Friction coefficients in a longitudinal direction between the finger pad and selected materials for different normal forces and curvatures

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This study investigated the effect of object curvature, normal force and material on skin friction coefficient. Twelve subjects slid their middle fingertip pad against a test object with small (11 mm), medium (18, 21 mm) or large (flat object) radii of curvature, while maintaining a normal force of 1, 10 or 20 N. Tested materials were aluminium and four rubber hoses. The average friction coefficient was 0.6 for aluminium and 0.9 for the rubber hoses. As normal force increased from 1 to 20 N, the average friction coefficient decreased 46%. Friction coefficient did not vary significantly with object curvature. The citation of friction coefficient data requires careful attention to normal force levels with which they are measured, but not so much to object curvature between 11 mm and infinity. This study provides skin friction coefficient data that are needed for design of objects that are manipulated with the hands. The investigation of the effect of object curvature on skin friction coefficient has important implications to ergonomics practices as many objects handled in everyday activities have curved surfaces.

Keywords: coefficient of friction; skin friction; surface curvature; skin deformation; hand friction

1. Introduction

1.1. Significance

Friction coefficient data are needed for design of objects and workstations to improve efficiency in force generation, to ensure that required force for completing a task does not exceed one's strength capacities and to prevent injuries due to slippage. High friction materials allow wheelchair users to push the wheelchair wheels with less muscle effort (Richter *et al.* 2006, Seo *et al.* 2008a) and consumers to open bottles and containers more easily (Nagashima and Konz 1986, Imrhan and Farahmand 1999, Seo *et al.* 2007, 2008b). High friction materials also allow workers to use screwdrivers or other hand tools with less force (Frederick and Armstrong 1995, Laroche *et al.* 2007) and to have greater rope-pulling capabilities (Wu *et al.* 2008). Low friction handles cause slippage of the hand, which leads to injury (Malker 1991 cited in Bobjer *et al.* 1993, Rubin *et al.* 2007). High force exertions due to the use of low friction objects can result in fatigue, pain, musculoskeletal disorders or injury (Rohmert 1973, Bystrom and Kilbom 1990, Bystrom and Fransson-Hall 1994, Kutluhan *et al.* 2001, National Research Council and Institute of Medicine 2001, Kao 2003, Wei *et al.* 2003). Cai *et al.* (2005) observed that fats reduce friction on tools used in the meat industry where the incidence of musculoskeletal disorders and other injuries is 3.5 times greater than other comparable industries.

1.2. Factors for friction coefficient: Normal force, contact area

While skin friction coefficient data are needed for the design of work objects or consumer products, the data are limited. Not only are friction coefficients unique for each material in contact with the hand (Buchholz *et al.* 1988, O'Meara and Smith 2002, Ohura *et al.* 2005, Laroche *et al.* 2007, Seo *et al.* accepted), it has also been shown that the friction coefficient for skin varies with normal force (Comaish and Bottoms 1971, El-Shimi 1977, Buchholz *et al.* 1988, Bobjer *et al.* 1993, Koudine *et al.* 2000, Sivamani *et al.* 2003, Seo *et al.* accepted) and contact area (Comaish and Bottoms 1971, Bullinger *et al.* 1979, Seo *et al.* accepted), contrary to the classical friction law by Amonton (1699) and Coulomb (1785).

The relationship between friction coefficient, contact area and normal force can be modelled by describing friction coefficient as a function of contact pressure (normal force divided by contact area). Using the data in Bobjer *et al.* (1993), the friction coefficient

for the finger pad in contact with a flat polycarbonate surface can be modelled as a log function of contact pressure (see Figure 1).

1.3. Relationship between contact area and curvature

Previous studies have shown that friction coefficient is related to contact area (Comaish and Bottoms 1971, Bullinger et al. 1979, Seo et al. accepted). The contact area is expected to be related to object curvature, as described hereafter. The contact area between a fingertip and an object can be estimated by the following equation provided in Timoshenko and Goodier (1970), assuming that the fingertip and the object are spheres:

$$\text{Contact area} = \pi \left[\frac{3}{4} F_n \frac{R_1 R_2}{R_1 + R_2} \left\{ \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right\} \right]^{2/3} \tag{1}$$

where F_n is normal force, R_1, v_1, and E_1 are the radius, the Poisson's ratio and the Young's modulus for the test object and R_2, v_2, and E_2 are the radius, the Poisson's ratio, and the Young's modulus for the fingertip. This equation suggests that the contact area increases with increasing radius of curvature of the object, as shown in Figure 2. This argument agrees with a simulation study by Wu and Dong (2005), who demonstrated that the contact area was, on average, 24% less for an object with a 12-mm radius of curvature than for a flat object (radius of curvature = ∞); however, their study did not expand on investigation of friction coefficient.

1.4. Study objectives

Even though many objects handled in everyday activities have curved surfaces, the effect of object curvature on friction coefficient has not been investigated. Previous friction coefficient measurements were conducted either on a flat object against skin (Comaish
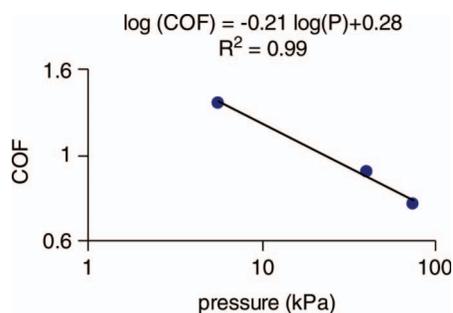
and Bottoms 1971, Bullinger et al. 1979, Buchholz et al. 1988, Bobjer et al. 1993, Seo et al. accepted) or a curved object only (Koudine et al. 2000, O'Meara and Smith 2002, Sivamani et al. 2003, Laroche et al. 2007). Therefore, this study investigates the effect of object curvature on friction coefficient for different normal force levels and for five materials commonly used in assembly plants.

2. Method

2.1. Procedure

A fractional factorial experiment was conducted in which coefficient of friction (dependent variable) was measured for selected materials, normal forces and radii of curvature (independent variables). The five materials tested were aluminium and four rubber hoses – hose A, B, C and D (see section 2.3 for the details of each hose). Normal force levels tested were 1, 10 and 20 N. The maximum normal force level tested was limited by the 5th percentile middle fingertip strength in full interphalangeal joint extension, 20.8 N (Li et al. 2000). Three radii of curvatures tested were small (11 mm), middle (21 or 18 mm) and large (∞: flat object). Aluminium and hoses A and B were tested for all three radii of curvatures, whereas hoses C and D were tested only for the small or middle radius of curvature, respectively.

Upon their arrival at the laboratory, subjects washed their hands with soap, rinsed with water and dried with paper towels 10 min prior to testing, to eliminate artefacts due to contaminants (Comaish and Bottoms 1971, Buchholz et al. 1988). Test objects with different radii of curvature and materials were presented horizontally to subjects in a random order. Subjects pressed down their middle fingertip pad against the test object until normal force matched the

Figure 1. Relationship between coefficient of friction (COF) and pressure (P in kPa) for the index finger in log scales using data from Bobjer et al. (1993).
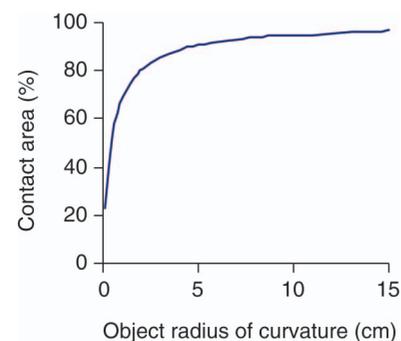

Figure 2. Expected contact area between the fingertip and an object as a function of object radius of curvature can be calculated using Equation (1) by Timoshenko and Goodier (1970). The radius of the fingertip is assumed to be 8 mm (Buchholz and Armstrong 1991). The contact area is normalised to that for a flat object.

target displayed on a computer screen. Then subjects pulled their finger towards the body, while maintaining the normal force at the target (see Figure 3). Normal force and friction force (pulling force) were recorded throughout a trial. Two LEDs were placed on the dorsal part of the middle fingertip and on the test object in order to capture the moment the fingertip started sliding on the test object (the next two paragraphs show the detailed procedure to determine the moment of finger slip). Friction coefficient was calculated as a ratio of normal force to friction force at the moment the finger slipped, as described previously (Amonton 1699, Coulomb 1785, Comaish and Bottoms 1971, Blau 1996, Koudine *et al.* 2000, O'Meara and Smith 2002, Sivamani *et al.* 2003, Laroche *et al.* 2007). Each condition was tested twice. The experiment consisted of a total of 66 trials, lasting for about 1 h.

The skin deforms in the longitudinal (distal-proximal) direction with friction force. So the movement of the LED on the middle fingertip nail is not the same as the movement of the volar epidermis of the middle fingertip pad. Therefore, a pilot study was performed in which the amount of longitudinal skin deformation was measured for normal force of 1, 10 and 20 N for three materials (aluminium, hoses A, B) and for two subjects (one male, one female). Using a ballpoint pen, two points were drawn on the lateral side of the middle fingertip, one at the dorsum of the middle fingertip, one at the volar middle fingertip pad. While a subject pressed down the middle fingertip against a test object at a target normal force and slid the fingertip proximally, the lateral side of the middle fingertip was videotaped (as shown in Figure 3).

Longitudinal skin deformation is the difference in the horizontal distance between the two points on the lateral fingertip at the beginning, when the finger is being pressed down, and at the end, when the middle fingertip pad slipped on the test object, as shown in Figure 3. Figure 4 plots longitudinal skin deformation as a function of normal force for aluminium and the two rubber hoses. Longitudinal skin deformation was not significantly different between two subjects (difference $= 0.1 \pm 0.3$ mm, $p > 0.05$) and between hose A and hose B ($p > 0.05$). Thus, two subjects' data were pooled and results for hoses A and B were combined in Figure 4. The average longitudinal skin deformation for aluminium was 0.25, 0.75 and 1.1 mm for target normal force of 1, 10 and 20 N, respectively. The average longitudinal skin deformation for the rubber hoses was 0.7, 1.0 and 1.6 mm for target normal force of 1, 10 and 20 N, respectively. Therefore, the LED's movement greater than these values for each condition was used as a threshold for skin slip.

2.2. Subjects

In total, 10 subjects (five males and five females) voluntarily participated in this study. Their mean age was 25 ± 6 years for males (ranging from 19 to 35 years) and 26 ± 4 years for females (ranging from 18 to 29 years). Subjects were university students or office workers. No callus, skin thickening or over-dryness was observed on their hands. They gave written informed consent prior to testing.

2.3. Apparatus

Aluminium rods of different radii were machined and polished with 100 grit sandpaper and then finished with a Maroon very fine Scotch-Brite pad (3M, St. Paul, MN). The roughness estimated using S-22
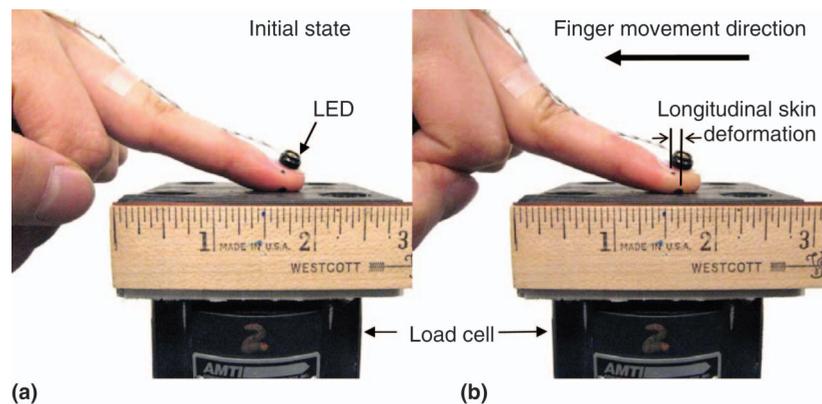
Figure 3. Fingertip pad making a contact with a test object on top of a load cell (no friction force applied yet) (a) and fingertip pulled towards the body (b). The picture on the right side was taken right before the fingertip pad slipped on the test object. The longitudinal skin deformation was estimated as a horizontal distance between two black dots, one right below the LED and the other one at the contact between the finger and the test object (right).
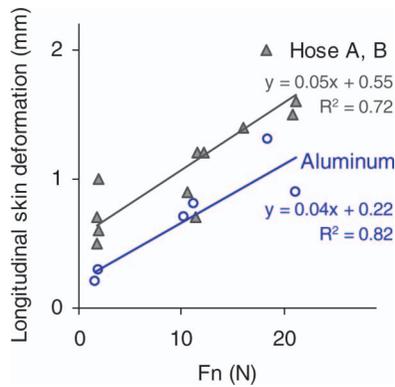
Figure 4. Longitudinal skin deformation (see Figure 3) as a function of normal force for rubber hose A and B (up, ▲) and for aluminium (down, ○)

Figure 5. Surface character of hose A.

Microfinish Comparator (GAR Electroforming Division, Danburg, CT) was 0.8 μm. Hose A was manufactured by Thermoid/HBD Industries, Inc (Bellefontaine, OH). It had a black textured surface with groove width of 0.7 mm and pitch of 0.1 mm (see Figure 5). Its maximum tensile strength was 0.37 MPa. Hoses B, C and D were from an automotive assembly plant. They had a black smooth surface and they were manufactured by Goodyear Inc (The Goodyear Tire and Rubber Company, Akron, OH). Hose B is a general radiator hose. It has minimum modulus of 4.5 MPa, minimum tensile strength of 4.9 MPa after oven ageing and minimum burst strength of 1.9 MPa. Hose C is used at the outlet of a radiator. It has minimum modulus of 4.5 MPa, minimum tensile strength of 5.3 MPa after oven ageing and minimum burst strength of 2.1 MPa. Hose D is used as a heater hose. The original (outer) radius was 18 mm for hose A, 21 mm for hoses B and C and 11 mm for hose D. To vary the radius of hoses A and B, a side of a hose was cut along the long axis and the hose's inner surface was glued to an aluminium rod of a smaller radius (to simulate the small radius of 11 mm) or to an aluminium plate (to simulate the large radius of curvature, r = ∞).

The test object was attached to a load cell, which measured normal force and friction force. The fingertip movement was recorded by OptoTrak® Certus™ Motion Tracking System (NDI; Waterloo, ON, Canada), which tracked the positions of LEDs on the fingertip throughout trials. Both force and position data were recorded at 30 Hz.

2.4. Statistical analysis

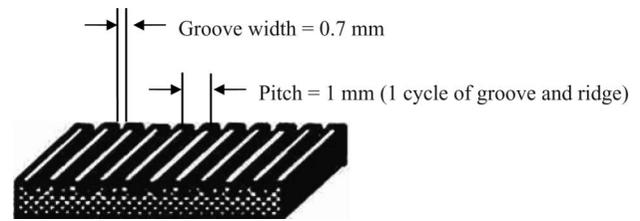Repeated measures ANOVA was performed to test whether friction coefficient is significantly associated with material, normal force, radius of curvature and their second-order interactions. Subjects were treated as a random variable. For factors that showed significant effects, Tukey pairwise comparisons were performed to evaluate differences between each level. MINITAB® (Minitab Inc., State College, PA, USA) Release 14 was used to perform statistical analyses.

3. Results

Friction coefficients for the five materials, three normal force levels and radii of curvature are summarised in Table 1. Material and normal force were found to be significant for friction coefficient ($p < 0.01$ for both), whereas the radius of curvature was not found significant ($p > 0.05$), as shown in the ANOVA table in Table 2. None of the second-order interactions was found to be significant (Table 2).

Average friction coefficient was 58% greater for the rubber hoses than for aluminium ($p < 0.01$). However, friction coefficients were not significantly different among the four rubber hoses, as shown in the pairwise comparison in Table 3 ($p > 0.05$). Average friction coefficient significantly decreased 46% as normal force increased from 1 to 10 N (material pooled; $p < 0.01$), as shown in Figure 6. The coefficient of friction did not significantly change between normal forces of 10 and 20 N, as shown in Table 3. Friction coefficient significantly varied with subject for rubber hoses ($p < 0.05$). It did not significantly vary with subject for aluminium ($p > 0.05$). Among-subject variance was twice greater than within-subject variance.

4. Discussion

4.1. Friction coefficient vs. curvature

Friction coefficient in the axial direction was not significantly associated with test object curvature for radius of curvature ranging from 11 mm to ∞ (flat object). Even though object curvature can be associated with less contact area and higher peak pressure for a given normal force (Wu and Dong 2005), the magnitude of those changes may not have been great enough to significantly alter friction coefficient. Using Equation (1), it can be calculated

Table 1. Mean $\pm$ SD friction coefficient for the five materials, three curvatures and three normal force levels (F_n) (12 subjects pooled).

Material	Target F_n (N)	Radius of curvature	Measured F_n (N)	COF	Average
Aluminium	1	∞ (flat)	1.6 $\pm$ 0.7	0.6 $\pm$ 0.4	0.6 $\pm$ 0.4
		21 mm	1.2 $\pm$ 0.3	1.0 $\pm$ 0.5	
		11 mm	1.4 $\pm$ 0.5	0.9 $\pm$ 0.5	
	10	∞ (flat)	10.8 $\pm$ 1.3	0.4 $\pm$ 0.3	
		21 mm	9.9 $\pm$ 0.6	0.5 $\pm$ 0.2	
		11 mm	10.2 $\pm$ 0.8	0.4 $\pm$ 0.1	
	20	∞ (flat)	19.6 $\pm$ 1.9	0.4 $\pm$ 0.2	
		21 mm	19.1 $\pm$ 2.0	0.4 $\pm$ 0.2	
		11 mm	18.7 $\pm$ 2.0	0.4 $\pm$ 0.2	
Hose A	1	∞ (flat)	1.3 $\pm$ 1.1	1.3 $\pm$ 0.7	0.8 $\pm$ 0.5
		18 mm	1.5 $\pm$ 0.6	1.2 $\pm$ 0.5	
		11 mm	1.9 $\pm$ 1.9	1.4 $\pm$ 0.6	
	10	∞ (flat)	10.7 $\pm$ 1.3	0.6 $\pm$ 0.2	
		18 mm	10.0 $\pm$ 1.1	0.6 $\pm$ 0.3	0.8 $\pm$ 0.5
		11 mm	9.8 $\pm$ 0.7	0.7 $\pm$ 0.3	
	20	∞ (flat)	19.5 $\pm$ 1.4	0.6 $\pm$ 0.2	
		18 mm	19.0 $\pm$ 1.3	0.6 $\pm$ 0.3	
		11 mm	19.0 $\pm$ 1.8	0.6 $\pm$ 0.2	
Hose B	1	∞ (flat)	1.9 $\pm$ 1.1	1.1 $\pm$ 0.5	0.9 $\pm$ 0.5
		21 mm	1.5 $\pm$ 0.6	1.1 $\pm$ 0.8	
		11 mm	1.4 $\pm$ 0.5	1.2 $\pm$ 0.5	
	10	∞ (flat)	10.0 $\pm$ 1.1	0.8 $\pm$ 0.4	
		21 mm	9.5 $\pm$ 1.0	0.7 $\pm$ 0.3	
		11 mm	9.8 $\pm$ 0.9	0.8 $\pm$ 0.2	
	20	∞ (flat)	19.4 $\pm$ 1.8	0.7 $\pm$ 0.3	
		21 mm	18.3 $\pm$ 2.1	0.7 $\pm$ 0.3	
		11 mm	17.9 $\pm$ 2.1	0.7 $\pm$ 0.3	
Hose C	1	21 mm	1.6 $\pm$ 0.8	1.2 $\pm$ 0.6	0.9 $\pm$ 0.5
	10	21 mm	9.8 $\pm$ 1.0	0.8 $\pm$ 0.3	
	20	21 mm	18.5 $\pm$ 2.1	0.7 $\pm$ 0.3	
Hose D	1	11 mm	1.5 $\pm$ 0.6	1.3 $\pm$ 0.6	0.9 $\pm$ 0.5
	10	11 mm	10.2 $\pm$ 1.2	0.7 $\pm$ 0.3	
	20	11 mm	18.6 $\pm$ 1.7	0.7 $\pm$ 0.3	

COF = coefficient of friction.

Table 2. ANOVA table for the coefficient of friction data in Table 1.

Source	DF	Adj SS	Adj MS	F	p
Subject	9	9.5095	1.0566	7.46	0.000
Material	4	4.1757	1.0439	7.37	0.000
Target normal force (F_n)	2	6.2069	3.1035	21.92	0.000
Radius of curvature	2	0.3247	0.1623	1.15	0.318
Material*F_n	6	0.8118	0.1353	0.96	0.455
Material*Radius of curvature	3	0.5028	0.1676	1.18	0.315
F_n*Radius of curvature	3	0.1767	0.0589	0.42	0.742
Error	609	86.2339	0.1416		
Total	638				

DF = degree of freedom; Adj SS = adjusted sum of squares; Adj MS = adjusted mean square.

that the contact area for a test object with the small radius of curvature, 11 mm, is 30% less than that for a flat test object, when the radius of the fingertip (R_2) is assumed to be 8 mm (Buchholz and Armstrong 1991). According to Wu and Dong (2005), the contact area for a test object with the radius of curvature of 12 mm is approximately 29% less than that for a flat test object for a normal force of 1 N. With the difference in contact area, pressure is also expected to differ by 30% on average. When the relationship between the logarithm of friction coefficient and the logarithm of pressure is inverse proportional with a slope of –0.21 as shown in Equation (1) and Figure 1, the friction coefficient is expected to differ by 7% between a flat object vs. an object with the radius of curvature of 11 mm. This 7.1% difference in friction coefficient was not experimentally demonstrated.

4.2. Friction coefficient vs. material

This paper reports friction coefficients for five selected materials that are prevalent in industry, for three

normal force levels and radii of curvature. Friction coefficients were not significantly different among the rubber hoses examined in this study; however, friction coefficients were significantly greater for the rubber hoses than for aluminium. The average friction coefficient for the four rubber hoses was 0.9, whereas the average friction coefficient for aluminium was 0.6. Comparisons of the coefficient of friction values with previous literature are discussed below.

4.3. Friction coefficient vs. normal force

Consistent with previous studies (Comaish and Bottoms 1971, El-Shimi 1977, Buchholz et al. 1988, Bobjer et al. 1993, Koudine et al. 2000, Sivamani et al. 2003, Seo et al. accepted), friction coefficients decreased with increasing normal force, especially for a low normal force range (Figure 6). Friction coefficients measured in this study were compared to those in previous studies (Buchholz et al. 1988, Seo et al. accepted) for

Table 3. Tukey multiple comparisons for the mean coefficient of friction between each material and each normal force level.

Factors	Levels	Tukey test
Material	Aluminium	a
	Hose A	b
	Hose B	b
	Hose C	b
	Hose D	b
Normal force	1 N	a
	10 N	b
	20 N	b

Note: The coefficient of friction for aluminium (group 'a') was significantly different than those for hoses A, B, C and D (group 'b'). The coefficient of friction for normal force of 1 N (group 'a') was significantly different for those for normal forces of 10 N and 20 N (group 'b'). The coefficient of friction was not significantly different between the four hoses or between the normal forces of 10 N and 20 N.

aluminium and rubber (hose) in Figure 7. Normal force on the middle fingertip pad in Seo et al. (accepted) was assumed to be an eighth of total normal force on the five fingertips (based on Kinoshita et al. 1996). Friction coefficient values in this study were not significantly different from those in the previous studies when compared for closest normal force levels ($p > 0.05$; see Figure 7).

Since friction coefficient may vary with normal force, citation of a friction coefficient value should be for the same or similar normal force levels only. In other words, when a biomechanical analysis requires a friction coefficient value, use of a friction coefficient measured for a higher or a lower normal force level than that in the analysis may result in underestimation or overestimation of friction coefficient, respectively. Average normal contact force during maximum torque exertions for females was reported to range from 4 to 22 N for one fingertip (other than the thumb) and from 22 to 45 N for the thumb (Seo and Armstrong 2006, Seo et al. 2007, 2008b, Chang et al. 2008). For males, it ranges from 10 to 43 N for one fingertip and 39 to 93 N for the thumb (Seo and Armstrong 2006, Seo et al. 2007, 2008b). Thus, the normal force range for which friction coefficients were measured in this study (1 to 20 N) may cover females' average normal force levels on the fingertip during maximum torque exertions; however, it may not cover the normal force levels on the thumb or males' average normal force levels during maximum torque exertions. With an increasing normal force level, however, friction coefficients become less sensitive to normal force as shown in Figure 6, Table 3 and Figure 7 (Note that friction coefficient and normal force in Figure 7 are in log scales). Therefore, it is more critical for low normal forces (less than 10 N) than for high normal forces to ensure that a normal force level used for measurement of a friction coefficient is similar with that for a biomechanical analysis.
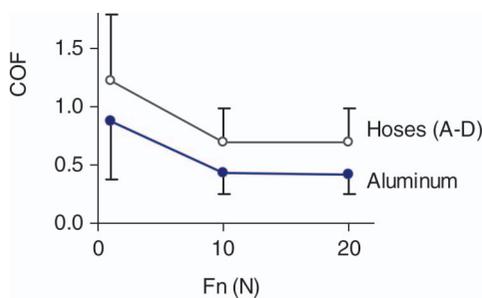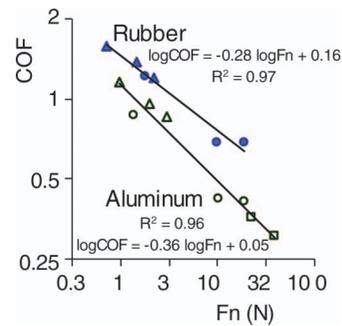

Figure 6. Friction coefficient between the fingertip and rubber hoses (up) and between the fingertip and aluminium (down) for three different normal force (four rubber hoses and subject pooled). COF = coefficient of friction.

Figure 7. Friction coefficient as a function of normal force for rubber (filled symbols) and for aluminium (unfilled symbols) from three studies ($\triangle$, Seo et al. accepted; $\circ$, the present study; $\square$, Buchholz et al. 1988) in log scales. COF = coefficient of friction.

4.4. *Friction coefficient vs. subject*

Friction coefficient between aluminium and finger skin did not vary significantly among subjects; however, friction coefficient between the rubber hoses and finger skin varied significantly among subjects. This among-subject variance (0.23 on average) was about twice greater than the average within-subject variance (0.13). It is possible that the surface of rubber hoses could have been polished from repetitive rubbing by the fingertip and changed its friction characteristics over time. However, no consistent trend between friction coefficient and test orders was observed over time. Significant between-subject variance may also be due to difference in perspiration rate and skin roughness between subjects.

4.5. *Limitation*

The present study examined skin friction coefficient in the longitudinal direction only. The coefficient of friction and skin deformation can be different when friction force is in a direction tangential to the radius of curvature or at the right angle to the finger. Future studies should investigate the effect of friction force direction on skin coefficient of friction and skin deformation.

Longitudinal skin deformation was measured only for two subjects in this study. Even though the amount of longitudinal skin deformation was found to be not significantly different between the two subjects, the relationship between skin deformation and force level still needs to be further investigated for the general population empirically or by simulation. Investigation of skin deformation with friction force can also be used for blister studies (Dai *et al.* 2006, Polliack and Scheinberg 2006, Xing *et al.* 2007) and pressure ulcer treatment (Ohura *et al.* 2005).

5. Conclusions

- Friction coefficients differ between aluminium and rubber, but not between different rubber hoses examined in this study.
- Friction coefficient decreased 46% as normal force increased from 1 to 20 N. It means that maximum coupling with maximum grip should assume the minimum friction coefficient.
- Friction coefficient did not vary significantly with object curvature. As shown in the contact area and friction coefficient calculations, changes in the contact area and pressure level were not enough to result in a significant change in friction coefficient, for object curvatures tested in this study.

- The citation of friction coefficient data requires care for normal force levels with which it was measured, but not so much for object curvature between 11 mm and infinity.

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