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# A comparison of two methods of measuring static coefficient of friction at low normal forces: a pilot study

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This study compares two methods for estimating static friction coefficients for skin. In the first method, referred to as the 'tilt method', a hand supporting a flat object is tilted until the object slides. The friction coefficient is estimated as the tangent of the angle of the object at the slip. The second method estimates the friction coefficient as the pull force required to begin moving a flat object over the surface of the hand, divided by object weight. Both methods were used to estimate friction coefficients for 12 subjects and three materials (cardboard, aluminium, rubber) against a flat hand and against fingertips. No differences in static friction coefficients were found between the two methods, except for that of rubber, where friction coefficient was 11% greater for the tilt method. As with previous studies, the friction coefficients varied with contact force and contact area. Static friction coefficient data are needed for analysis and design of objects that are grasped or manipulated with the hand. The tilt method described in this study can easily be used by ergonomic practitioners to estimate static friction coefficients in the field in a timely manner.

**Keywords:** skin friction; hand friction; friction measurement; hand; coefficient of friction

## 1. Introduction

This paper reviews some key studies of factors affecting skin friction and then describes a simple method for measuring static coefficients of friction for analysis and design of work object. This simple and fast procedure could help industrial designers or consumer product designers to estimate static coefficients of friction between the hand and other materials for the design of efficient and safe work tools, handles and controls.

Low friction between the hand and object can cause hand slippage and hand and finger injuries (Malker 1991, Cai *et al*. 2005). In addition, insufficient friction between the hand and object can make it difficult for people to open packaging (Department of Trade and Industry 1997, McConnell 2004) or to perform required tasks (propelling a wheelchair: Richter *et al*. 2006, periodontal work: Laroche *et al*. 2007), as friction is directly related to a person's ability to apply torque (Nagashima and Konz 1986, Lewis *et al*. 2007, Seo *et al*. 2008a, Yoxall and Janson 2008) or thrust force (Seo *et al*. 2008b) on an object. To prevent injuries due to hand slippage and to improve manipulability of objects using the hand, static coefficient of friction data between the hand and other materials are needed to design objects with adequate friction.

While friction coefficient data between two solid materials are available in mechanical handbooks (Dorf 2003), friction coefficient data for skin that ergonomics practitioners can use are limited. The classical friction law developed by Amonton (1699) and Coulomb (1785) states that the coefficient of friction is independent of the normal force, the speed of movement and the size of the contact area between two surfaces; however, these laws are based on the observations of solid materials with limited elastic properties. Contemporary studies have shown that human skin exhibits viscoelastic properties, deforms non-linearly and deviates from these laws (Bobjer *et al*. 1993, Sivamani *et al*. 2003a, Bobjer 2004). The complex behaviour of skin makes it particularly difficult to measure the static coefficient of friction accurately with consistent results. It also means that the coefficient of friction between the hand and a given material cannot be characterised as a single number, since the coefficient of friction varies with a number of factors, such as normal force and contact area as described below.

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### 1.1. *Factors affecting the coefficient of friction between skin and other materials*

The coefficient of friction ($\mu$) is defined by the ratio of friction force to normal force between two contacting surfaces. The static friction force, the maximum force that can be applied perpendicular to a given normal force without moving, is used to calculate the static coefficient of friction ($\mu_s$). The dynamic or kinetic friction force, the force required to maintain movement of one surface past another for a given normal force, is used to calculate the dynamic or kinetic coefficient of friction ($\mu_k$) (Bowden and Tabor 1959, Blau 1996).

#### *1.1.1. Normal force*

Studies indicate that coefficients of friction between skin and an object increase with decreasing normal force as shown in Figure 1 (Comaish and Bottoms 1971, El-Shimi 1977, Bullinger *et al.* 1979, Wolfram 1983, Buchholz *et al.* 1988, Koudine *et al.* 2000, Sivamani *et al.* 2003b, Bobjer 2004, Tomlinson *et al.* 2007a; see Table 1 for detailed information about these previous studies). In other words, the smaller the normal force, the higher the ratio of friction force to normal force. For example, Bobjer (2004) reported that the static coefficient of friction between a polycarbonate material and the pads of the thumb and index finger increased from 0.77 to 1.32 when normal force decreased from 20 to 1 N.

It may be because the skin is deformable and the contact area increases with normal force as described by Herz equation (Wolfram 1983):

$$A = \left[K\frac{W}{E}\right]^{2/3} \tag{1}$$

where A is the contact area, W is the normal force, E is Young's modulus of skin and K is a colligative term including average dimension of adhesive contact. The friction coefficient is the ratio of friction force to normal force. Friction force is proportional to the contact area according to the adhesion theory (Wolfram 1983). Thus, the friction coefficient can be expressed in the following equation (Wolfram 1983, Zatsiorsky 2002):

$$\mu = \frac{\text{Friction force}}{W} \propto \left[\frac{K}{E}\right]^{2/3} W^{-1/3} \tag{2}$$

The equation demonstrates that the friction coefficient is inversely related to the normal force. Experimental data in Figure 1 support that the coefficient of friction increases exponentially as normal force decreases. It should be noted that this relationship observed for normal and hydrated skin may not be seen for rough dry skin (Adams *et al.* 2007) and for some materials (silk, polyester, cotton, rayon; Savescu *et al.* 2008).

#### *1.1.2. Contact area*

The coefficient of friction is affected by how an object is gripped, e.g. pinch grip vs. power grip, which affects the area of contact between the hand and the work object. Previous studies (Comaish and Bottoms 1971, Bullinger *et al.* 1979) have shown that the static coefficient of friction increases with increasing contact area between the hand and a work object. Bullinger *et al.* (1979) reported that the static coefficient of friction between an object and the pads of the thumb and index finger was approximately 20% of the static

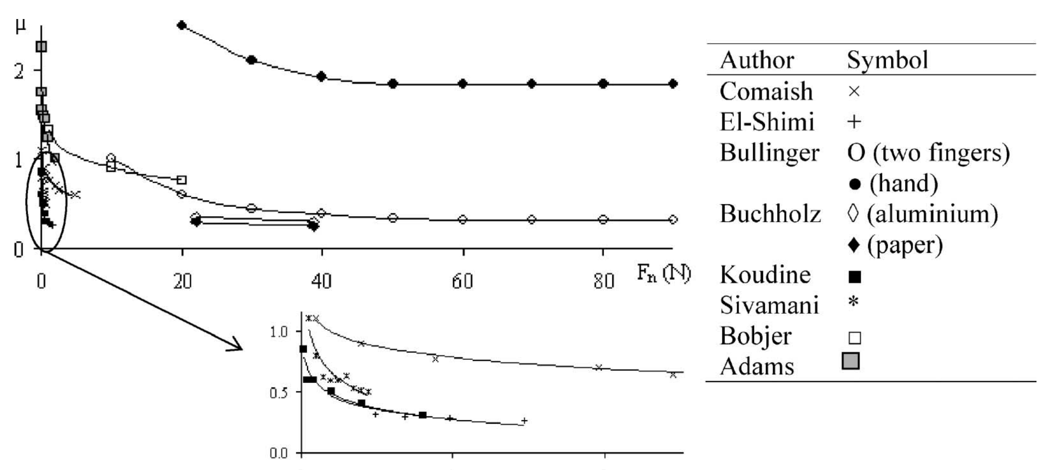



Figure 1. Coefficient of friction ($\mu$) vs. normal force (Fn) for previous studies on a linear scale. See Table 1 for detailed information of each study. Data for Comaish and Bottoms (1971) are from the sub-experiment with a constant contact area and varying normal force. Data for Adams *et al.* (2007) are for wet skin and glass only.

Table 1. Previous studies that examined the static or dynamic coefficient of friction ($\mu_s$, $\mu_k$, respectively) as a function of normal force ($F_n$) and contact area.

| Author | Anatomical Site | $F_n$ (N) | Material | Response | Model | Method |
|---|---|---|---|---|---|---|
| Comaish | Mid tibia, abdominal, hand | 0.03 – 9.8 | Polythene | $\mu_s/\mu_k$ | – | Fixed $F_n$. Friction force increased until the object slid for $\mu_s$ (standard method). For $\mu_k$, the object moved with a constant velocity against skin. Measured friction and normal forces used to calculate $\mu_s$ or $\mu_k$. |
| Koudine | Forearm | 0.02 – 0.8 | Glass | $\mu_s/\mu_k$ | $\log(\mu) \propto 0.28 \times \log(F_n)$ | |
| Buchholz | Index finger + thumb pad | 22.1, 38.7 | Aluminium<br>Paper | $\mu_s$ | $\mu = 0.430 - 0.00320 \times F_n$<br>$\mu = 0.345 - 0.00241 \times F_n$ | |
| Bullinger | Index finger + thumb pad<br>Palmar side of hand | 10 – 90 | Unspecified | $\mu_s/\mu_k$ | – | |
| Bobjer ('93, '04) | Index finger pad | 1, 10, 20 | Polycarbonate | $\mu_s/\mu_k$ | – | |
| Sivamani | Dorsal skin of fingers | 0.05 – 0.44 | Stainless steel | $\mu_k$ | $\log(\mu) \propto -0.32 \times \log(F_n)$ | |
| Adams | (Wet) Volar forearm | 0.08 – 2 | Glass | $\mu_s/\mu_k$ | $\log(\mu) \propto -0.17 \times \log(F_n)$ | |
| Wolfram | Theoretical analysis | – | – | – | $\log(\mu) \propto -1/3 \times \log(F_n)$ | – |
| El-Shimi | Volar forearm | 0.20 – 1.96 | Stainless steel | $\mu_k$ | – | Fixed $F_n$. Rotating probe at a constant rpm. Torque and $F_n$ used to calculate $\mu_k$. |

coefficient of friction between the object and a flat hand. Comaish and Bottoms (1971) reported that the static coefficient of friction increased from 0.3 to 0.6 when the area of contact increased from 6.2 to 9.3 cm$^2$.

For a given pinch or power grip, contact area can be affected by normal force. A normal force applied to skin causes the skin to deform and increases the area of contact between the skin and the object as illustrated in Equation 1 and demonstrated experimentally (Bullinger *et al.* 1979, Bobjer *et al.* 1993, Nakazawa *et al.* 2000). For example, Bobjer *et al.* (1993) reported that the contact area between the index finger pad and a flat surface increased from 175 to 270 mm$^2$ as normal force increased from 1 to 20 N. In addition, Bullinger *et al.* (1979) reported that the area of contact for a flat hand against a flat object increased from 50 to 73 cm$^2$ as the normal force increased from 10 to 50 N, above which the contact area appears to remain almost constant.

The average maximum grip force is 490 and 270 N for males and females (20 to 59 years old), respectively, and the average maximum pinch force between the thumb and index fingertip is 80 and 50 N for male and female (20 to 59 years old), respectively (Mathiowetz *et al.* 1985). These maximum grip and pinch force values are well above the normal force range in which Bullinger *et al.* (1979) found that both the coefficient of friction and the contact area became almost constant for a flat hand and for two fingers (thumb and index finger). Thus, normal force appears to have the greatest effect on the contact area and the coefficient of static friction at force levels well below maximum pinch and grip strengths.

### *1.1.3. Hydration and sweat*

It appears that moistened skin yields the highest coefficient of friction, as opposed to skin with excessive moisture (Naylor 1955, Sulzberger *et al.* 1966, Bullinger *et al.* 1979, Dawson 1997, Sivamani *et al.* 2003a, Gitis and Sivamani 2004) or dry skin (El-Shimi 1977, Highley *et al.* 1977, Bullinger *et al.* 1979, Nacht *et al.* 1981, Buchholz *et al.* 1988, Loden *et al.* 1992, Smith *et al.* 1997, Koudine *et al.* 2000, Sivamani *et al.* 2003b, Bobjer 2004, Lewis *et al.* 2007, Zackrisson *et al.* 2008). For instance, El-Shimi (1977) reported that the dynamic coefficient of friction with polished stainless steel for the skin with serious dryness was 59% of that for normal skin. Comaish and Bottoms (1971) reported that the static coefficient of friction with Teflon increased five-fold after the hand was immersed in warm water for 30 min and then carefully dried.

When subjects were exposed to higher temperature or humidity and the wind was blocked to increase perspiration, the coefficient of friction increased 38%

on average (Naylor 1955, Prall 1973). Smith *et al.* (1997) reported that the static coefficient of friction decreased 33% following a blockade of sweat excretion, which reduced sweating in the hand. Most experts agree that moisture softens the skin and the softened skin deforms more with contact force, which results in increased contact area between the skin and an object, thus a higher coefficient of friction. (Prall 1973, El-Shimi 1977, Nacht *et al.* 1981, Wolfram 1983, Sivamani *et al.* 2003c, Bobjer 2004, Adams *et al.* 2007). Therefore, it appears that moistening the skin within normal physiological ranges will generally increase skin friction.

For experiments that require subjects to wash their hands in order to eliminate contaminates, at least 10 to 15 min must be allowed between the exposure to water and the onset of the experiment. Once exposed to water, it takes time for the skin to lose moisture to the ambient and gradually reacquire the steady state of its hydration level. El-Shimi (1977), Highley *et al.* (1977), Nacht *et al.* (1981), Sivamani *et al.* (2003b) and Adams *et al.* (2007) reported that 2, 6, 10, 17 and 30 min, respectively, were required to obtain a constant coefficient of friction value after the hand was exposed to water.

#### 1.1.4. *Surface texture, lubricant, and moisturiser*

Coefficient of friction is affected by the surface texture of the work object and by the presence of lubricant. Altering a smooth polymer surface with 0.5 to 1.5 mm-wide grooves at right angles to the direction of friction force resulted in 71% lower dynamic friction than for a corresponding non-grooved surface under normal hand conditions (Bobjer *et al.* 1993). The opposite trend was found under the presence of lubricants. The grooved surface exhibited a 173% higher dynamic coefficient of friction than the non-grooved surface under the presence of lubricants such as glycerol, paraffin oil and lard (Bobjer *et al.* 1993). O'Meara and Smith (2001, 2002) reported that the static coefficient of friction for knurled steel was on average 73% higher than that for smooth steel when the hand was soapy.

Application of lubricants or moisturisers on the skin can result in initial decrease in the coefficient of friction (Highley *et al.* 1977, Nacht *et al.* 1981, Koudine *et al.* 2000, Lewis *et al.* 2007) or immediate increase in the coefficient of friction (Prall 1973, Nacht *et al.* 1981, Batt *et al.* 1988, Sivamani *et al.* 2003b) depending on the greasiness (Nacht *et al.* 1981). In the long term, lubricant moisturisers prevent moisture in the skin from evaporating and hydrate the skin, thus increasing the coefficient of friction (Highley *et al.* 1977, Nacht *et al.* 1981, Batt *et al.* 1988, Koudine *et al.* 2000, Sivamani *et al.* 2003b). The hydration effect lasted for more than 4 h (Nacht *et al.* 1981, Batt *et al.* 1988, Sivamani *et al.* 2003b). For example, Koudine *et al.* (2000) reported that the static coefficient of friction initially decreased to 30–50% of the initial value in 2 min after the application of cosmetic products. This decrease was followed by an increase of 2.4 times the initial value, on average, after 20 min.

#### 1.1.5. *Movement between skin and work object*

Friction is related to the direction of the friction force and the speed of motion. Jones and Hunter (1992) suggested that coefficients of friction for friction forces acting from the fingertips towards the palm might be greater than those for the opposite direction. Bullinger *et al.* (1979) reported that dynamic coefficients of friction for friction forces acting at right angles to the palmar sides of the fingers were 28% greater than those acting parallel. This may be related to greater stiffness in the pointing direction compared to that in the perpendicular direction (Nakazawa *et al.* 2000). Dynamic coefficients of friction have been shown to be, on average, 30% greater than corresponding static values (Bullinger *et al.* 1979, Bobjer 2004). Friction forces increased as velocity increased from zero for dry skin (Johnson *et al.* 1993, Bobjer 2004). For hydrated skin, after the initial increase, friction forces decreased about 60% for higher velocities (Johnson *et al.* 1993, Bobjer 2004).

#### 1.1.6. *Gender/ethnicity/age/anatomical sites*

No significant difference in the static or dynamic coefficient of friction has been reported with regard to gender (Cua *et al.* 1990, 1995, O'Meara and Smith 2001, Sivamani *et al.* 2003c), ethnicity (Sivamani *et al.* 2003c, Tomlinson *et al.* 2007b) or age (Cua *et al.* 1990, 1995, O'Meara and Smith 2001, Egawa *et al.* 2002, Sivamani *et al.* 2003c) for 11 anatomical sites including the palm and the volar forearm. Significant differences have been reported for different anatomical sites (Comaish and Bottoms 1971, Cua *et al.* 1990, 1995, Elsner *et al.* 1990, Koudine *et al.* 2000, Sivamani *et al.* 2003c). According to Cua *et al.* (1990, 1995), the forehead and postauricular area yielded the highest dynamic coefficient of friction ($0.34 \pm 0.02$), with the palm in the middle range ($0.21 \pm 0.01$) and the abdomen the lowest ($0.12 \pm 0.01$), using Teflon as the test material. Comaish and Bottoms (1971) reported that the static coefficient of friction on the palmar side of the hand ($1.3 \pm 0.7$) was 2.5 times higher than that on the dorsum of the hand. This difference in the coefficient of friction among anatomical sites may be attributed to different hydration levels among sites (Cua *et al.* 1990).

The literature shows that the coefficient of friction for skin is sensitive to normal force, contact area, velocity, direction of movement, hydration, sweat, lubricants and anatomical sites. Consequently, friction coefficient data between skin and other materials under various conditions are limited. In addition, most friction coefficient measurements are performed using specially developed equipment that requires force sensors and data acquisition systems at the minimum (Lewis *et al.* 2007) and motors and controllers to control force and speed (Bullinger *et al.* 1979, Buchholz *et al.* 1988, Bobjer *et al.* 1993, Asserin *et al.* 2000, Koudine *et al.* 2000, Sivamani *et al.* 2003b, Adams *et al.* 2007, Savescu *et al.* 2008). The authors of the present study believe that a simple method for measuring static coefficient of friction that does not require sophisticated equipment will be useful for ergonomics practitioners and product designers.

This paper describes a simple method that can be easily used for measuring the static coefficient of friction between the hand and other materials. It compares the simple method with a traditional method. This paper also uses the two methods to examine the effects of normal contact force, materials and hand contact areas on the static coefficient of friction. The simple method described in this paper allows ergonomics practitioners and industrial designers to easily estimate the static coefficient of friction between the hand and other materials.

## 2. Methods

Two methods for measuring static coefficients of friction are examined. The methods are referred to as the 'standard' method and the 'tilt' method. In both methods, the static coefficient of friction is calculated as the ratio of the friction force ($F_f$) to the normal force ($F_n$) when the object begins to slide, as described by Amonton (1699), Coulomb (1785), Naylor (1955), Comaish and Bottoms (1971), Yamaguchi (1990), Blau (1996), Koudine *et al.* (2000) and O'Meara and Smith (2001).

### 2.1. Standard method

The standard method is the most commonly used method for measuring coefficient of friction where the normal force is controlled and the friction force is measured when an object starts sliding against the skin (for measuring the static coefficient of friction) or while an object is moving against the skin (for the dynamic coefficient of friction) (Comaish and Bottoms 1971, Bullinger *et al.* 1979, Buchholz *et al.* 1988, Bobjer *et al.* 1993, Koudine *et al.* 2000, O'Meara and Smith 2002, Sivamani *et al.* 2003b, Lewis *et al.* 2007, see Table 1). In this study, the standard method entails placing the flat plate with a known weight on the hand or fingertips while the plate is connected to a force transducer by a cord (Figure 2a). The subject then increases the horizontal force on the plate until the hand begins to slide.

Friction force was measured using a transducer (SM-50; Interface Inc., Scottsdale, AZ, USA) and recorded on a computer using LabView (National Instruments, Inc., Austin, TX, USA) during the entire trial. Measured friction force was displayed online on a computer monitor in front of the subject along with a reference line. Subjects were asked to track the reference line to control the friction force build-up rate. A sample friction force vs. time plot is shown in Figure 2b. The entire sequence was videotaped using a digital video camera at 29.97 frames per second (National Television System Committee (NTSC) standard). The videos were then converted to AVI format with an effective frame rate of 29.97. Apple QuickTime was used to play the video and detect the slip angle. QuickTime enables users to advance the video one frame at a time so that the slip can be detected within approximately one-thirtieth of a second (1 s/29.97). The static coefficient of friction was then calculated as the ratio of the friction force (measured by the force transducer at the time the plate began to slide) to the plate weight. Subjects were allowed to practise the force tracking before participating in the test.

### 2.2. Tilt method

The 'tilt' method entails holding a flat plate in the hand. The hand and forearm are then tilted at a steady rate until the plate begins to slide, as shown in Figure 3a. The friction force is equal to W sin $\theta$, and normal force is equal to W cos $\theta$, where W is the weight of the plate and $\theta$ is the angle of the plate with regard to the horizontal at the time the plate begins to slide. As the plate is tilted, friction force increases and normal force decreases, as shown in Figure 3b. It can be shown that the static coefficient of friction is equal to tan $\theta$, where $\theta$ is the angle at which the plate begins to slide.

The entire sequence was videotaped using the digital video camera. A horizontal reference line was drawn in the background wall and was in the field of view for the video camera. The videos were used to visually detect the slip between the hand and the plate as described earlier for the standard method. At the slip, the video was paused and the image was printed. The printed image was used to measure the tilt angle, $\theta$, against the horizontal reference line (see Figure 3). The static coefficient of friction was then calculated as the tangent of the tilt angle. Subjects were

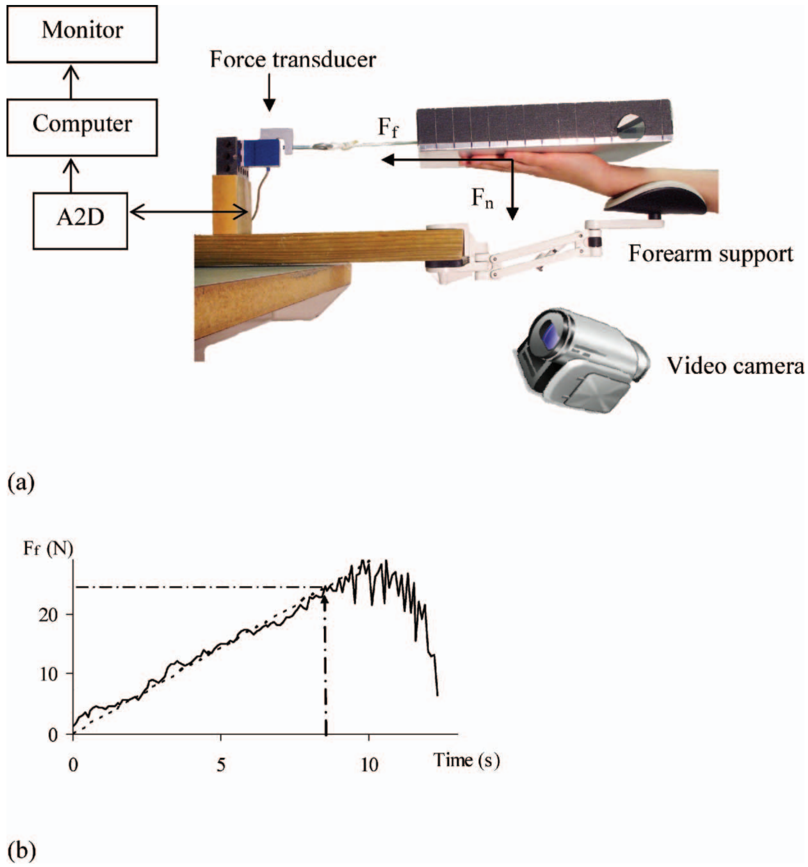



Figure 2. Standard method: Friction force was measured by a force transducer, recorded in a computer and displayed on a computer monitor (a). A sample plot of friction force is shown (b). Subjects were instructed to track the dashed reference line that increased at a prescribed rate. The solid line represents the actual friction force exerted by a subject. The point at which the hand slipped (marked by an arrow in (b)) was visually determined by inspecting the video.

instructed to pay attention to an analogue timer in order to rotate their forearm around their elbow joint 90° for 6 s with an angular velocity as constant as possible.

### 2.3. *Subjects*

In total, 12 university students and employees (six males, six females, average age 31 years, age ranging from 24 to 43 years) volunteered to participate. None of them was engaged in regular physical work. No calluses or skin thickening was observed on their hands. All subjects signed an informed consent form prior to participation in the study. All subjects' hand length and breadth were measured as described by Garrett (1971) at the end of the experiment. Then the measured hand length and breadth were multiplied to roughly estimate the hand size. In addition, the length and breadth of the distal pads of the thumb and index finger were measured to roughly estimate the contact area of the pads of fingertips.

### 2.4. *Treatment*

To eliminate possible artefacts due to contaminants, subjects washed their hands with hand soap and rinsed with tap water. They dried their hands with paper towels and air dried for 15 min at room temperature, prior to the experiment. This procedure was used by Comaish and Bottoms (1971) and Buchholz *et al.* (1988). The bottom of the plates and subjects' hands were wiped with a KIM clean paper and a paper towel respectively, every six trials.

### 2.5. *Test procedure*

First, the tilt method was tested, using 12 subjects, for three materials (rubber, polished aluminium, cardboard), two hand contact locations (five fingertips vs. flat palm) and three plate weights (10, 20, 30 N). The maximum tested plate weight, 30 N, was determined as 20% of the maximum upper arm strength for 5th percentile females in the initial posture of the tilt method – 90° elbow flexion and a straight

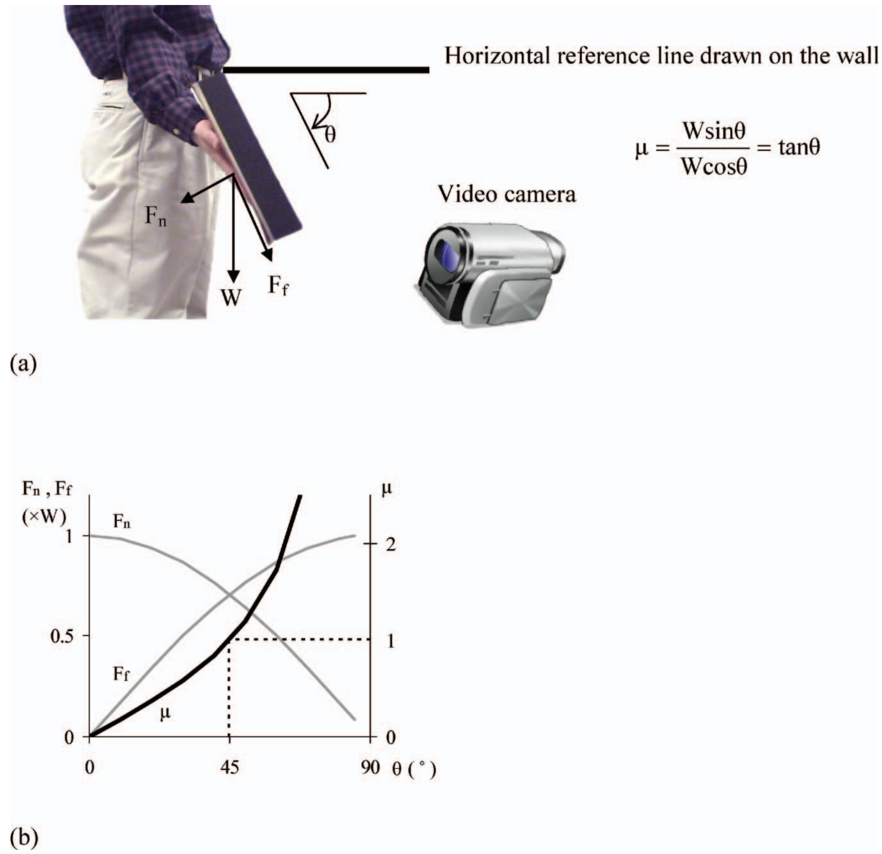



Figure 3. Tilt method: Subjects tilted the hand and forearm at a steady rate until the plate began to slide while the entire sequence was videotaped (a). The normal (Wcos $\theta$) and friction (Wsin $\theta$) forces vary as a function of tilt angle, $\theta$(b). The tilt angle was visually determined by inspecting the video.

wrist (with anthropometry data from Webb Associates (1978) and elbow joint moment strength from Schanne (1972) after correction for population strengths of Stobbe (1982 cited Chaffin *et al*. 1999). The average normal force ($F_n$) and friction force build-up rate ($dF_f$ /dt) at the moment the plate slipped were calculated by Wcos $\theta$ and Wcos $\theta \times$ d $\theta$/dt, respectively, where $\theta$ is the angle at the moment the plate slipped. The angular velocity was assumed to be 15°/s, as subjects were instructed to rotate their forearm around their elbow joint 90° for 6 s with an angular velocity as constant as possible. Table 2 shows the average normal force and friction force build-up rate that were calculated from the tilt method for each condition (subjects pooled). The normal forces, $F_n$, ranged from 4.2 to 27 N. The friction force build-up rate, $dF_f$ /dt, ranged from 0.8 to 5.4 N/s. Then, the same subjects participated in the experiment, using the standard method to measure the static coefficient of friction. To test comparable normal forces and friction force build-up rates with the tilt and standard methods, plate weights used in the standard methods

Table 2. The normal force ($F_n$) and friction force build-up rate ($dF_f$/dt) at the point where the plate slipped are shown for each condition for the tilt method tests.

| Material | Contact location | Tilt method plate weight (N) | $F_n$ (N) | $dF_f$ /dt (N/s) |
|---|---|---|---|---|
| Cardboard | Palm | 10 | 8.9 | 1.7 |
| | | 20 | 18.0 | 3.5 |
| | | 30 | 27.0 | 5.3 |
| | | 10 | 8.9 | 1.8 |
| | Fingertips | 20 | 18.0 | 3.5 |
| | | 30 | 27.0 | 5.4 |
| Aluminium | Palm | 10 | 6.0 | 1.2 |
| | | 20 | 13.1 | 2.6 |
| | | 30 | 19.8 | 3.9 |
| | Fingertips | 10 | 6.8 | 1.3 |
| | | 20 | 14.1 | 2.8 |
| | | 30 | 21.3 | 4.2 |
| Rubber | Palm | 10 | 4.2 | 0.8 |
| | | 20 | 9.7 | 1.9 |
| | | 30 | 14.5 | 2.8 |
| | Fingertips | 10 | 5.0 | 1.0 |
| | | 20 | 10.4 | 2.0 |
| | | 30 | 15.5 | 3.0 |

were adjusted to the average normal forces of the tilt method in Table 2. Also, the increment rates of the reference forces that were tracked by subjects were adjusted to the average friction force build-up rates of the tilt method in Table 2. Each condition was tested three times in randomised blocks.

## 3. Results

The average static coefficients of friction measured using the tilt and the standard method for each normal force and hand contact location are shown in Table 3. The average static coefficient of friction (subjects, hand contact location, normal force and method pooled) in this experiment was 0.46 ± 0.17, 1.11 ± 0.48 and 1.60 ± 0.44 for cardboard, aluminium and rubber, respectively. The average static coefficients of friction for the tilt and the standard method for each normal force and material are plotted in Figure 4. The average static coefficients of friction from the tilt and the standard methods were not statistically different for aluminium or cardboard ($p > 0.05$); however, the coefficient of friction for rubber was, on average, 11% greater ($p < 0.05$) for the tilt method than the standard method. The same conclusions were made by the method proposed by Bland and Altman (1986) for assessing agreement between two methods of clinical measurement.

A linear regression analysis was performed to examine the relationship between the log of the static coefficient of friction, the log of normal force, hand contact location, hand size and method for each material. The log transformations of the static coefficient of friction and normal force were used in the regression analysis to be consistent with the observations from other studies (see Figure 1; Table 1). The significance of each factor was determined, in addition to correlation coefficients ($r^2$), as shown in Table 4. The static coefficient of friction significantly changed with normal force, hand contact location and hand size. The static coefficient of friction varied with method, only for rubber.

The static coefficient of friction vs. normal force is plotted in Figure 4, Figure 5 and Figure 6a,b. The regression analysis (Table 4) shows that the static coefficient of friction increased significantly with decreasing normal force. From Figure 4 and Figure 5, it can be seen that the average static coefficient of friction for rubber decreased 26% from 1.9 to 1.4 as normal force increases 247% from 4.6 to 15.0 N (method, hand contact location and hand size pooled). The average static coefficient of friction decreased 31% from 1.3 to 0.9 and 20% from 0.5 to 0.4 for aluminium and cardboard as the normal force increased 220% from 6.4 to 20.6 N and 203% from 8.9 to 27 N, respectively (method, hand contact location and hand size pooled). Figure 6b shows a significant relationship between the log of the static coefficient of friction and the log of normal force for all three materials ($R^2 = 0.96$ to 1, method, hand contact location and hand size pooled).

The average static coefficient of friction for each hand contact location is shown in Table 3, Figure 5

Table 3. The mean ± standard deviation static coefficient of friction ($\mu_s$) for 12 subjects are shown for different materials (cardboard, aluminium, rubber), hand contact locations (palm, fingertips), normal forces ($F_n$), and methods (tilt, standard).

| Material | Hand Contact | $F_n$ (N) | Method: Tilt | Method: Standard | Method pooled | Hand contact, $F_n$, Method pooled |
|---|---|---|---|---|---|---|
| Cardboard | Palm | 8.9 | 0.51 ± 0.13 | 0.55 ± 0.21 | 0.53 ± 0.17 | 0.46 ± 0.17 |
| | | 18.0 | 0.46 ± 0.12 | 0.44 ± 0.16 | 0.45 ± 0.14 | |
| | | 27.0 | 0.47 ± 0.13 | 0.41 ± 0.16 | 0.44 ± 0.15 | |
| | Fingertips | 8.9 | 0.50 ± 0.17 | 0.48 ± 0.22 | 0.49 ± 0.20 | |
| | | 18.0 | 0.47 ± 0.16 | 0.43 ± 0.17 | 0.45 ± 0.16 | |
| | | 27.0 | 0.41 ± 0.14 | 0.39 ± 0.18 | 0.40 ± 0.16 | |
| Aluminium | Palm | 6.0 | 1.46 ± 0.71 | 1.47 ± 0.65 | 1.47 ± 0.67 | 1.11 ± 0.48 |
| | | 13.1 | 1.24 ± 0.44 | 1.18 ± 0.45 | 1.21 ± 0.44 | |
| | | 19.8 | 1.10 ± 0.38 | 0.85 ± 0.28 | 0.98 ± 0.36 | |
| | Fingertips | 6.8 | 1.11 ± 0.44 | 1.19 ± 0.47 | 1.15 ± 0.46 | |
| | | 14.1 | 1.05 ± 0.36 | 0.96 ± 0.36 | 1.01 ± 0.36 | |
| | | 21.3 | 0.88 ± 0.22 | 0.86 ± 0.35 | 0.87 ± 0.29 | |
| Rubber | Palm | 4.2 | 2.19 ± 0.64 | 1.96 ± 0.46 | 2.07 ± 0.57 | 1.60 ± 0.44 |
| | | 9.7 | 1.74 ± 0.31 | 1.57 ± 0.35 | 1.66 ± 0.34 | |
| | | 14.5 | 1.58 ± 0.25 | 1.43 ± 0.27 | 1.50 ± 0.27 | |
| | Fingertips | 5.0 | 1.66 ± 0.28 | 1.57 ± 0.45 | 1.62 ± 0.38 | |
| | | 10.4 | 1.54 ± 0.30 | 1.37 ± 0.29 | 1.46 ± 0.31 | |
| | | 15.5 | 1.38 ± 0.26 | 1.20 ± 0.23 | 1.29 ± 0.26 | |

and Figure 6a. The regression analysis (Table 4) shows that the static coefficient of friction is significantly greater with the palm than with the fingertips for rubber and aluminium. By using the palm instead of the fingertips, the static coefficient of friction increased 20, 21 and 6%, for rubber, aluminium and cardboard, respectively (method, normal force and hand size pooled). Figure 6c plots the static coefficient of friction as a function of pressure (normal force divided by contact area) on a log scale (hand size and method pooled). A significant relationship was found between the log of the static coefficient of friction and the log of pressure ($R^2 = 0.73$ for rubber, 0.65 for aluminium, 0.40 for cardboard).

The average static coefficients of friction as a function of hand size are shown in Figure 7, when the hand size was approximated as hand width times hand length ($cm^2$) (method, hand contact location and normal force pooled). As the hand size increased from small (average = 136 $cm^2$ ranging from 124 to 148 $cm^2$) to large (average = 164 $cm^2$, ranging from 153 to 176 $cm^2$), the average static coefficient of friction increased approximately 16, 11 and 3% for cardboard, aluminium and rubber, respectively (method, normal force and hand contact location pooled). The regression analysis (Table 4) shows a significant relationship between static coefficient of friction and hand size.

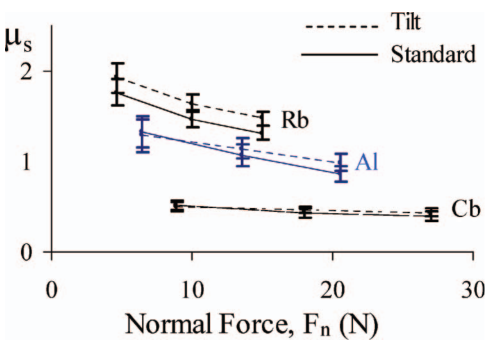



Figure 4. Mean ± standard error static coefficient of friction based on the tilt and standard methods for palmar skin and three different materials (Rb = rubber; Al = aluminium; Cb = cardboard) vs. normal force. Data for hand contact location and subjects are pooled.

Variance in friction coefficient measurement was not significantly different between the two methods. Variance in friction coefficient measurement can be attributed to difference in friction coefficient between subjects (between-subject variance) and variance over repeated measures (within-subject variance). For both methods and all conditions, between-subject variance was significantly greater than within-subject variance ($p < 0.01$).

## 4. Discussion

### *4.1. Tilt method vs. standard method*

The purpose of this study was to compare two methods for measuring the static coefficient of friction between palmar skin and selected materials at low force levels. The tilt method worked as well as the standard method under nearly all conditions. Measurement error was not different between the two methods.

As any method has its own shortcomings, the tilt method has a few drawbacks. Even though the results with the tilt and standard methods agreed with each

Table 4. Regression results for the log of static coefficient of friction (log $\mu_s$) as a function of method.

| Material | Variable | Parameter($\beta$) | Standard Error | $p$-value | $R^2$ |
|---|---|---|---|---|---|
| Cardboard | Intercept | −0.847 | 0.120 | <0.01 | 0.30 |
| | Method | 0.035 | 0.021 | 0.10 | |
| | Location | 0.032 | 0.021 | 0.14 | |
| | Log ($F_n$) | −0.170 | 0.054 | <0.01 | |
| | Hand size | 0.004 | 0.001 | <0.01 | |
| Aluminium | Intercept | −0.414 | 0.137 | <0.01 | 0.31 |
| | Method | 0.035 | 0.025 | 0.17 | |
| | Location | 0.064 | 0.025 | 0.01 | |
| | Log ($F_n$) | −0.261 | 0.060 | <0.01 | |
| | Hand size | 0.004 | 0.001 | <0.01 | |
| Rubber | Intercept | 0.137 | 0.063 | 0.03 | 0.48 |
| | Method | 0.047 | 0.012 | <0.01 | |
| | Location | 0.065 | 0.012 | <0.01 | |
| | Log ($F_n$) | −0.219 | 0.028 | <0.01 | |
| | Hand size | 0.001 | 0.000 | <0.01 | |

Note: Tilt method: M = 1; standard method: M = 0; hand contact location (flat palm: L = 1; fingertips: L = 0), logarithm of normal force (log $F_n$, $F_n$ in Newton) and hand size (H in $cm^2$).
Regression model: $\log \mu_s = \beta_{Intercept} + \beta_{Method} \times M + \beta_{Location} \times L + \beta_{\log Fn} \times \log F_n + \beta_{Hand\ Size} \times H$.

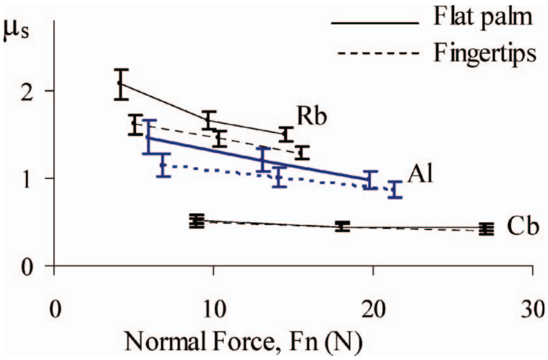



Figure 5. Mean ± standard error static coefficient of friction from palm vs. fingertips contact with three different materials (Rb = rubber; Al = aluminum; Cb = cardboard) vs. normal force. Methods and subjects are pooled.

other in most cases, results for rubber using the tilt method were different than those using the standard method. The static coefficient of friction between the hand and rubber with the tilt method was 11% higher than that with the standard method. For the tilt method, the static coefficient of friction was estimated by Tan $\theta$. The tangent function is non-linear and increases at a greater rate for large values of $\theta$ than for small values (see Figure 3b). For the static coefficient of friction greater than 1.0, the slip angle ($\theta$) is greater than 45°. A small delay in reporting the slip point for large angles will result in overestimating the static coefficient of friction. For example, the static coefficient of friction between rubber and the flat palm with 4.2 N of normal force measured 2.19 using the tilt method and 1.96 using the standard method. These high-static friction coefficient values correspond to the slip angles of 65° and 63°, respectively; only a 2° difference. Thus, higher static coefficients of friction using the tilt method could have resulted from a delay in detecting a high slip angle for rubber. Therefore, care needs to be given to this potential overestimation of friction coefficient when high friction materials are measured with the tilt method.

Another expected drawback is that it would be hard to determine coefficients of friction for high normal forces using the tilt method – particularly for materials with high coefficients of friction. For the tilt method, the elbow becomes a limiting factor for holding a high load at the beginning of the trial. As discussed earlier, 30N is 20% of the maximum load that women in the lowest 5th percentile can lift in the initial posture of the tilt method (with anthropometry data from Webb Associates (1978) and elbow joint moment strength from Schanne (1972) after corrected for population strengths of Stobbe (1982 cited Chaffin *et al.* 1999). An external mechanical support would be required to help subjects to support heavier loads. In addition, with the tilt method, the normal force decreases from the beginning to the end of the test ($F_n = W\cos\theta$); thus, the normal force will be smaller at the end of the test than at the beginning. Therefore, the use of the tilt method is most suitable for situations in which objects are handled with low forces, such as the use of a drill or a screwdriver (Hall 1997).

In spite of these disadvantages, the tilt method is still preferred due to the following reasons:

(1) The tilt method can be easily used by investigators who need a quick estimate of the static coefficient of friction at low force levels for evaluation and design of work equipment. The tilt method does not require measuring equipment and software, thus eliminating the need for calibration and setup. Ergonomics practitioners or designers can use this tilt method only with a video camera and a video player. Thus, it provides the static coefficient of friction in a timely manner.

(2) The tilt method can easily be used in the field. This provides relevant information about the static coefficient of friction in the workers' environment. It appears that the tilt method can also be used in the presence of contaminates to estimate the static coefficient of friction experienced by workers in the fields.

(3) Different directions of friction force can be easily tested with the tilt method, which would provide relevant information depending on the interested task features. This simple and fast measurement of the static coefficient of friction between the hand and other materials would enable industrial designers or consumer product designers to design the appropriate friction from the safety and performance standpoint.

### *4.2. Normal force and contact area*

Consistent with previous studies (Comaish and Bottoms 1971, El-Shimi 1977, Bullinger *et al.* 1979, Buchholz *et al.* 1988, Koudine *et al.* 2000, Sivamani *et al.* 2003b, Bobjer 2004, Tomlinson *et al.* 2007a), the static coefficient of friction increased with decreasing normal force (Figure 6) and with increasing contact area (Figure 5). The data from the present study are not identical with any of the data from the previous studies, since each study used different materials, anatomical sites, hand contact locations, and dynamic/static conditions (see Table 1 for detailed information

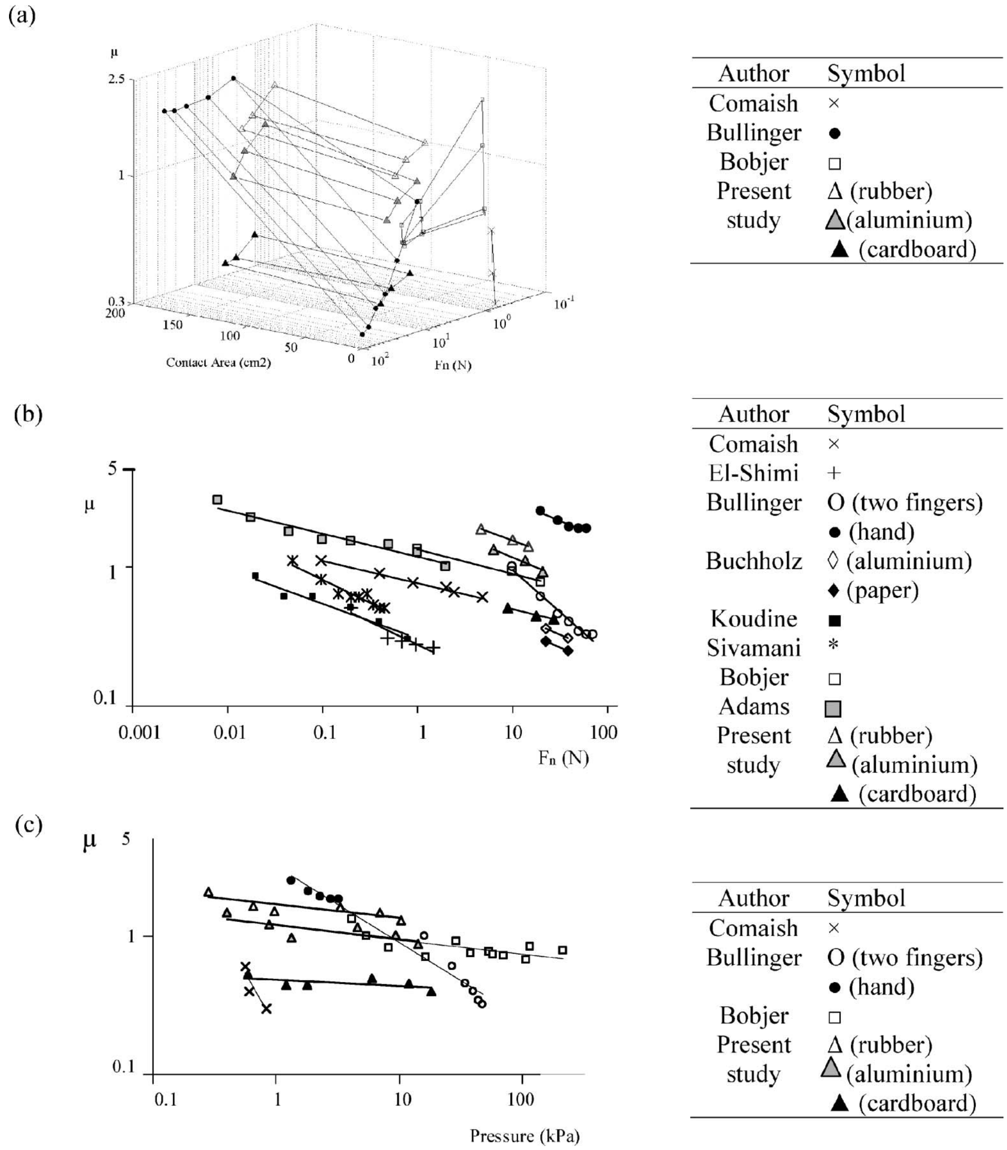
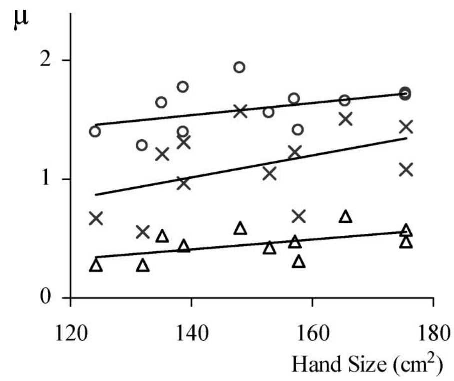



Figure 6. Comparison of present results with previous studies: (a) coefficients of friction ($\mu$) vs. normal force (Fn) and contact area (a flat palm area = 150 cm$^2$, fingertips area = 15 cm$^2$, hand sizes pooled), (b) $\mu$ vs. normal force (Fn) on a log scale (hand contact locations, hand sizes pooled) and (c) $\mu$ vs. pressure on a log scale (hand sizes pooled). See Table 1 for detailed information of each study. Data for Comaish and Bottoms (1971) in (a) and (c) are from the sub-experiment with a constant normal force and varying contact area, and data in (b) are from the sub-experiment with a constant contact area and varying normal force. Data for Adams *et al.* (2007) are for wet skin and glass only.

about the previous studies). Consistent trends between the present study and the previous studies are described in detail as follows.

Both the present study and previous studies have shown that the coefficient of friction increases with decreasing normal force (Table 3, Figure 6a,b). Furthermore, a high linearity was observed between the log of the static coefficient of friction and the log of the normal force in the present study ($R^2$ = 0.96 to 1 for all three materials), as shown in Figure 6b, which agrees with the statements by Wolfram (1983), Koudine *et al.* (2000) and Sivamani *et al.* (2003b) and the data from previous studies (Comaish and Bottoms 1971, El-Shimi 1977, Bullinger *et al.* 1979, Koudine *et al.* 2000, Sivamani *et al.* 2003b, Bobjer 2004).

As for the effect of the contact area, the coefficient of friction increased with increasing contact area both in the present study and previous studies (Comaish and Bottoms 1971, Bullinger *et al.* 1979, Bobjer *et al.* 1993, O'Meara and Smith 2001), as shown in Table 3,




| Symbol | Material |
|---|---|
| O | Rubber |
| × | Aluminium |
| Δ | Cardboard |

Figure 7. Coefficient of friction ($\mu$) vs. hand size (O: rubber; $\times$: aluminum; $\Delta$: cardboard). Method, hand contact location and normal force are pooled.

Figure 5, Figure 6a and Figure 7. In particular, the static coefficient of friction with a large hand (average estimated hand size = 164 cm$^2$) was on average 10% higher than that with a small hand (average estimated hand size = 136 cm$^2$) under the same normal force in the present study ($p < 0.05$) (see Figure 7). Moreover, the static coefficient of friction was, on average, 13% higher when the entire palm was in contact compared to when only fingertips were in contact with the object under the same normal force (see Figure 5, Figure 6a, Table 3). Increase in coefficient of friction for a larger contact area has been thought to be attributed to more adhesion taking place between the two surfaces (Tomlinson *et al.* 2007a). This implies that having more contact with an object, e.g. by using a palm instead of fingertips, yields a higher ratio of friction force to normal force.

The effects of both the normal force and contact area on the coefficient of friction can be shown in a combined form, pressure (normal force/contact area) in Figure 6c, for the present study as well as for previous studies (Comaish and Bottoms 1971, Bullinger *et al.* 1979, Bobjer *et al.* 1993). A consistent trend can be found among these studies; that is, the coefficient of friction non-linearly increases as pressure decreases in a similar manner that can be found between the coefficient of friction and normal force (Figure 6b). High correlation coefficients were found between the log of the static coefficient of friction and the log of pressure in the present study ($R^2 = 0.40$ to 0.73), but they were not as high as those with the normal force. This difference may be attributed to the roughly estimated contact area in this study. As shown by Bullinger *et al.* (1979) and Bobjer *et al.* (1993), increasing normal force deforms skin, thus increasing the contact area between the skin and an object. The present study could not separate the effects of the contact area and the contact force on friction. Contact area was only approximated by the width and length of a hand or fingertips. This approximation method may have introduced error in estimating the real area of contact. Measuring a contact area using hand prints as described by Bullinger *et al.* (1979) and Bobjer *et al.* (1993) would help study the relationship between the coefficient of friction and pressure in greater precision.

### 4.3. *Comparison of* $\mu_s$ *with Buchholz et al. (1988)*

The common materials between this study and Buchholz *et al.* (1988) are cardboard (paper) and aluminium. The static coefficients of friction for cardboard and aluminium measured in this study were compared with those for paper and aluminium in Buchholz *et al.* (1988). In the present study, the average static coefficient of friction for cardboard was 0.46 for a normal force of 8.9 to 27.0 N. For aluminium, the average static coefficient of friction was 1.11 for a normal force of 6.0 to 21.3 N. In Buchholz *et al.* (1988), the average static coefficient of friction was 0.29 for paper and 0.36 for aluminium when each fingertip had a normal force of 22 N. Normal force of 22 N for each fingertip means a total of 110 N for the five fingertips (uniform force distribution assumed). When the normal force of 110 N and an average hand size of 150 cm$^2$ are plugged into the regression model in Table 4, the static coefficient of friction is calculated to be 0.27 and 0.47 for cardboard and aluminium, respectively. Even though cardboard is not exactly the same material as the computer paper used in Buchholz *et al.* (1988), the estimated static coefficient of friction from the regression model, 0.27, was almost the same as that measured in Buchholz *et al.* (1988), 0.29. However, for aluminium, the estimated static coefficient of friction from the regression model, 0.47, was still 31% higher than that measured in Buchholz *et al.* (1988), 0.36. It should be noted that 110 N is quite beyond the range of the normal force measured in the present study (6.0–21.3 N for aluminium), which may explain the difference. Furthermore, the difference in surface finish could have resulted in the difference in the static coefficient of friction between the present study and the study by Buchholz *et al.* (1988). It is quite conceivable that the extent to which aluminium was polished may be different between the studies and Bobjer *et al.* (1993) have shown that different surface textures result in different coefficients of friction. Comparison of coefficients of friction between studies requires careful consideration, not only of variables but also of methodologies and material preparation.

### 4.4. *Variance between subjects*

The coefficient of friction varied between subjects to a greater extent than between trials within subject. This difference in friction coefficient between subjects may be due to difference in perspiration rate and skin roughness between subjects. In the present study, skin moisture level was not controlled to the same degree as Adams *et al.* (2007), which may have contributed to the high inter-subject variability. However, the resulting variance is representative of conditions that occur when products or work objects are used. Therefore, not only the mean but also the range of the coefficient of friction should be considered in design of work objects for the general population.

### 4.5. *Future studies*

In the present study, only contact with a flat surface was investigated, with uniform force distribution assumed. Future studies should examine 3-D objects, such as cylinders, and different hand postures that would result in different contact area and force distributions. It has been shown that different contact areas result in different coefficients of friction. The total friction force can be described as a sum of local friction forces. Each local friction force is an outcome of the local normal force multiplied by the coefficient of friction at that pressure level. If the relationship between the log of the coefficient of friction and the log of pressure is indeed linear, then different force distributions – changes in local coefficients of friction – cause different total friction force. This means that the coefficient of friction differs by force distribution under the same total normal force. Therefore, a close investigation of the coefficient of friction in relation to contact area and force distribution is desired. It would enable the estimation of friction forces at various configurations.

Another desired study would be an investigation of the effect of the friction force build-up rate on the static coefficient of friction or the speed of tilting in the tilt method. A constant speed of tilting, 15°/s, was maintained in this study. Increasing tilt speed might lead to overestimating the slip angle. At the same time, it might lead to slippage at a lower angle due to inertia and less viscous deformation of the skin. Further investigations need to quantify the effect of tilt speed.

Only one operator analysed the entire data in this study. Future studies should examine if the static coefficient of friction data would differ by operators. It should quantify how much variance in the static coefficient of friction would be attributed to different operators.

This study examined the static coefficient of friction for the palm (whole palmar side of the hand) and the fingertips only. The coefficient of friction may vary depending on local regions within the hand. For example, the static coefficient of friction for the fingertip may be different from that for the palm centre due to potential difference in hydration. Future studies may examine the static coefficient of friction for different sites of the hand.

### 4.6. *Impact of this study*

The simple tilt method described in this paper would allow industrial and product designers to readily estimate the static friction coefficient data and thus incorporate this information into their designs. Improvements in surface friction of work objects would help prevent injuries due to slippage of handles in domestic as well as occupational settings. It would also enhance the efficiency of the force transfer from the body to external objects and, thus, the control of an object by the hand.

## 5. Conclusion

- A simple tilt method can be used to measure the static coefficient of friction between the hand and other materials readily in the field, except when using materials with high coefficients of friction.
- The static coefficient of friction for the hand increased with increasing contact area and with decreasing normal force. The result compared favourably with previous studies.
- Further investigations of the static coefficient of friction in relation to contact area, force distribution, surface shape and friction force build-up rate will allow the estimation of friction forces in various task configurations and properties.

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