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Investigation of Experimental Devices for Finger Active and Passive Tactile Friction Analysis

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Abstract

Complicated tribological behavior occurs when human fingers touch and perceive the surfaces of objects. In this process, people use their exploration style with different conditions, such as contact load, sliding speed, sliding direction, and angle of orientation between fingers and object surface consciously or unconsciously. This work addressed interlaboratory experimental devices for finger active and passive tactile friction analysis, showing two types of finger movement. In active sliding experiment, the participant slid their finger freely against the object surface, requiring the subject to control the motion conditions themselves. For passive sliding experiments, these motion conditions were adjusted by the device. Several analysis parameters, such as contact force, vibration acceleration signals, vibration magnitude, and fingerprint deformation were recorded simultaneously. Noticeable friction differences were observed when comparing active sliding and passive sliding. For passive sliding, stick-slip behavior occurred when sliding in the distal direction, evidenced by observing the friction force and the related deformation of the fingerprint ridges. The employed devices showed good repeatability and high reliability, which enriched the design of the experimental platform and provided guidance to the standardization research in the field of tactile friction.

Keywords Finger friction, Experimental device, Active sliding, Passive sliding, Rotating

1 Introduction

Touch is an essential sense for humans to perceive the external environment. During the process of tactile perception, the finger slides over the surface of an object and different mechanoreceptors are stimulated by skin deformation and produce electrical signals that are transmitted to the cerebral cortex. The frictional behavior of contacts in which the human fingerpad is one of the interacting partners is often referred to as tactile friction [1–3]. The tribological mechanism in the contact is intricate, due to the complex mechanical, physiological and pathological properties of skin. Analyzing the tactile friction behavior of the finger could deepen our understanding of the mechanisms involved in tactile perception [4, 5] and is important for the tactile design of intelligent robots [6–8], as well as for the comfort-focused design of products and packaging [9, 10].

Developing a highly accurate experimental device to assess and analyze tactile friction has great significance. Using these devices, a range of finger touch parameters could be varied, including sliding, grasping, lifting, rotating, tapping, vibrating, static touching, and touching with a specific tool. Table 1 shows an overview of experimental devices described in the literature to analyze various finger touch behaviors [11–22]. André et al. [11] used

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Table 1 Experimental devices used in previous research for different modes of touch including sliding, tapping, rotating and vibrating

First author (Year)	Mode of touch	Analysis parameters
Andre (2011) [11]	Sliding	Contact force, skin deformation
Fagiani (2012) [12]	Sliding	Contact force, acceleration signal
Liu (2013) [13]	Sliding	Friction force, normal force
Nagano (2014) [14]	Sliding	Shear force, sliding displacement and vibration cues
Zhang (2016) [15]	Sliding	Contact force, acceleration signal
Messaoud (2016) [16]	Sliding	Contact force
Gueorguiev (2017) [17]	Sliding	Contact force
Sümer (2018) [18]	Sliding	Contact force, acceleration signal
Serina (1997) [19]	Tapping	Contact force and fingertip vertical displacement
Jindrich (2002) [20]	Tapping	Fingertip position and contact force
Lewis (2007) [21]	Rotating	Human torques used in opening bottles and jars
Soneda (2010) [22]	Vibrating	Contact area, contact load

an optical apparatus and a force sensor to record the skin deformation and tangential force during finger sliding, in which the applied normal force was controlled by the participants. Nagano et al. [14] designed an apparatus that made it possible to apply precisely controlled shear forces, sliding displacements and vibration cues to the fingerpad via a moving surface in the radial and ulnar directions. Zhang et al. [15] developed a device that could control the normal force and the orientation between the finger and sample surface, the acceleration vibration was also recorded during the finger passive sliding in the proximal and distal direction. Sümer et al. [18] investigated an experimental set-up for finger active sliding, measuring the contact force, sliding velocity and acceleration signals. Jindrich et al. [20] developed an apparatus for measuring fingertip position and fingertip force during a tapping task. Lewis et al. [21] designed a jar-like device to record the torque whilst opening the lid of the jar. Soneda et al. [22] measured the apparent and real contact areas of the fingerpad and the vibrotactile thresholds under a controlled contact load by using an exciter with a total-reflection prism. These experimental devices for the analysis of finger tactile friction behavior mainly focus on a single mode of touch, whilst recording the various mechanical signals. The sliding motion may be divided into active sliding and passive sliding; during active sliding experiments people actively slide their finger against a tactile stimulus, whilst during passive sliding experiments the tactile stimulus is mounted onto a sample table that is typically driven by a mechanical device, whilst the finger is held in a fixed position.

To better understand the differences between active and passive sliding, this research discussed and compared results obtained from active and passive finger sliding movements, using two different setups, one at Imperial College London (IC), UK, and the other at Southwest Jiaotong University (SWJTU), China. Figure 1 shows the function of devices, representing active movement for the IC device and passive movement for the SWJTU device. This passive movement was performed using a recently developed set-up with a modular design, enabling both sliding and rotating. The devices were all calibrated before the experiment. Different mechanical and dynamical signals and fingerprint deformation were recorded accurately and simultaneously [1, 23].

2 Sample and Preparation

Polytetrafluoroethylene (PTFE) specimens with dimensions of 30 mm × 70 mm × 1.5 mm were selected in this study. Three PTFE plates, noted as PTFE#1, PTFE#2 and PTFE#3 with increasing surface roughness were used. Table 2 displays optical images of the PTFE samples, measured using a confocal laser microscope (Olympus, OLS5000), showing obvious roughness differences. Detailed information can be found in Ref. [24].

3 Active Finger Sliding

3.1 Participant

One male Asian postgraduate student, aged 26 years old, from Imperial College London was recruited in this experiment. The index finger of the dominant hand was used in the research. All tests were performed in situ and were noninvasive. All measurements were conducted at room temperature of 24±1° with a relative humidity of 27%–55%. The study protocol was approved by the Imperial College London Science, Engineering and Technology Research Ethics Committee (SETREC), reference 20IC6258.

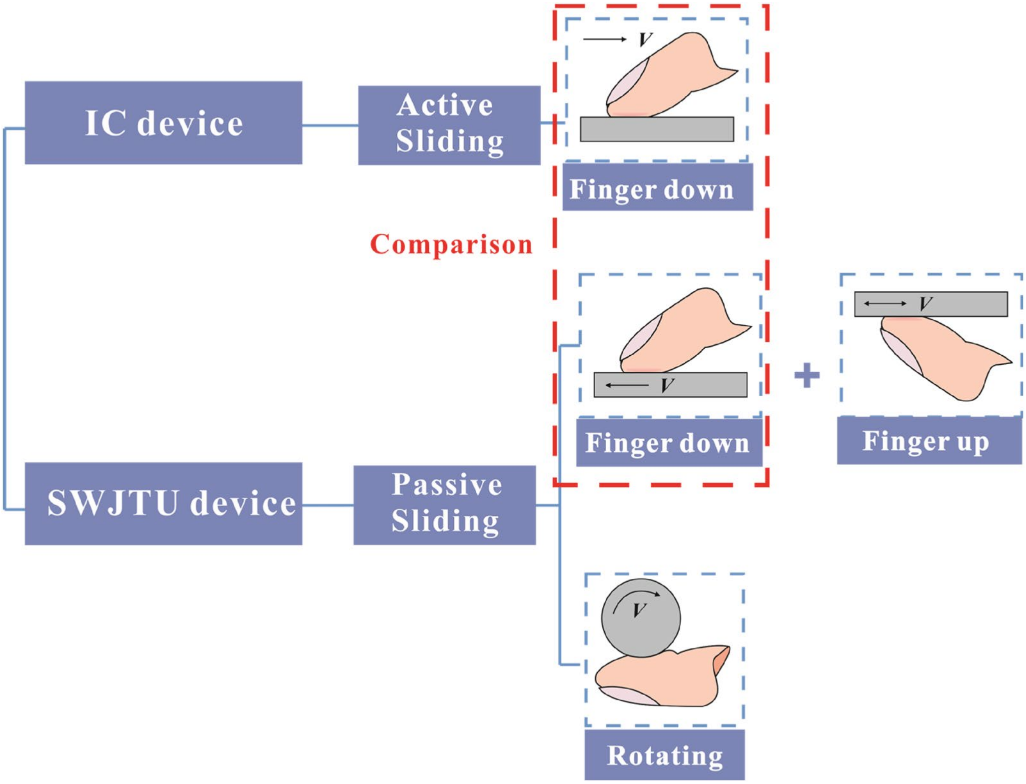


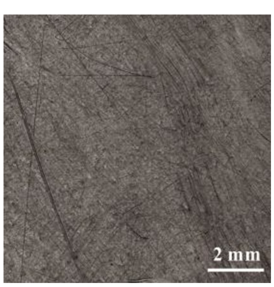
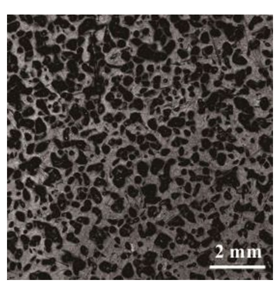
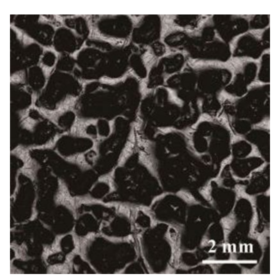
Figure 1 Schematic of different functions for IC and SWJTU device

3.2 Experimental Device and Procedure

A three-axis force/torque transducer as shown in Figure 2 (Gamma, ATI Industrial Automation, Apex, NC, USA) [1] was used in the experiment. The ATI force transducer measures the forces and torques with six degrees of freedom. This means that the normal force (z-direction) and the two forces in the tangential or xy-plane were measured, as well as the torques around the x, y and z-axes. The sensing range of the force measurement was 65 N in the tangential direction and 200 N in the normal direction, with a resolution of 12.5 mN and 25 mN respectively. The sampling frequency was set at 10 kHz.

A petri dish with a glued PTFE sample was attached to the load cell, using double-sided adhesive tape. The participant actively slid the index finger in the x-direction (towards his body) whilst applying a normal load of 1 ±

Table 2 Information on PTFE samples including surface roughness S_q and optical images

Sample	PTFE#1	PTFE#2	PTFE#3
S_q (μm)	4.11	20.76	67.17
Optical image			

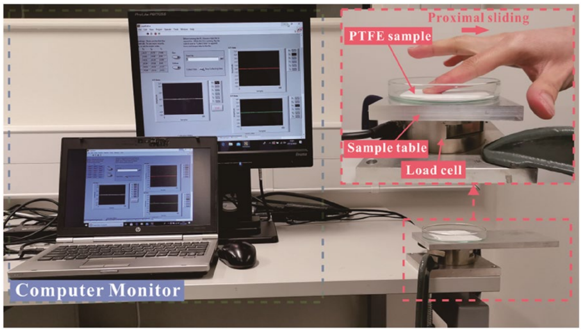


Figure 2 Experimental set-up for active finger sliding

0.1 N. The angle of orientation between the finger and the sample surface was measured using a protractor to be approximately 30°. The participant was asked to complete the sliding motion along the entire length of the 70 mm long sample within 7 s, corresponding to a nominal sliding speed of 10 mm/s. The participant was allowed to familiarize himself with the motion conditions (force, velocity and finger orientation) prior to commencing the formal test, since the conditions need to be controlled artificially. He was also asked to clean the finger with hand sanitizer before each test to reduce the influence of grease and moisture on the finger. The measurements were repeated three times for each PTFE sample.

3.3 Results

Figure 3 shows the various experimental parameters measured during a single-finger sliding action. From the measured dataset, the friction coefficient was calculated as the ratio of the total tangential load (friction force) and the normal force, as shown in Figure 3(a). The sliding phase is indicated by the red dotted box. The normal force fluctuated around 1 N, and the mean friction coefficient was 0.67. The sliding displacements in the x-and the y-direction and the sliding speed captured in the sliding region are displayed in Figure 3(b). The sliding speed of the finger was calculated from the sliding displacement for each time step, i.e. for each measurement point, the moment around the axis perpendicular to the sliding direction was divided by the normal load, providing a location, or distance from the perpendicular axis. As participants were asked to move their fingers in the x-direction, the sliding displacement in the y-direction was relatively constant at 0, whilst the displacement in the x-direction increased approximately linearly. The total sliding distance was about 60 mm. The average velocity obtained during the measurements was 10.06 ± 3.07 mm/s, indicating that the velocity, as controlled by the participant, showed a significant oscillation.

Figure 4 shows the friction coefficient measured for the three PTFE samples. The average friction coefficient for the smooth specimen PTFE#1 exceeded 1 and the friction coefficients for the rougher specimens PTFE#2 and PTFE#3 were lower and had a similar value. This indicates that the coefficient of friction tends to decrease with the increase of surface roughness. Each sliding motion against the same test sample was performed three times, and the standard deviation was shown using error bars.

The fast Fourier transform (FFT) was used to convert the friction force signal from its original time domain to a representation in the frequency domain. The relevant frequency spectra for active sliding against PTFE#3 are shown in Figure 5. In this case, the dominant frequencies of 96.21 and 234.42 Hz were not obvious with relatively low magnitude values.

4 Passive Finger Sliding

4.1 Participant

In this experiment, three postgraduate students, two males and one female ranging in age between 25–27 years old, were recruited from Southwest Jiaotong University, to perform three different tasks respectively. All participants volunteered and signed a statement "I voluntarily participate in the current scientific experiment and I currently have no physical problems and have had no mental disorders within the last 6 months". The index finger of the dominant hand was used in the experiments. Participants were required to clean their fingers with hand sanitizer 2 min before each measurement. All measurements were performed in situ and were noninvasive. All the tests were conducted at the same ambient temperature of 25±1 °C and relative humidity of 60%–70%. The study protocol was approved by the Medical Ethics Committee of Southwest Jiaotong University, reference SWJTU-2106-005(BS).

4.2 Experimental Device

The custom experimental device is characterized by the modular design, using MCU-based embedded designs to perform data and command control, as well as finger contact movement including sliding and rotating movement. Figure 6 shows a block diagram of the control cabinet. The microprogrammed control unit (MCU) was connected to the PC through an actuating part (PL-2303) and connected to the LCD screen device (for key input monitor) through a universal asynchronous transmitter (UART). In the control cabinet, two types of motor operations could be performed: the sliding part was carried out by controlling an actuator; the rotating part was operated by loading the drive chip (ULN2303A) for transmitting the pulse signal to the server. In addition, MCU could read the ambient temperature through an analog-to-digital converter (ADC), use infrared light sensor to adjust the displacement of the sample table and initialize the relevant position, connect the gyroscope through UART to read the value of contact angle between the finger and the sample surface. The whole device used a direct current (DC) power supply.

The set-up installed on a vibration-reduction platform, with a 2 kHz data acquisition system (Jiangsu Donghua Testing Technology Ltd., China), is shown in Figure 7. The device has a modular design (Figure 7(a)) allowing a range of different contact configurations, including finger sliding and a rotating movement of a specimen. The purple dashed line shows the finger sliding part, indicating two possible configurations of 'finger down' and 'finger up' by changing the sample table and the position of the finger support. The device is equipped with an emergency stop button which participants may press when they feel uncomfortable during the test. In that case, the test will stop.

For sliding movement (Figure 7(b)), a contact microphone (CM-01B from TE connectivity, with a sensitivity of 40 V/mm) was installed in the sample table and used to measure the vibration magnitude in the finger-sample contact. A load cell (3CXX strain gauge three-axis force transducer, Nanli Sensing Apparatus) with a measurement range of 100 N and a resolution of 5 mN was installed under the sample table and connected to a servo motor through an adapter plate. The motor was used to adjust the height position of the sample table for performing different loading conditions. These above parts

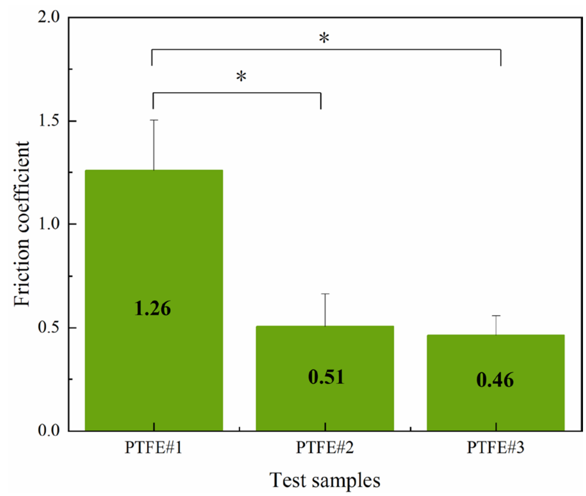


Figure 4 Friction coefficient measured for three PTFE samples. Each test was performed three times, the error bars indicate the standard deviation. The "*" indicates a significant difference ($p < 0.05$) between two results

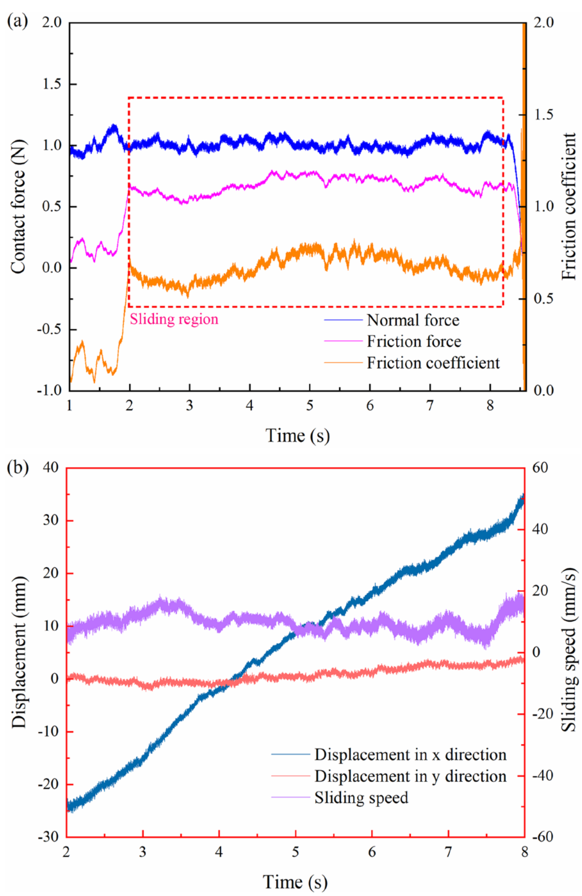


Figure 3 Analysis parameters for active sliding against PTFE#3, including (**a**) contact force and friction coefficient, (**b**) sliding displacement and sliding speed

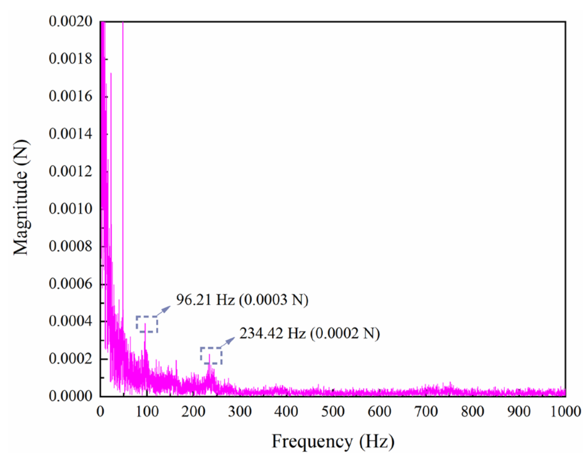


Figure 5 The frequency spectra of friction force signal measured in active sliding against PTFE#3 with dominant frequencies of 96.21 and 234.42 Hz

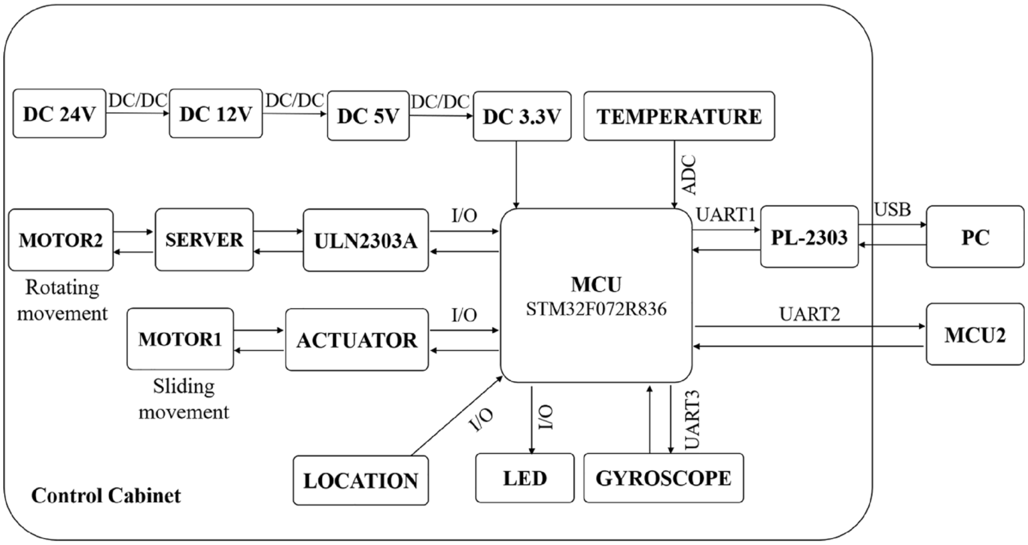


Figure 6 Block diagram of control cabinet of experimental set-up

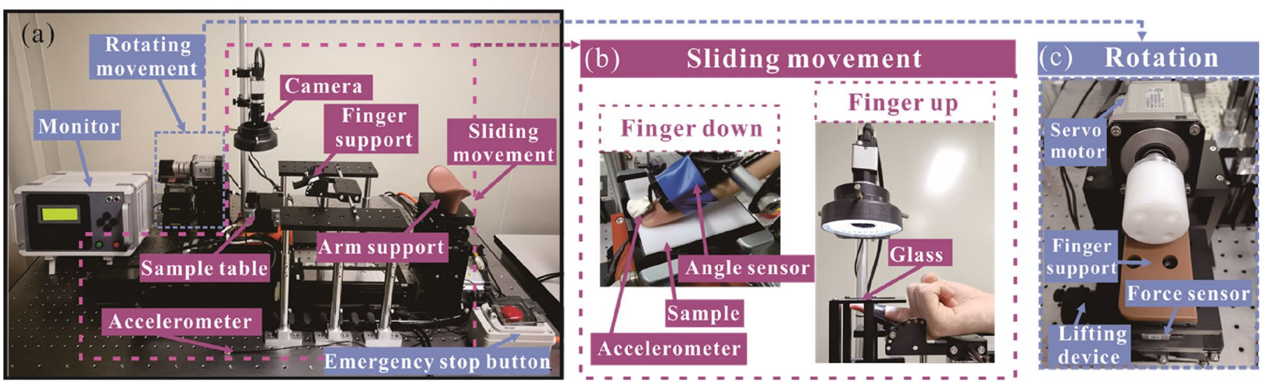


Figure 7 (**a**) Experimental set-up with modular design, (**b**) Two types of sliding movement, including two configurations of 'finger down' and 'finger up', (**c**) Passive test with rotating sample

were implemented on a ball screw-driving device driven by a stepper motor that moves the sample table back and forth over a distance of 600 mm with a sliding speed ranging between 0 and 100 mm/s. Fingers can be placed on finger support with an angle sensor (Triple-axis MEMS gyroscope MPU-9250, InvenSense Inc.) allowing measurement of the angle between the finger and test sample. An accelerometer (MXR7250VW, MEMSIC Inc., with a measurement range of $\pm$5 g and a resolution of 250 mV/g) was glued on the fingernail to measure the vibration signals in the finger sliding contact. The arm of participants could be placed on the arm support mounted on a lifting device allowing adjust its height to increase the comfort level for participants during the test. However, participants were asked to relax their fingers after every three sliding tests. Performing tests over long durations using the finger support would possibly congest the finger skin and cause an indentation. In the 'finger up' configuration, the sample table was replaced by a glass sample table to enable visualization using a camera. The camera with a frame rate of 815 s^{-1} and a resolution of 640 $\times$ 480 pixels was used to record the contact area of the finger. A monitor showing several experimental data, including the angle of orientation, motion state, movement speed, etc., was used to control the position of the sample table.

For the passive test with a rotating sample (Figure 7(c)), to reduce the radial runout, a polycarbonate/acrylonitrile butadiene styrene (PC-ABS) sample was fixed on the central shaft of a stepper motor and the sample material could be replaced according to the specific experimental requirement. The set-up can rotate with a maximum velocity of 1525 r/min. A finger support was installed on two single-point load cells (F4802 with force measurement of 10 kg in the normal and tangential direction, WIKA Alexander Wiegand SE & Co. KG) through a lifting device. The loading force between the finger and PC-ABS sample was applied by manually adjusting the height of the lifting device. Rotating experiments may be used to assess friction and grip with curved surface products such as bottles and caps, balls, steering wheels, etc., making it useful for packaging design as well as for ergonomic research, which aims to improve comfort and functionality.

4.3 Procedure of 'Finger Down' Sliding and Results

One male participant was recruited to perform the 'finger down' test. The participant was asked to put his finger and arm into the relevant supports. The back of the finger was close to the clamp and wrapped with tape. The sample table was moved to the appropriate position below the finger and the contact was loaded by adjusting the table height. The experimental parameters were set to the same parameters of the active sliding test, with a normal load of 1±0.1 N, an orientation angle of 30±1°, and a sliding speed of 10 mm/s. The same three PTFE samples used in the active tests were used and measured three times in the test.

Figure 8 displays the analysis parameters for the finger sliding against PTFE#3. Figure 8(a) shows the normal force, friction force, and friction coefficient. The dashed red box indicates the sliding region, with an average normal force of 1±0.1 N, represented by the blue line, which shows no significant fluctuation. Figure 8(b) shows the vibration acceleration and vibration magnitude signals, describing a continuous movement against the PTFE sample, without obvious oscillations. An additional set of data (Figure 9) shows a similar trend compared to Figure 8. This illustrates the repeatability of the experiments and the reliability of the setup.

The mean friction coefficients measured for three different PTFE samples are shown in Figure 10, indicating mean values of 0.95, 0.88 and 0.64 for PTFE#1, PTFE#2 and PTFE#3 respectively. These values were calculated from the steady sliding region, marked red in Figure 8(a). It can be observed that the friction coefficients measured for PTFE#1 and PTFE#2 were similar and the value for PTFE#3 was the lowest. Figure 11 shows the frequency spectra for passive sliding against PTFE#3 through the fast Fourier transform with the dominant frequencies of 95.19 Hz and 508.08 Hz.

4.4 Procedure of 'Finger Up' Sliding and Results

Another male participant was asked to perform the 'finger up' test to investigate the effect of sliding direction on finger skin deformation. Two sliding directions were used, proximal (glass moving away from the human body) and distal (glass moving towards the body) respectively. The sliding speed of the sample table with the glass specimen was set to 5 mm/s. The orientation angle between the finger and the glass surface was 25±1°.

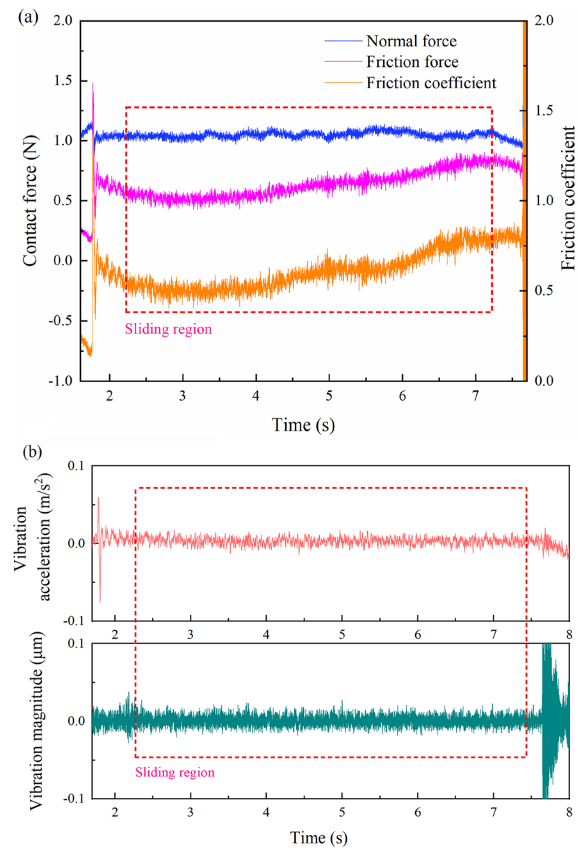


Figure 8 Analysis parameters for passive sliding against PTFE#3, including (**a**) contact force and friction coefficient, (**b**) vibration acceleration and vibration magnitude

Figure 12 shows the instant contact area and friction force in the proximal and distal directions. It can be observed that the fingerprint deformed differently, depending on the sliding direction. This corresponds to previous findings [15]. The contour of the contact area is indicated by the blue dashed line. For proximal sliding, the contact area between the finger and the glass increased compared to static contact. In addition, the radius of curvature of the fingerprint ridges decreased, and the distance between the fingerprint ridges increased. A smooth friction force without obvious fluctuations was measured, which indicates a state of full slip of the contact area, resulting in a continuous, stable and non-fluctuating movement. In the distal direction, the fingerprint ridges were squeezed together, and the distance between the ridges decreased. Two states of deformation in the

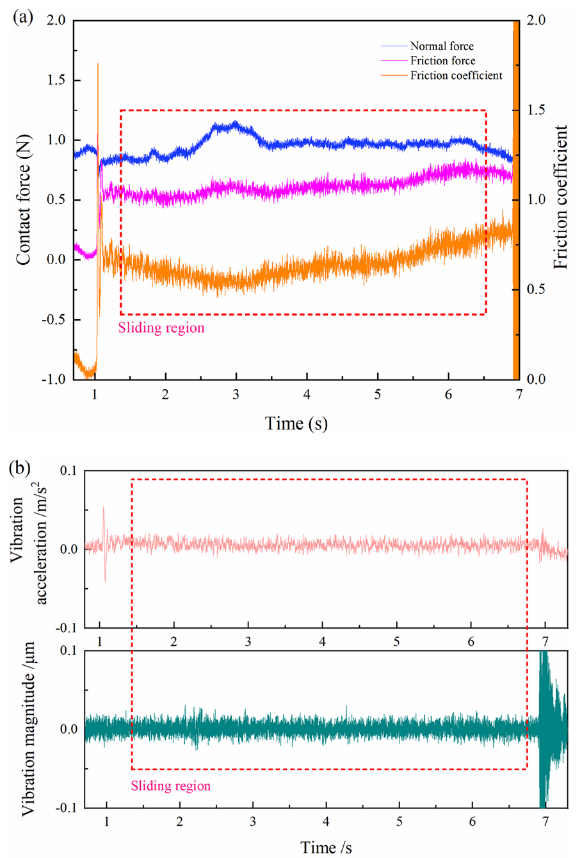


Figure 9 Analysis parameters for passive sliding against PTFE#3, including contact force, friction coefficient, vibration acceleration and vibration magnitude

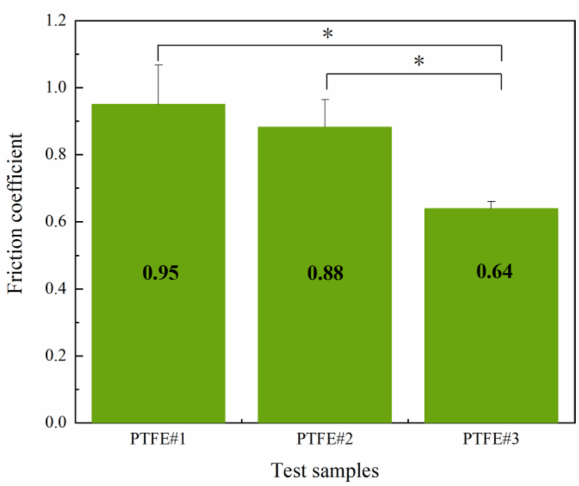


Figure 10 Friction coefficient measured for three PTFE samples. Each test was performed three times, the error bars indicate the standard deviation. The "*" indicates a significant difference ($p < 0.05$) between two results

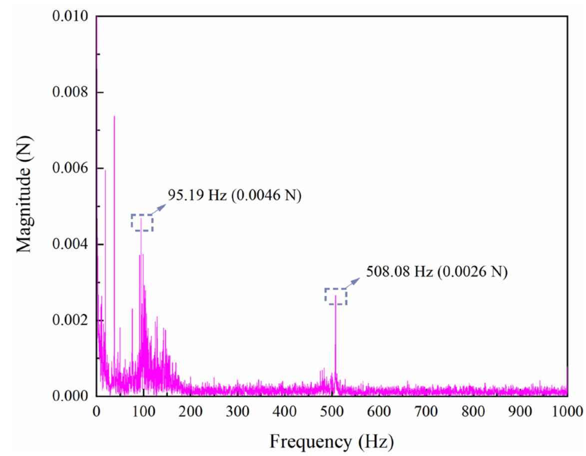


Figure 11 The frequency spectra of friction force signal measured in passive sliding against PTFE#3 with dominant frequencies of 95.19 and 508.08 Hz

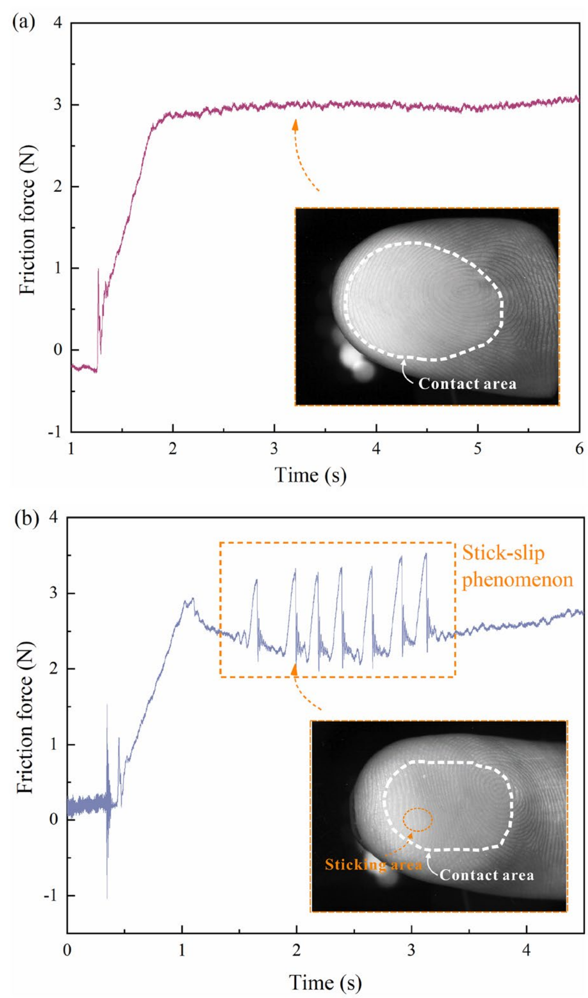


Figure 12 Friction force and contact area measured during the finger sliding (**a**) in the proximal and (**b**) distal direction

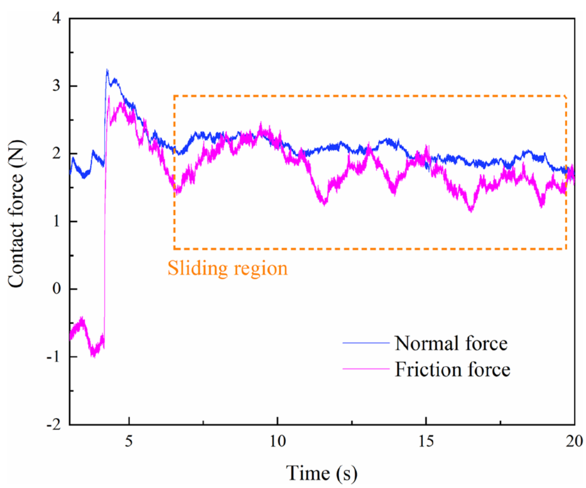


Figure 13 Normal force and friction force for rotating movement

contact area can be distinguished, including full slip and localized stick-slip. The relatively smooth part of the friction force curve indicated the full slip state, and there was no area where the skin and the glass were sticking. The large rise of friction force coincided with the development and growth of a sticking area inside of the contact zone. The periphery of this stick stayed in a slip state. A more detailed analysis of the dynamics of fingerpad contacts is provided in Refs. [23, 25], in which it was shown that the stick-slip behavior occurred more easily in distal sliding compared to proximal sliding, and also occurred more easily at reduced sliding speeds.

4.5 Procedure of Rotating Movement and Results

One female participant was recruited for the rotating specimen test. The index finger was placed on the finger support, and the loading force between the finger and the PC-ABS sample with a diameter of 35.2 mm was adjusted through the lifting device. The normal force was set as 2 ± 0.1 N, and the angle of orientation was 0°. The rotating direction was clockwise with a rotating speed of 12 r/min.

Figure 13 shows the contact force for finger rotating movement, including normal force and friction force. The normal force shows a relatively stable curve, and the friction force is with obvious oscillations during the rotating movement. The normal force fluctuated around 2 N with a mean value of 2.03 N in the sliding region.

5 Discussion

Two types of finger sliding were introduced and compared in this paper, active finger sliding and passive finger sliding performed using two different experimental setups. The device at IC, for active touch, was mainly comprised of a force transducer, that recorded the forces and torques along the three axes. The device at SWJTU, for passive touch, had a modular design allowing both sliding and rotating movement whilst measuring a range of mechanical and dynamical signals as well as fingerprint deformation. More details about the two types of behavior will be discussed below.

5.1 Active Finger Sliding

Sliding freely on different surfaces of objects is a normal and comfortable method for humans to touch and perceive the external environment. Motion conditions, such as the sliding speed, normal load, orientation angle and sliding direction, are normally changed both consciously and unconsciously to better identify the object's surface. However, in the study, the participant was asked to control these parameters within narrow bands. To enable this, the participant was required to familiarize himself with different motion conditions before the formal experiments commenced. The normal force could be controlled by observing the real-time measured load on the computer monitor. Figure 3(b) showed that the sliding speed fluctuated significantly around the prescribed value of 10 mm/s with a large standard deviation, indicating that the velocity profile was unstable during the sliding. Under the premise of the existence of individual differences, this would result in certain randomness to experimental results and be not conducive to the trend analysis of data. Indeed, Ref. [25] showed that the effect of velocity on friction values measured in tactile sliding can be substantial.

5.2 Passive Finger Sliding

The passive experiments were performed by fixating the finger in the set-up, and subsequent loading against a moving sample. The motion conditions were all adjusted and controlled by the device. It means that the experimental data are relatively stable and reproducible. The force measurement and dynamical signals show smooth movement against the PTFE sample. The 'finger up' configuration can be easily transformed by changing the sample table and the orientation of the finger support. In this part, the fingerprint deformation and contact force were recorded simultaneously and dynamically. In the proximal direction, the finger sliding showed a relatively stable movement by showing a smooth, relatively constant friction force. In the distal direction, a large rise of friction force indicated the occurrence of stick-slip in the contact. Such asymmetric frictional behavior in two sliding directions is modulated by a range of factors, including the external force and variations in the skin stiffness, which are influenced by the geometry of the finger, including the fingernail, as well as the different friction properties in the two sliding directions [23].

By comparing the friction coefficient, it can be found that for active sliding, high friction occurred for the smooth sample, and lower and similar values of friction for the two rough surfaces. In passive sliding, the individual differences were smaller, whilst similar values of friction were measured for the smooth surfaces PTFE #1 and #2 and lower friction for the rougher PTFE#3. By comparing the dominant frequency of friction fore signals by using FFT, all the frequency peaks fell between 0–1000 Hz which corresponds to the range of perceived frequency of the mechanoreceptors [26]. The dominant frequency shows 96.21 and 234.42 Hz with lower magnitude values for the active sliding and shows 95.19 and 508.08 Hz for the passive sliding. The value of the first dominant frequency was similar in the two sliding types while the second one was different. These results pose an interesting case, and it is hypothesized that the different trends of friction results for active and passive sliding might be caused by the two sliding types. As the motion of the finger is affected by the interphalangeal joint, in the active test, the participant freely slid their finger against the static sample, without consciously controlling the joint, thus keeping the finger relatively relaxed during the sliding. In the passive tests, the finger was fixed to a support structure using adhesive tape. The back of the finger was then held tightly to the support meaning that the motion of the interphalangeal joint was restricted. This created a completely different type of dynamics, which would influence the tribological behavior during the sliding test. Whilst specific values in these tests differ because two different participants and two devices were used, the different trends obtained in these results indicate higher friction for a smooth sample and a lower one for a rough sample. The main reason for this phenomenon was that within certain ranges, the real contact area of finger skin decreased with increasing sample roughness, resulting in a reduction in adhesion between two surfaces [1, 27]. It is commonly accepted that skin friction was attributed to the effects of the adhesion and deformation behavior of the finger. Within certain ranges of contacting surface roughness, the friction properties of human skin were dominated by adhesion term and the deformation component can be ignored. The adhesion force decreased with the increase of surface roughness, resulting in the decrease of friction coefficient on rougher surfaces.

5.3 Limitation

There are some limitations in this study. First, two experimental devices were used to analyze the finger's active and passive sliding behavior, which may bring the difference in friction results. Secondly, a limited number of participants were performed in this study, and the effect of gender difference and skin hydration should be further considered. In addition, relating the brain response using EEG, fMRI, or fNIRS method to finger friction measurement could deepen the understanding of the difference between active and passive touch. All these considerations will be important to fully reveal the underlying mechanism of finger active and passive sliding behavior.

6 Conclusions

This work investigated two different experimental devices for finger active and passive friction behavior, including sliding and rotating movement. The contributions of this research can be summarized as follows:

(1) Several mechanical signals and fingerprint deformation were measured accurately and simultaneously, showing good repeatability and high reliability of devices.
(2) Obvious friction differences were observed when comparing active sliding and passive sliding, which might be due to the motion conditions, experimental devices and participants.
(3) For passive sliding, stick-slip behavior occurs when sliding in the distal direction, evidenced by observing friction force and the related fingerprint deformation.

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Not applicable.

Author contributions
XZ wrote the manuscript and did the analysis. MM and ZJ revised the manuscript. JM and XS contributed to the design of experimental device. YH was in charge of the production of SWJTU device. All authors read and approved the final manuscript.

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Availability of data and materials
The data used to support the findings of this study are available from the corresponding author upon request.

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