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4 AUTHORS:


Poh Kiat Ng
Multimedia University, Malacca, Malaysia


Adi Saptari
Technical University of Malaysia Malacca


Kian Siong Jee
Multimedia University

Tan Yue Hang
Multimedia University

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The Effects of Size on Pinch Force in Loaded and Unloaded Conditions

[1]Poh Kiat Ng, [2]Adi Saptari, [2]Kian Siong Jee, [1]Yue Hang Tan

[1]*Faculty of Engineering and Technology, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, 75450 Malacca Malaysia*
[2]*Department of Manufacturing Management, Faculty of Manufacturing Engineering, Technical University of Malaysia Malacca, Hang Tuah Jaya, 76100 Durian Tunggal, Malacca, Malaysia*

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ABSTRACT

Background: High-force pinch exertions in manual work frequently cause hand- or finger-related injuries and musculoskeletal disorders, predominantly if they involve manual precision work such as manipulating small machine knobs or dials. In meticulous work that engages pinch grips, object size can perhaps have a considerable effect on pinch force. **Objective:** The aim of this study is to determine the effects of size on pinch force, with an emphasis on small apparatus such as knobs that are operated in loaded and unloaded conditions. **Results:** This study concludes that pinch force is significantly affected by size under a loaded condition. For an unloaded condition, size does not significantly affect pinch force since there is no loading effect from the structure which causes the forces to be similar across different sizes. The average pinch force exerted on the large size knobs is the lowest compared to the other sizes since the fingers extend further and cause the contact area between the finger pads and the object surface to be lesser. This eventually lowers the applied normal force. **Conclusion:** This study contributes to the knowledge of the effects of object size on pinch force. It can potentially be used as a reference in the enhancement of both safety and design so as to allow hand-related manual work to be less strenuous and more accommodating to the users' fingers.

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INTRODUCTION

Despite the industrial advancements in many manufacturing firms, hands and fingers are still primary tools for high precision manufacturing work and are often used to pinch, grip and manipulate objects such as fasteners, clips and electronic components. However, high-force pinch force exertions can cause fatigue, discomfort and injury to the hand in industrial populations (Shivers *et al*., 2002).

Besides that, the sizes of various tools and objects can also play a role in the productivity of industrial workers and the development of musculoskeletal disorders such as carpal tunnel syndrome, tendinitis and ganglionitics (Aldien *et al*., 2005; Kong *et al*., 2004). In association to this, researchers posit that grip force reduces as the object size increases (Edgren *et al*., 2004; Seo and Armstrong, 2008). Researchers also believe that this is due to the lack of skin deformation on the palmar side of the hand that causes a reduction in the grip's contact area, which leads to a reduction in grip force (Seo and Armstrong, 2008).

The aforesaid literature presents the comprehensiveness of the researches that have been carried out on grip force and how size affects grip force. However, there are still limited studies carried out on the effects of size on pinch force. Hence, this study aims to determine the effects of size on pinch force, with an emphasis on small apparatus such as knobs that are operated using pinch grips.

Size:

According to Mannerfelt (1966), size can refer to how large or small an object is. A size of an object can also be defined as the relative extent of the object or the object's overall dimensions or physical magnitude (Ng and Saptari, 2014). In relation to this, the size of an object can also be a basic ergonomics criterion in various designs. In designing and manufacturing, understanding the biodynamic response of a grip based on the size of an object is of critical importance for safety and musculoskeletal health reasons (Aldien *et al*., 2005).

A size of an object can affect the contact area where it is gripped. According to some researchers, the contact area decreases as the gripped object's size increases (Edgren *et al*., 2004; Grant *et al*., 1992; Seo

Corresponding Author: Poh Kiat Ng, Faculty of Engineering and Technology, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, 75450 Malacca Malaysia.
Tel: +606-2523044 E-mail: pkng@mmu.edu.my

and Armstrong, 2008). This phenomenon may have been due to the lack of skin deformation on the palmar side of the hand which results in a reduced contact area of the grip (Bobjer *et al*., 1993; Seo and Armstrong, 2008; Welcome *et al*., 2004). Furthermore, during gripping, forces are concentrated on the fingertips, which can cause the middle and proximal phalanges to lift off as the distal interphalangeal joint rotates, thus reducing the total contact area (Amis, 1987; Gurram *et al*., 1993; Gurram *et al*., 1995; Kong *et al*., 2004; Kong and Lowe, 2005a; Kong and Lowe, 2005b; Kong *et al*., 2007; Lee and Rim, 1991; Pylatiuk *et al*., 2006; Radhakrishnan and Nagaravindra, 1993; Seo *et al*., 2007).

According to Gill *et al*. (1985), some of the biomechanical factors that can affect pinch force include pinch techniques, pinch width (known as the distance of a thumb from the other fingers), wrist angles, finger joint angles and contact area between the finger and the object. Gill *et al*. (1985) suggested that the size of most objects is designed to vary depending on gender.

Most studies postulated that the adult male handgrip size is around 50-60 mm while the adult female handgrip size is around 45-55 mm (Bechtol, 1954; Cotten and Bonnell, 1969; Cotten and Johnson, 1970; Dvir, 1997; Hertzberg, 1955; Montoye and Faulkner, 1965; Petrosky *et al*., 1980). The maximum grip span however may be defined differently since different individuals have different hand sizes. Based on the hand size of various individuals, it is posited that a tool grip span should be designed in a position which maximises one's handgrip force (Gill *et al*., 1985).

The type of pinch technique may also vary depending on the size of the object. Studies show that when the pinch width of a pinch grip on a typical pinch gauge is about 16-18 mm, and when the maximum contact area between the finger and object is about 20×14 mm, the finger joints tend to bent naturally (Gill *et al*., 1985). A spherical object with a large diameter for example, can be held using a pinch grip, but may require a larger extension of fingers (Napier, 1956). Figure 1 shows the capacity of fingers to grip various diameters based on a pinch grip.

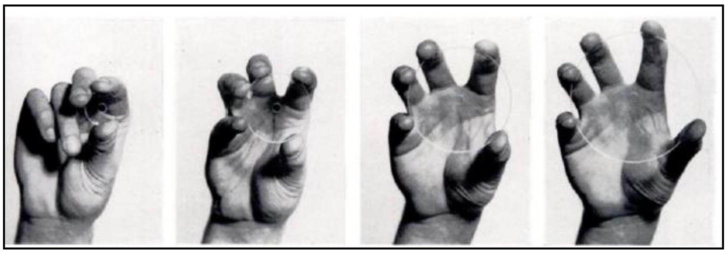


Fig. 1: The Capacity of Fingers to Grip Various Diameters (Napier, 1956).

According to Imrhan and Rahman (1995), the pinch width range of the lateral, chuck and pulp-2 pinches are about 20-140 mm. Their investigation also shows that the chuck pinch is stronger as compared to the lateral and pulp-2 pinch, while the lateral pinch is stronger than the pulp-2 pinch when the pinch width is 20 to 56 mm. However, the lateral pinch becomes weaker with a pinch width of 68 to 92 mm.

Some people find it difficult to execute a lateral pinch at 68 mm of pinch width because of the abduction of the metacarpal-phalangeal joint of the thumb and excessive stretching on its tendons (Imrhan and Rahman, 1995). Most people fail to perform this pinch when the pinch width is more than 92 mm (Imrhan and Rahman, 1995). Imrhan and Rahman (1995) also mentioned that when the pinch width is 20 mm, the pinch force of the lateral pinch is 1.2 times stronger than pulp-2 pinch, while the chuck pinch is 1.2 times stronger than the lateral pinch.

As the gripping/pinching diameter of the gripped/pinched object changes, the hand torque also changes (Gill *et al*., 1985). According to Pheasant and O'Neill (1975), when the gripped object has a very large diameter, the hand torque exertion on a cylindrical shaped object will decrease due to a loss in grip force. People may find it hard to twist or turn a very small or very large object (small or large diameter object) due to a loss in biomechanical leverage in the grip/pinch (Smith and Benge, 1985).

Besides that, it was also found that grip force reduces as the size of a gripped object increases (Edgren *et al*., 2004; Grant *et al*., 1992; Seo and Armstrong, 2008). This may be because when a gripped object's size is larger, the fingers open more and the moment arms for the finger flexor muscles decrease, thus causing a reduction in grip forces (An *et al*., 1979; An *et al*., 1983; Fowler *et al*., 2001; Seo and Armstrong, 2008).

As the size of an object decreases, the contact area where it is gripped will also reduce further (Pheasant and O'Neill, 1975; Welcome *et al*., 2004; Yakou *et al*., 1997). This decrease may be due to the reduced available handle surface area (Pheasant and O'Neill, 1975; Rohles *et al*., 1983; Seo and Armstrong, 2008; Yakou *et al*., 1997). Moreover, when gripping a smaller object, the finger flexion creates folds in the skin and results in a reduced contact with the object (Seo and Armstrong, 2008).

The size of an object may affect the maximum acceptable weight of a load, the maximum acceptable weights of the lifts, the total expenditure of the energy and the maximum stresses on the spine (Ayoub and Mital, 1989; Ciriello, 2003; Ciriello, 2007; Jung and Jung, 2010). In the manufacturing industry, the size of tool handles often has a substantial effect on the biomechanical, physiological and perceived physical stress of the workers (Jung and Jung, 2010).

The gripping and handling of a tool handle presents a very irregular distribution of forces at the hand surface which varies significantly with different object sizes (Gurram *et al*., 1995). Gripping a large object may encourage individuals to apply a grip force over the entire hand surface in contact with the object including the fingertips, which results in relatively higher pressure in the lateral side of the palm even when a push force is absent (Aldien *et al*., 2005). In summary, the size of the object can affect the variations in grip force and is hypothesised to potentially affect the variations in pinch force as well.

To classify the sizes of the knobs more specifically, a benchmarking review was done on 7 manufacturing firms in Malaysia (Bonsheng, 2012; Chestten, 2012; Linp-Omter, 2012; Supply, 2012; WDS Component, 2012; Winco, 2011; Winco, 2012a; Winco, 2012b; Winco, 2012c; Winco, 2012d; Yo-Jia, 2012). Based on the benchmarking exercise, the large, small and medium size classifications of knobs in this study can be represented in Table 1.

Table 1: The Classification of Knob Sizes.

Knob Shape	Small Size (mm)	Large Size (mm)	Medium Size (mm)
Spherical	10 ~ 15	60 ~ 65	35 ~ 40
Cylindrical	10 ~ 15	55 ~ 60	25 ~ 30
Taper	20 ~ 25	45 ~ 50	35 ~ 40
Square	30 ~35	40 ~ 45	35 ~ 40
4-lobes	20 ~ 25	75 ~ 80	45 ~ 50
5-lobes	30 ~ 35	60 ~ 65	45 ~ 50
6-lobes	25 ~ 30	70 ~ 75	40 ~ 45
7-lobes	25 ~ 30	75 ~ 80	45 ~ 50
8-lobes	30 ~ 35	75 ~ 80	50 ~ 55
9 or more lobes	25 ~ 30	70 ~ 75	45 ~ 50

One of the ways to classify an object's size is by measuring its diameter. In this study, large, medium and small sizes of knobs are used and classified based on the knob's diameter. Based on the commonly used knob shapes benchmarked in the previous section, this study chose to emphasise on cylindrical, spherical and 5-lobes shaped knobs. The large size for a 5-lobes knob and cylindrical knob ranges from 60 mm to 65 mm (based on the benchmarked diameters). The large size for a spherical knob ranges from 55 mm to 60 mm in diameter.

For medium sized knobs, the benchmarking findings show that medium knobs are defined between the sizes of 25 mm to 50 mm in diameter. In the case of the 3 common knobs identified for this study, medium size cylindrical knobs range from 25 mm to 30 mm in diameter, while medium size spherical knobs range from 35 mm to 40 mm in diameter. Medium size 5-lobes knobs range from 45 mm to 50 mm in diameter.

Benchmarking findings also point out that a small size cylindrical and spherical knob both range from 10 mm to 15 mm in diameter. A small size 5-lobes knob on the other hand ranges from 30 mm to 35 mm in diameter. The aforementioned benchmarking findings justify the limits of the sizes used to fabricate the knobs for this experiment. On the whole, these desktop benchmarking results serve as preliminary guidelines to justify the selection of certain knob sizes for this study.

Screw knobs:

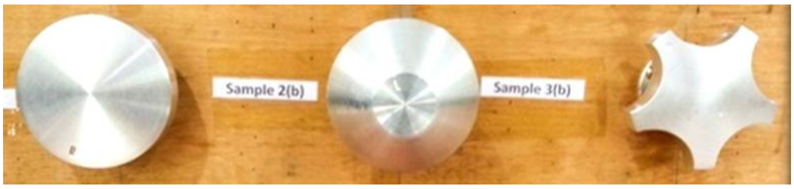
One of the most common knobs used in most industries and daily living activities are screw knobs (Monroe, 2013). Most screw knobs are engineered and manufactured with reference to standardise requirements. Screw knobs are used in all sorts of common and industrial product designs, such as machines, hand tools, doors, furniture and electronic apparatus (Monroe, 2013).

Since screw knobs are widely used, there should be various types of shapes and sizes of knobs produced by a range of suppliers to accommodate different functions. Some examples of different knob shapes available are spherical, cylindrical, lobe, square, taper and wing/T-shaped knobs (Chestten, 2012; Supply, 2012).

The different shapes and sizes of screw knobs resemble those of other commonly used objects such as pipe valves, small screwdrivers, door knobs, plastic bottle caps and control switches. Hence, screw knobs are selected to be used as the apparatus of this study in order to represent other types of commonly used objects in daily living and the industry.

Screw knobs:

Screw knobs were used as the apparatus for this study since they involve pinch-related activities and can be used generally on almost any machine, hand tool, device or furniture (Monroe, 2013). The shapes of the knobs were chosen based on the commonness of their design in various tools, apparatus and machines. The shapes include cylindrical, spherical and 5-lobes shapes. The benchmarking results also suggested three sizes for all the screw knobs, which included the large sizes (see Figure 2), the medium sizes (see Figure 3.5) and the small sizes (see Figure 3.6).



(a)

(b)

(c)

Fig. 2: Large, Medium and Small Screw Knobs.

Methodology:

In order to accurately measure the pinch force exerted on the screw knobs under a combination of factors, 3 Flexiforce sensors (from Tekscan Inc) were used for this experiment. The sensors can be used to measure both static and dynamic forces (up to 1000 lb or 4446.22 N), and are thin enough to enable non-intrusive measurements.

The participation in the experiment is based on voluntary basis, where each participant is required to sign their consent to participate in the experiment before the experimentation can begin. Seo (2008) used a number of 12 participants in her study, which is a sufficient for the experiment to conduct accurate inferential statistical analyses. However, this study proposes to involve approximately 32 participants in order to further improve the accuracy of the experiment results.

The protocol requires the participants to assume a seated posture. After taking a seat, the participants are asked to wear a customised glove that exposed their thumb, fore finger and middle finger of the participants. This customised glove is used to allow the sensors to be firmly intact with the fingers and stagnant on the palm at all times. A wrist strap is used to fasten on the participant’s wrist to ensure that the sensor positions were well maintained. Figure 3 shows the complete setup of the sensors.

Fig. 3: Complete Setup of the Sensors.

Each participant is required to pinch every knob with the 3 commonly used pinch techniques, as identified by Smith and Benge (1985). The knobs are to be twisted using both clockwise and counterclockwise torque directions. Figure 4(a) presents an example of how a three-jaw chuck pinch technique is applied, while Figure 4(b) shows how a pulp-2 pinch technique is applied. Figure 4(c) shows an example of how a lateral pinch technique is applied. Specific details on how the pinch force data are being measured and recorded are explained in the next section.

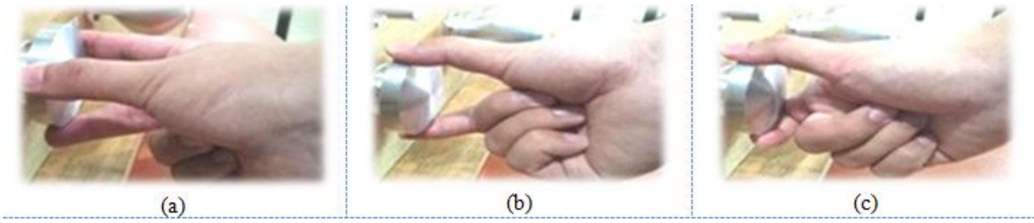


Fig. 4: The 3 Commonly Used Pinch Techniques (Smith and Benge, 1985).

There are two different conditions prepared for the application of different object sizes in pinch activity, namely a loaded and unloaded condition. For the unloaded condition, a simple wooden structure is used to attach all the screw knobs (See Figure 5). The screw knobs are fitted into all the holes prepared based on the diameter of the screw knobs. This wooden structure fulfils the unloaded condition because it does give any resistance whatsoever when the knobs are being pinched and turned in the structure.

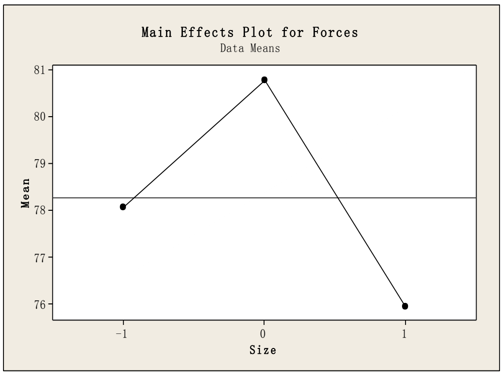
Fig. 5: Unloaded Wooden Structure.

Fig. 6: Loaded Wooden Structure with Knob Adapter and Indicators.

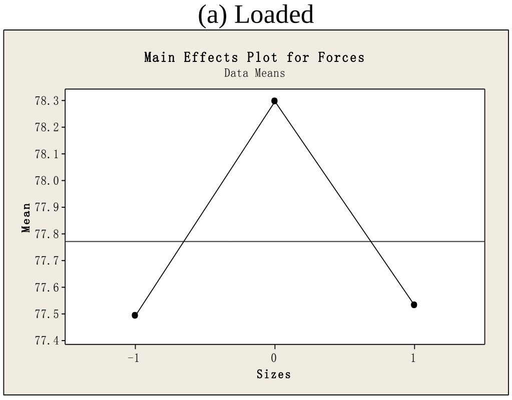
For the loaded condition, actual door knob mechanisms are embedded into a wooden structure (See Figure 6). The frontend of the door knobs are modified to an adapter that allows the screw knobs to be attached. This basically allows the screw knobs to be twisted with a loading effect. Thus, the loading effect for the screw knob is simulated by borrowing the principle of a normal door knob mechanism. When the screw knobs are fitted into the holes of the adapter and turned, the door knobs behind the adapter create a counter force that simulates this loading effect. For this study, the analysis of variance (ANOVA) is used to determine the significance of the effects of size on pinch force. Minitab version 16 is used for the ANOVA.

RESULTS AND DISCUSSIONS

Figure 7(a) and Figure 7(b) present the factorial plots for the effect of object size on pinch force for the loaded and unloaded structure. The loaded one in Figure 7(a) suggests that the mean pinch force exerted on the medium size screw knob (0) is 80.7981g (highest), which is 3.37% higher than the force exerted on the small size screw knob (-1) (78.0714g) (intermediate) and 6.00% higher than the force exerted on the large size screw knob (1) (75.9443g) (lowest).



(a) Loaded



(b) Unloaded

Fig. 7: Factorial Plot of Object Size (Note: -1 refers to small, 0 refers to medium, 1 refers to large).

Some researchers suggest that the rate of increase in normal force varies according to the object's weight (Johansson and Westling, 1984). Researchers also posit that normal force scales with object weight in order to economise effort (Johansson and Westling, 1988). This phenomenon can be explained through Newton's second law of motion. Newton's second law states that when a force acts on an object, it will cause the object to accelerate. The larger the mass of the object, the greater the force required to cause it to accelerate.

Based on the aforementioned understanding, it is reasonable to note that as the size of the knob increases, its mass also increases, causing the pinch force required to turn the knob to increase. This phenomenon is seen in the increase of pinch forces from the small knob to medium knob.

However, when it came to the large knob, instead of increasing to its maximum level, the pinch force decreased to the lowest value. This finding is consistent with studies by researchers who found that the average pinch force increases from the pinch span of 1 to 5 cm (small to medium size), peaks at 5 cm (medium size) and declines at 7cm (large size) onwards (Dempsey and Ayoub, 1996; Fathallah *et al*., 1991). This decrease could be due to the reduction in contact area. Researchers have also suggested that object size directly affects force due to the contact area of the gripped object (Ng and Saptari, 2014; Seo, 2008; Seo *et al*., 2007; Seo *et al*., 2008). This phenomenon is further explained in Figure 8.

Figure 8 illustrates how the fingertip force can be affected based on the contact area across different sizes of objects. According to Seo and Armstrong (2008), the increase in object size causes the middle and proximal phalanges to lift off while pinching. A lift off from these two phalanges would weaken the pinch force as the contact area right up to the fingertip also decreases. Hence, this explains why the medium knob generated the highest pinch force instead of the large knob.

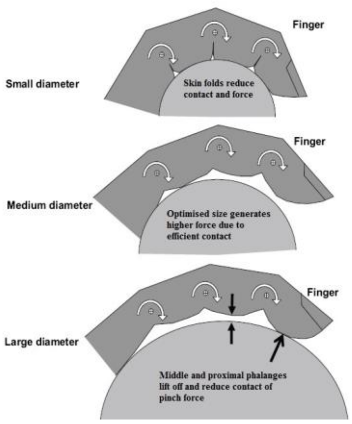


Fig. 8: Contact Area across Different Object Sizes (Seo and Armstrong, 2008).

Another way to explain the pinch force pattern by the large knob would be to refer to Newton's first law of motion, which states that an object at rest stays at rest and an object in motion stays in motion with the same speed and in the same direction unless acted upon by an unbalanced force. A larger object would have larger inertial mass. Due to its larger inertia, the knob may resist the velocity to slow down, and continue to turn even when the participant may not be exerting much force to turn the knob. The inertia of the large knob itself may have lessened the external force requirement to turn the knob, which led to the reduction of pinch force exertion. Besides this, researchers have previously suggested that normal force change is over 3 times greater for a load than for an unload (Winstein *et al*., 1991).

For the one without loading in Figure 7(b), it appears that the mean pinch force exerted on the medium size screw knob (0) is 78.2924g (highest), which is 1.02% higher than the force exerted on the small size screw knob (-1) (77.4907g) (lowest) and 0.97% higher than the force exerted on the large size screw knob (1) (77.5312g) (intermediate). However, the difference between the pinch force generated for the large knob and the small knob is not significant (only a difference of 0.0405g).

This is perhaps because the absence of the loading in the structure causes a lack of resistance in turning the knobs. Since there is no loading effect while turning the knobs, the frictional force (F_f) would decrease over the kinetic friction coefficient ($\boldsymbol{\mu_k}$), causing the normal force (F_n) to also decrease. The formula that represents this relationship as described by Hibbeler (2012) is:

$$\boldsymbol{F_n = \frac{F_f}{\mu_k}} \quad (1)$$

For the ANOVA, it is found that pinch force is significantly affected by object size under the condition of the loaded structure ($p < 0.05$). However, these results are found to be inconsistent with those of the unloaded structure. For the unloaded structure, the effects of size on pinch force are not significant ($p > 0.05$). Since the structure is without loading, the participants may have not been able to differentiate their efforts in turning the different sizes of knobs. This caused the pinch forces to be uniform across different sizes and thus confirming the reason for the insignificance in the effects of object sizes on pinch force.

Conclusion:

From the results observed, it is confirmed that pinch force is significantly affected by object size ($p < 0.05$) for the loaded structure, but not significantly affected by object size for the unloaded structure. This was due in part to the absence of the loading effect from the structure which caused the forces to be similar across different sizes. Furthermore, the average pinch force exerted on the large size knobs appears to be the lowest among the other 2 sizes (medium and small) since the fingers extend further, causing the contact area between the finger pads and the object surface to be lesser, and the applied normal force to be lower.

This study contributes to the knowledge of the effects of object size on pinch force. With these findings, designers can potentially design objects that are operated with pinch grips to be safer and more suitable for certain manual, sedentary or general tasks. This study also indirectly opens a door of possibilities for researchers to develop frameworks that emphasise on further enhancing the safety margin of pinch grip forces in a more precise, systematic and rational way. On the whole, this study can potentially be used as a reference in the enhancement of both safety and design so as to allow hand-related manual work to be less strenuous and more accommodating to the users' fingers.

For future directions of this research, it is proposed that the impacts of various muscular activities on pinch force are be investigated by using the SEMG (Surface Electromyography) which can record signals from the Thenar muscles during a pinch grip. The investigation of muscular contribution in pinch grips would be beneficial for the understanding of the pinch strength capability of individuals during a pinching activity. It also helps identify the underlying muscles responsible in generating a certain amount of pinch force. It may be important for researchers to consider the frequency of pinch grips and the ability of maintaining the pinch grip forces with time due to fatigue.

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