the limited moment arm.

4.3. Handle surface and torque direction

The rubber-finished handles resulted in, on average, 31% greater maximum torque compared with the aluminium-finished handles for both shapes (Figure 3c, 35% and 28% increases for the circular and elliptic
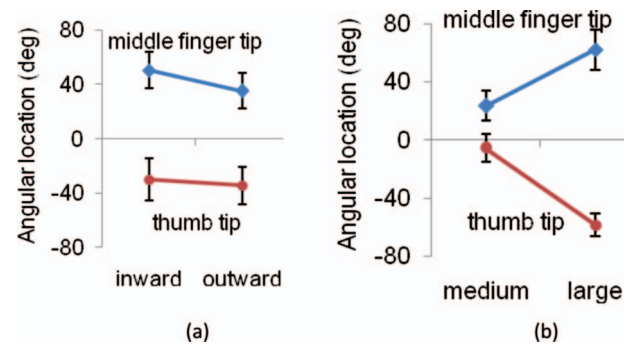

Figure 7. Angular locations of the thumb tip and the middle finger tip on elliptic cylinder handles (φ in Figure 2) significantly varied for torque direction (a) and handle size (b). Only elliptic cylinder handle data are shown. For each figure, all other conditions not specified were pooled.

cylinders, respectively), likely due to the increase in the coefficient of friction for the rubber surface. Mean total normal force was 11% less for the rubber handles than for the aluminium handles (Figure 4c), probably due to slightly greater handle size and subsequent reduction in grip strength from the 2-mm-thick rubber sheet compared with 0.2-mm thick aluminium sheet (Seo *et al.* 2008a). Despite reduced total normal force, increased coefficient of friction and hand-handle frictional coupling resulted in greater maximum torque for the rubber than for the aluminium handles, as anticipated in Equation (5). This finding is consistent with the previous studies that demonstrated that increased coefficient of friction between the hand and handle can increase hand strength that utilises friction force such as push/pull along the long axis of handles or holding onto a handle until the hand slips (Kong *et al.* 2007, Seo *et al.* 2008a,b, 2010, Seo 2009, Young *et al.* 2009).

Torque direction did not significantly affect the subjects' maximum torque. However, torque direction affected how the subjects gripped the handle and distributed the hand force. Specifically, during inward torque generation, subjects shifted the hand position relative to the handle clockwise when viewed from the top (Figure 7a) so that the thenar eminence could contact the fourth quadrant near the semi-major axis and the four fingers' major forces could be applied to the second quadrant near the semi-major axis (Figure 6a-top). During outward torque generation, subjects shifted the hand position counterclockwise so that the thenar eminence could contact the third quadrant and the four fingers' major forces could be applied to the first quadrant (Figure 6a-bottom). Any obstructions to placement of the hand and distribution of hand force accordingly may lead to reduced torque strength for workers.

4.4. Comparison to model prediction

The effects of handle shape, size, and surface on the ratio of maximum torque (output) to total normal force (input) empirically observed (Table 1b) were compared favourably with the model predictions (Table 1a). Both the empirical data and models suggest that torque output per given normal force is greater for the circular, large-size, and rubber-finished cylinders than for the elliptic, medium-size, and aluminium-finished cylinders. Our anticipation that non-uniform normal force distribution might lead to greater torque to normal force ratios for the elliptic than the circular cylinders was not supported by the experimental results. Rather, the observed 25% increase in torque for the elliptic cylinders appears to be related to 58% increase in total normal force that the subjects could generate on the elliptic than the circular cylinders. The empirically observed torque to normal force ratios were, on average, 26% lower than the predicted ratios. The consistently lower ratios for empirical observations than the model predictions may be because the predicted ratios are for maximal possible torque per given normal force, assuming that people apply maximum possible friction forces (up to slippage) at all points of the contact, which is unlikely in reality.

The model can predict only the ratio of maximum possible torque to uniform normal force. The model, however, does not predict how much grip force people can apply for different handle shapes and sizes. For instance, the total normal force varied, on average, 58% between the two handle shapes and 54% between the two handle sizes in the present study (Figure 4a and b). Such large variations in the total normal force significantly affected the subjects' maximum torque. Without the knowledge of grip force that people can apply for varying grip conditions, the model is currently limited in its ability to predict maximum torque. Further studies that aim to predict grip force capability for varying handle shapes and corresponding hand postures (Kong *et al.* 2007, Domalain *et al.* 2008, Seo and Armstrong 2008, Lee *et al.* 2009) would help improve the torque prediction capacity.

4.5. Future studies

Future studies may look into designing handles with irregular cross sections that achieve the best balance between maximising grip force and maximising torque. For example, asymmetric handles may be investigated to identify their significant advantages for climbing, body support, tools, and package opening (Rowson and Yoxall 2011), which may have a high impact on handle design to maximise efficiency in force/torque application in daily living. A further systematic investigation of various semi-major vs. semi-minor axis length ratios of elliptic shapes and associated hand postures could improve our understanding of the handle shape effects on grip force and torque exertions. In addition to maximising torque capabilities, user discomfort associated with high force concentration with varying handle shapes needs to be considered in determining the optimum handle shapes, especially for the tasks that require prolonged or repetitive exertions. Consideration of the effect of handle shape on people's grasping strategy, movement speed, and speed of force application to handles could also assist improving safety of products or tools for particular tasks (Chang *et al.* 2008, Kuo *et al.* 2009, Carse *et al.* 2011, Rowson and Yoxall 2011).

The present study investigated torque exertion on an unconstrained vertical handle in an unconstrained manner only. Other gripping situations such as fixed handles (Seo and Armstrong 2009), horizontally or obliquely oriented handles (Kong *et al.* 2007, Okunribido and Haslegrave 2008), and presence of obstruction in the way of gripping (Grieshaber *et al.* 2009) may be further examined to evaluate the model. In the present study, only normal force distribution was examined. Since friction force is limited by the product of the coefficient of friction and normal force, normal force distribution provides insight into possible friction force distribution. Upon availability of technology for a thin sensor measuring friction force, friction force distribution information may provide a complete picture of how people apply torque.

5. Conclusions

The present study demonstrated that people adjusted their hand position on elliptic cylinders depending on the direction of torque application and increased hand normal force by 58% and maximum torque by 25% for the elliptic cylinders compared with the circular cylinders. Increased maximum torque with the elliptic cylinders could be achieved by allowing people to position their hands as they think optimally. In addition, the present study demonstrated that longer moment arms for the large-size than for the medium-size handles resulted in an increased maximum torque, although total normal force was greater for the medium-size than for the large-size handles. This finding illustrates that a handle size that allows for maximum torque is different from that for maximum grip force. Greater frictional coupling at the hand–handle interface resulted in greater maximum torque for the rubber-finished than for the aluminium-finished handles. Handle shape, size, and surface can be modified to help increase a person's torque capacity. Such handle redesign has the potential to contribute to ease of performing activities, efficient

torque generation in daily living, and reduced risk of musculoskeletal injuries.

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