Evaluation of friction behaviour on human finger skin considering precision grip task

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Abstract. Human hands perform daily different tasks and the fingers skin comes in contact with many surfaces and objects. Grip task of objects can be performed by using different combination of the fingers. Precision grip task is influenced by several factors which decide the grip force of the individuals performing the task. This study aims to evaluate in vivo the coefficient of friction (COF) between a steel cylinder and the skin of fingers’ phalanges from both hands for three healthy subjects. The experiments were realized in a reciprocating-sliding contact with normal loads of 1 N and 2 N and sliding speed of 1 mm/s. Also, indentation tests were realized in order to determine the skin deformation of the fingers phalanges under normal loads. The indentation results show that distal phalanges (fingertip) play a significant role in deciding the grip force. The friction tests reveal that the coefficient of friction varies between 0.3 and 1.1 along the fingers phalanges according to the age, gender and skin structure of the test subjects. The distal phalanges of index and middle fingers showed the highest value of the coefficient of friction in the case of the subjects that mainly use the right hand. These aspects can be considered in developing devices for grip and sensing tasks applications.

1. Introduction

Human skin is the biggest organ in the human body. It is a complex structure material composed of three layers (epidermis, dermis and subcutaneous fat) with different mechanical properties. It is very important to understand skin friction in particular though as this plays a critical role in many tasks of daily living [1] and leisure activities [2,3] that involve gripping, feeling and manipulating objects.

When a product slides over the skin, the lateral friction force acting at the skin-product interface is governed by both adhesion and deformation phenomena and is affected by many factors. The mechanical contact parameters are vertical load, loading duration, contact pressure and sliding speed [4]. Factors of skin conditions include surface topography, anatomical sites, sebum level, and moisture level [5,6], which can vary depending on the gender and age of subjects [7]. Factor of intermediary substance include the presence of water or cosmetic products [5].

There are a lot of papers in literature that studied skin tribology and one of the major limitations is the inherent variability between human test subjects. There is large scatter in almost all in vivo measurements related to skin. Coefficient of friction, for example, can vary between 0.1 and 2.5 for the same type of test and the effective Young’s modulus between 4 kPa and 57 MPa [8]. Also, testing methods used to study the skin friction are very different. Reciprocating-sliding of a rigid body or plane surface on soft skin is mainly used. Spherical probes such as steel ball and cylinder (PTFE, Aluminium, Polyamide) and smooth or rough surfaces (glass, paper, rubber, plastics) were slides
against various anatomical skin sites (forearm, fingertip, abdominal, palm) at different loads and sliding speeds [1-4,6,7,9-13].

When reciprocating-sliding a small spherical rigid body on soft skin the material surrounding the contact area is cyclically deformed and relaxed; friction and lateral skin displacement cause the skin to become compressed in front of the probe, forming a “bow-wave”, and stretched behind. The bow-wave formation results in wrapping of the skin over the probe surface on its leading side. This causes a rotation of the normal force vector and leads to extra resistance in the direction of sliding. Recently, in order to avoid the formation of the bow-wave the authors proposed a new testing methodology by using a steel cylinder perpendicular to the finger in order to have a constant deformation and contact pressure during the reciprocating-sliding tests. Firstly, the effective Young modulus of the finger skin can be determined from the indentation process by fitting the experimental data with the Hertzian’s deformation theory. Secondly, the authors have obtained very interesting “butterfly” curves for the coefficient of friction never reported in literature that evidenced the lateral deformations of the finger tissue and the sliding phases [14-17].

In precision grip task, adequate amount of grip force is applied and regulated proportionately to load force fluctuations. The grip force applied exceeds the minimal force required to avoid slips. Safety margin is the excess force determined by the friction between the skin and the object. Moreover continuous variations in the grip force, suggest that fingertip moisture impacts grip force strategy. Patients with palmar hydrosis or excessive sweating have difficulties in object manipulation and show increased coefficient of friction [18].

Thus, the strategies underlying grip force mechanisms alter with the number of the fingers that grasp the object, the contact region along the fingers phalanges and the levels of fingertip moisture. Beside the friction behaviour of the fingertip there are no studies that reveal the deformation and the coefficient of friction on the other fingers phalanges that can be significant for the safety and stability of grip tasks.

The aim of this paper is to evaluate the lateral deformation and the coefficient of friction of the fingers phalanges. The results evidence differences in mechanical and frictional behaviour of the finger phalanges for both hands according to gender, age and skin structure of three subjects.

2. Experimental details

2.1. Participants

Experiments were carried out in vivo using a smooth steel cylinder probe reciprocating-sliding against the fingers from both hands of three healthy subjects without any hand dysfunction or neurological disorders: male (37 and 67 year-old) and female (34 year-old). No preparations were made prior to the measurements in order to capture the natural condition of their daily lives, including ageing effect.

2.2. Test and equipment

Indentation and friction tests were carried out using Tribometer UMT 2 (Bruker) equipped with a dual friction/load sensor up to 20 N: normal load ($F_N$) in vertical direction (carriage moves up-down), tangential force ($F_T$) and friction force ($F_f$) in horizontal direction (slider moves left-right). The hand of each subject was horizontal placed on the table of tribometer and relaxed during the tests. Figure 1 shows the general view of the tribometer and the contact between the cylinder and the finger phalanges.

The tribometer can monitor all the test parameters such as normal load, tangential force, vertical and horizontal displacement, time and velocity. The coefficient of friction (COF) is automatically calculated in the UMT control software as the ratio between friction force and normal load.

Indentation tests were carried out by imposing to the carriage a 4 mm vertical displacement that presses the cylinder on the finger at a velocity of 0.1 mm/s. The normal force ($F_N$) resulting as the reaction force of the finger tissue in vertical direction was captured by the load cell of the tribometer.
Indentation tests were realized on the fingers phalanges of all the test subjects in room conditions. Experimental data of force and displacement were used to evaluate the mechanical behaviour of the fingers. The relevant test parameters for friction tests are summarized in Table 1.

Table 1. Experimental conditions for indentation test.

| Test parameters                  |       |
|----------------------------------|-------|
| Probe cylinder diameter          | 6.96 mm|
| Probe cylinder length            | 40 mm |
| Vertical displacement            | 4 mm  |
| Indentation speed                | 0.1 mm/s|
| Skin condition                   | "Dry" skin |
| Environment                      | 22°C, 50% relative humidity |
| Anatomical sites                 | Fingers phalanges of hands |
Table 2. Experimental conditions for friction test.

| Test parameters                  |                   |
|----------------------------------|-------------------|
| Probe cylinder diameter          | 6.96 mm           |
| Probe cylinder length            | 40 mm             |
| Normal force, $F_z$              | 1 N and 2 N       |
| Sliding velocity, $v$            | 1 mm/s            |
| Stroke length                    | 60 mm             |
| Skin condition                   | “Dry” skin, washed and dried skin |
| Environment                      | 22°C, 50% relative humidity |
| Anatomical sites                 | Fingers phalanges of hands |

3. Results and discussion

3.1. Indentation of the finger skin

Figure 2 illustrates the variation of the normal force with the imposed displacement for the index and middle finger phalanges on the left hand of young man. The minus sign is because the reaction force acts in the upper normal direction of the load cell.

![Figure 2](image)

From Figure 2 it can be observed that the deformation behavior under indentation process is different along the finger phalanges due to the size, geometry and structure of the phalanges tissue. Distal and middle phalanges show higher force at a maximum of 4 mm displacement for both index and middle finger. The maximum indentation forces for both index and middle finger phalanges of 37 year-old man left hand are summarized in table 3.

Figure 3 illustrates the variation of normal load with deformation of the distal phalange from the middle finger according to the gender of the test subjects. It can be observed that young man has the highest force at a deformation of 4 mm compare to the other subjects. The maximum indentation forces for distal phalax from right middle finger of test subjects are summarized in table 4. We supposed that this difference is because the finger skin of the old man is become less elastic due to the ageing. Therefore, we supposed that the old man needs to apply at least twice the grip force that of young man in order to lift an object, as was previously reported [19]. This remark can be also valid to the young woman.
Table 3. Indentation results for left hand of 37 year-old man subject.

| Finger | Phalanx | Maximum indentation force [N] |
|--------|---------|-----------------------------|
| index  | distal  | 12.5                        |
|        | middle  | 10.3                        |
|        | proximal| 2.4                         |
| middle | distal  | 7.2                         |
|        | middle  | 5.2                         |
|        | proximal| 3.4                         |

Figure 3. Indentation results for all test subjects.

Table 4. Indentation results test subjects.

| Test subject     | Maximum indentation force at distal phalanx of right middle finger [N] |
|------------------|------------------------------------------------------------------------|
| Male 37 year-old | 9                                                                      |
| Female 34 year-old| 2                                                                      |
| Male 67 year-old | 2.8                                                                    |

3.2. The coefficient of friction on finger phalanges

Figure 4 illustrates the typical variation of the tangential force as function of the position of the probe along its stroke. In all cases, the skin friction behavior showed a “stick” or static friction phase when the probe start the movement and change the direction with no relative sliding between the cylinder and the skin surface, followed by a “slip” phase in which relative sliding occurs.

The friction behaviour can be described as follows, begin from the start point: during the initial stick phase, elastic deformation of the skin occurs and friction force increase until sliding occurs. At the end of the stroke the friction force is still non-zero because the skin is still strained elastically. During the following stick phase in the reverse direction, as the skin relaxes, the friction force decreases, passes through zero and the increases again at the same value but with reversed sign as the elastic deformation of the skin is repeated in the opposite direction.
Figure 4. Typical variation of friction force as function of probe lateral position.

Figure 5 and 6 shows the coefficient of friction for old man subject determined immediately after the skin was washed with soap and dried and “dry” skin, respectively. Normal load applied to the probe was 2 N and the sliding velocity of 1 mm/s. In table 5 are summarized the average values of the coefficient of friction measured for left hand middle finger phalanges in both test conditions.

Table 5. Friction results for left hand middle finger phalanges of 67 year-old subject.

| Phalanx | Average coefficient of friction |
|---------|--------------------------------|
|         | Skin washed and dried | “dry” skin |
| distal  | 1.06                | 0.56   |
| middle  | 0.76                | 0.35   |
| proximal| 0.5                 | 0.45   |
Figure 6. COF vs time for the middle finger phalange from left hand of old man – “dry” skin condition.

From figure 5 it can be observed that after the hand is washed and dried due to a low level of sebum on the skin, the coefficient of friction for the distal phalange (fingertip) is about 1 and decrease to 0.4 - 0.5 for proximal phalange. Figure 6 shows that when the skin is in “dry” condition, usually during the daily lives at office for example, the coefficient of friction is twice as small for distal phalange and about 0.2 - 0.3 for middle phalange compared to the washed and dried skin condition. This may be significant in determining the grip force for many precision grip tasks.

In figure 7 and 8 are illustrated the coefficient of friction for young man and young woman, respectively, on the middle finger phalanges from left hand measured in “dry” skin condition at a normal load of 1 N and sliding velocity of 1 mm/s. It can be observed that the coefficient of friction for young man is similar compared to the old man with some small differences on the distal phalange. In the case of the young woman higher values for coefficient of friction were observed that can appear due to a relative higher level of moisture and sebum on his hand. We mention that the temperature of his hand was lower than the temperature of the young man. In table 6 are summarized the average values of the coefficient of friction for left middle finger phalanges of young test subjects in “dry” skin condition.

Figure 7. COF vs time for the middle finger phalanges from left hand of young man at Fz=1 N and sliding velocity v=1 mm/s, “dry” skin.
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Figure 8. COF vs time for the middle finger phalanges from left hand of young woman at $F_s=1$ N and sliding velocity $v=1$ mm/s, “dry” skin.

Table 6. Friction results for left hand middle finger phalanges of young test subjects in “dry” skin condition.

| Phalax     | Average coefficient of friction | Male 37 year-old | Female 34 year-old |
|------------|---------------------------------|-------------------|--------------------|
| distal     |                                 | 0.65              | 0.88               |
| middle     |                                 | 0.46              | 0.8                |
| proximal   |                                 | 0.32              | 0.75               |

3.3. The coefficient of friction on the distal phalanges from left and right hand

The results show that the coefficient of friction varies from left to right hand for the test subjects. This may be due to the difference in the skin structure and the preference in using the left or right hand. In figure 9 and 10 are presented the variation of the coefficient of friction with time for left and right hand of young man.

Figure 9. COF vs time for distal phalange on left hand fingers of young man, “dry” skin
From figure 9 it can be observed that the coefficient of friction for the fingertip of index and middle fingers are quite lower than the coefficient of friction for ring and little fingers. In contrast, from figure 10 it can be observed that the coefficient of friction for the fingertip of the index and middle fingers from right hand are higher than the other fingers. This may be explained by the fact that young man is using more the right hand and for that the grip force is calibrated according to the friction and skin structure. In table 7 are summarized the average values of the coefficient of friction for distal phalanx of index, middle, ring and little finger from left and right hand in “dry” skin condition.

![Figure 10. COF vs time for distal phalange on right hand fingers of young man, “dry” skin](image)

**Table 7.** Friction results on distal phalanx of young male fingers subject for left and right hand in “dry” skin condition.

| Finger | Average coefficient of friction |
|--------|--------------------------------|
|        | Left hand | Right hand |
| index  | 0.54      | 0.7        |
| middle | 0.6       | 0.74       |
| ring   | 0.82      | 0.48       |
| little | 0.76      | 0.52       |

Figure 11 and 12 illustrate the variation of the coefficient of friction on distal phalanges of fingers for the young woman. The differences in the coefficient of friction of the fingers are more clearly evidenced on the right hand of the female subjects with values of up to 1 for the distal phalange of the index finger. On the left hand the coefficient of friction of the fingers is more appropriate with a mean value of 0.7. Therefore, the differences between hands can be explained by the same reason as in the case of male subjects such as the preference in using the right hand in daily activities. In table 8 are summarized the average values of the coefficient of friction for distal phalanx of index, middle, ring and little finger from left and right hand in “dry” skin condition.

**Table 8.** Friction results on distal phalanx of young female fingers subject for left and right hand in “dry” skin condition.

| Finger | Average coefficient of friction |
|--------|--------------------------------|
|        | Left hand | Right hand |
| index  | 0.7       | 1.04       |
| middle | 0.72      | 0.88       |
| ring   | 0.88      | 0.72       |
| little | 0.64      | 0.6        |
Figure 11. COF vs time for distal phalange on left hand fingers of young woman, “dry” skin

Figure 12. COF vs time for distal phalange on right hand fingers of young woman, “dry” skin

Figure 13 shows the images taken with a microscope in order to evidence the surface structure of the finger phalanges. The results obtained in friction tests can be correlated also with the skin structure. The ridges of distal phalanges (fingerprint) are responsible for the highest values of the coefficient of friction and force because they are primary used in sensing, manipulating and gripping tasks. The middle and proximal phalanges have different pattern of the ridges and this is related with lower values of the coefficient of friction. These phalanges are not mainly used for sensing tasks but are important for the safety and stability of the prehension when the objects are grasping with all the fingers.
4. Conclusions

In this paper the authors studied the deformation and the friction behavior of the human fingers skin along the phalanges for three human subjects. The mechanical and frictional behavior of the fingers skin was evaluated according to the experimental methodology recently proposed by the authors.

The mechanical behavior of the finger skin was evaluated in the indentation process by pressing a steel cylinder on the fingers phalanges with a controlled displacement at an indentation velocity of 0.1 mm/s. The indentation results suggest that fingers phalanges have different mechanical behavior. The distal phalanges (fingertips) have the highest elasticity and thus can apply the highest grip force. This is due to the reason that the distal phalanges are primarily used in touching, sensing and gripping the surface and objects. Considering the age, gender and skin structure, the results showed that the fingers skin of old man and young women is stiffer and to have a certain level of force in a grasp task they need to apply at least twice the grip force that of young man. Thus, the stiffness of the finger skin can influence the precision of grasping and manipulating the objects, especially the small objects.

Friction tests were performed by laterally driven a steel cylinder perpendicular to the finger in a reciprocating-sliding fashion. As we expected, the friction results evidenced that the distal phalanges have the highest values of the coefficient of friction due to the ridges (fingerprint) from the surface skin. The other phalanges have lower values of the coefficient of friction due to the skin structure, especially for male subjects. We have observed that the coefficient of friction of the finger phalanges for the female subject showed to be quite similar with high values of up to 1. Also, the results clearly evidenced the differences in the friction behaviour from left and right hand.

Our findings suggest that the type of grip is influenced by the contact region between the fingers and the object in terms of friction and finger skin deformation. Also, the grip force and friction can be different from left to right hand.

For further directions, the authors take into account to determine the tangential elastic modulus (Coulomb) and to develop a mathematical model of the frictional behaviour for the finger skin considering precision grip tasks.
5. References

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