Simple and Reliable Method to Estimate the Fingertip Static Coefficient of Friction in Precision Grip

Allan Barrea, David Córdova Bulens, Philippe Lefèvre, and Jean-Louis Thonnard

Abstract—The static coefficient of friction (μ_{static}) plays an important role in dexterous object manipulation. Minimal normal force (i.e., grip force) needed to avoid dropping an object is determined by the tangential force at the fingertip-object contact and the frictional properties of the skin-object contact. Although frequently assumed to be constant for all levels of normal force (NF, the force normal to the contact), μ_{static} actually varies nonlinearly with NF and increases at low NF levels. No method is currently available to measure the relationship between μ_{static} and NF easily. Therefore, we propose a new method allowing the simple and reliable measurement of the fingertip μ_{static} at different NF levels, as well as an algorithm for determining μ_{static} from measured forces and torques. Our method is based on active, back-and-forth movements of a subject's finger on the surface of a fixed six-axis force and torque sensor. μ_{static} is computed as the ratio of the tangential to the normal force at slip onset. A negative power law captures the relationship between μ_{static} and NF. Our method allows the continuous estimation of μ_{static} as a function of NF during dexterous manipulation, based on the relationship between μ_{static} and NF measured before manipulation.

Index Terms—Biomechanics, neuroscience, human, friction, fingertip skin, prehension

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1 INTRODUCTION

Humans have the remarkable capacity to manipulate small objects with great dexterity. In precision grip (i.e., when holding an object between the thumb and index finger), contact forces at the fingertip-object interface are typically decomposed into two components: the force normal to the object's surface and directly controlled by the subject (normal force, NF), and the force tangential to the object's surface and resulting from the object's weight and inertial forces (tangential force, TF) [1]. To ensure a stable grasp of the object under predictable conditions, the central nervous system continuously scales and synchronizes NF to the varying TF [2], [3].

To examine how NF follows the variations of TF, Westling and Johansson introduced the concept of the "safety margin", defined as the difference between the exerted NF and the minimal NF that would prevent slippage [4]. This indicator is widely used when examining human performance in dexterous manipulation tasks [5], [6], [7]. To compute the safety margin, one must measure the instantaneous NF and estimate the minimal NF necessary to prevent object drop. The latter is achieved by measuring the static coefficient of friction (μ_{static}) at the fingertip-object contact. In precision grip, μ_{static} is defined as the ratio of TF over NF when the object starts slipping.

In contact mechanics, Amontons' law describes frictional forces as being proportional to the applied load and independent of the apparent contact area [8]. This property indicates that μ_{static} is constant and independent of the normal force (i.e., the force perpendicular to the contact surface). However, several studies have reported that the human skin μ_{static} varies nonlinearly with normal force [9], [10], [11], [12], such that Amontons' law cannot be applied to fingertip-object contact. Normal force varies continuously during object manipulation, in order to compensate for inertial forces. Therefore, to obtain a good estimate of μ_{static} at each moment during a manipulation task, μ_{static} must be measured at the fingertip-object interface for the whole range of normal force variation.

To evaluate the fingertip μ_{static}, the slip onset must be accurately detected. Several methods for this detection have been developed. The most popular method in dexterous manipulation is the one proposed by Westling and Johansson in [4]. In this seminal study, the authors asked subjects to grasp and lift an instrumented manipulandum with the thumb and index finger. Then, subjects released the grip slowly until the object dropped.

Despite its popularity, this technique suffers from several drawbacks. First, it does not account for the dependence of μ_{static} on NF. Indeed, inertial forces are negligible in this method and therefore NF at slip onset is only determined by the weight of the manipulated object. Second, the measurements are highly variable between trials. Indeed, the slip onset is very difficult to detect because of the rapid variation of force signals at this moment. Thus, obtaining a reliable estimate of μ_{static} with this method would require very long and tedious testing, with numerous repetitions to compensate

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- *A. Barrea, D. Córdova Bulens, and P. Lefèvre are with the Institute of Neuroscience and ICTEAM Institute, Université catholique de Louvain, Brussels (B-1200) and Louvain-la-Neuve (B-1348), Belgium. E-mail: {allan.barrea, david.cordova, philippe.lefevre}@uclouvain.be.*
- *J.-L. Thonnard is with the Institute of Neuroscience, Université catholique de Louvain and the Physical and Rehabilitation Medicine Department, Cliniques Universitaires Saint-Luc, Brussels (B-1200), Belgium. E-mail: jean-louis.thonnard@uclouvain.be.*

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for variability and different manipulandum weights to test different values of NF. Finally, this method requires fine motor coordination. Therefore, it is difficult to use with patients exhibiting motor impairments or with children.

To overcome these limitations, André et al. proposed a method able to capture the dependence of μ_{static} on NF in [10]. They asked subjects to pinch a manipulandum equipped with force sensors between the thumb and index finger, and to maintain NF at a prescribed level. Then, springs connected to the manipulandum were loaded by a linear actuator, which progressively increased TF. This caused the fingers to slip on the contact surface. Although this procedure allows μ_{static} to be measured for several values of NF, it also has some shortcomings. Specifically, this method requires a dedicated device to move the manipulandum, and the procedure cannot be carried out quickly. Similarly to this method, other studies have also investigated the idea of moving the contact surface relative to the finger with an actuator [13], [14].

In short, μ_{static} is necessary to estimate the safety margin in dexterous manipulation, and varies with NF. However, no method is currently available that is able to capture quickly the dependence of μ_{static} on NF. Here, we propose a new method to measure μ_{static} while accounting for the effect of NF. This method enables the continuous estimation of μ_{static} during dexterous object manipulation, based on the relationship between μ_{static} and NF measured before manipulation. Our experimental procedure is accompanied by a dedicated algorithm able to detect slip onsets automatically from the data in order to compute μ_{static}.

2 MATERIALS AND METHODS

2.1 Subjects

Twelve healthy subjects (age: 18–60 years; 9 men, 3 women) participated in the study. All subjects provided informed consent to participate in the procedure, which was approved by the local ethics committee.

2.2 Apparatus

For this experiment, we used a manipulandum (Fig. 1A) equipped with two six-axis force and torque sensors (Mini-40 F/T sensors, ATI Industrial Automation, NC, USA) covered with Kapton polyimide film (DuPont, DE, USA). The manipulandum was fixed on a table (Fig. 1B). Forces and torques were recorded at a rate of 1 kHz with resolutions of 1/50 N (for force) and 1/4,000 Nm (for torque). A screen, placed in front of subjects, provided real-time visual feedback of the average NF applied on the manipulandum by the thumb and index finger.

The fingertip moisture of the subjects was measured with a dedicated moisture sensor (Corneometer CM 825, Courage + Khazaka electronic GmbH, Köln, Germany, measuring moisture content at the level of the stratum corneum). This sensor provides measures ranging from 20 to 120 arbitrary units, a higher number corresponding to a moister skin [15], [16].

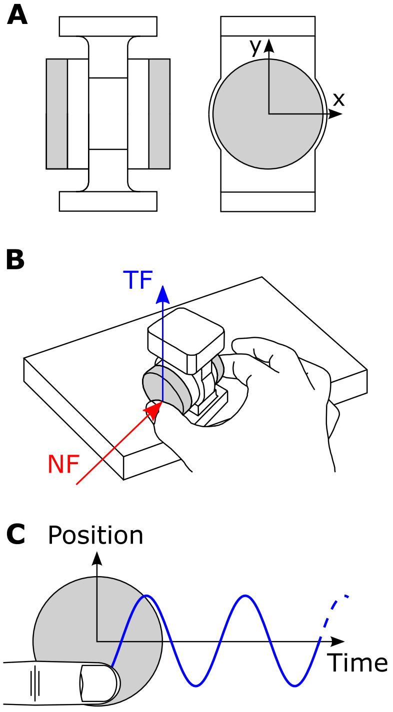

Fig. 1. *Setup.* (A) Manipulandum used for the experiment. The manipulandum was equipped with two six-axis force and torque sensors (shaded in gray), which were covered with Kapton polyimide film (DuPont, DE, USA). (B) Subjects pinched the manipulandum, which was fixed on a table, between their thumb and index finger. Fingertip-object interaction forces were decomposed into components normal (NF) and tangential (TF) to the sensor surface. (C) During trials, subjects performed vertical back-and-forth movements with their hand without releasing their grip. Blue curve shows the vertical trajectory of a finger moving on a force sensor.

2.3 Experimental Procedure

Before performing the experiment, all subjects washed their hands using water and soap. The hands were rested for approximately 10 minutes, to allow the skin to regain its natural hydration level. Subjects sat in front of the table to which the manipulandum was fixed. During a typical trial, subjects pinched the fixed manipulandum and performed five vertical back-and-forth movements with their hand at moderate speed without releasing their grip (Fig. 1C). With the help of visual feedback, subjects were asked to adjust their NF to a given reference level at the beginning of each trial, and to maintain their NF close to this reference level throughout the trial. Subjects were invited to rub the manipulandum at a natural pace. The measured rubbing speed ranged between 5 and 15 mm/s. After completing five vertical back-and-forth movements, subjects stopped rubbing the manipulandum and released their grip. Moisture levels of the thumb and index finger were measured at the beginning of the experiment and after each trial. Forces and torques were continuously recorded during trials.

Reference NF levels for the five trials were 0.5, 1, 2, 4, and 8 N. This range was tested in a previous study [10], which found that μ_{static} varied dramatically with NF values below 5 N. Subjects found it difficult to maintain their NF precisely at the instructed level during a trial, as illustrated in Fig. 2C. However, as their NF values remained close to the reference

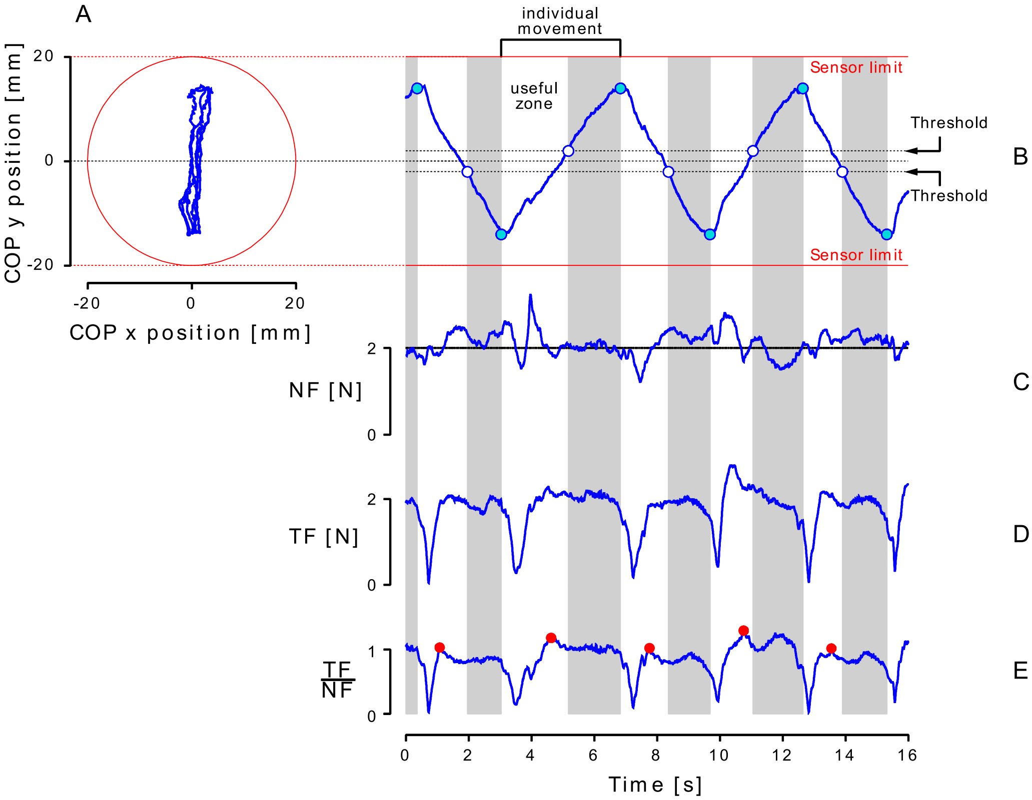

Fig. 2. *Typical traces and description of the method.* Data represent a subset of the complete trial for subject S03 with a reference NF of 2 N. (A) COP trajectory (blue curve) on the force sensor and force sensor boundary (red circle). (B) Data were chunked into individual movements based on the extrema (blue dots) of the vertical COP trajectory (blue curve). “Useful zone” (white) for each movement starts at an extremum of the COP and ends when the COP crosses a custom threshold (white dots). Such a zone corresponds to the portion of a movement where the slip onset is expected to occur. Red lines indicate force sensor boundaries. (C) Force exerted by the subject normally to the surface of the sensor (NF, blue curve) and reference NF level (black line). (D) Force exerted by the subject tangentially to the surface of the sensor (TF, blue curve). (E) Ratio of TF/NF (blue curve) and maxima of TF/NF in each useful zone (red dots), indicating slip onsets. μ_{static} was measured as TF/NF at slip onsets. Finally, we observed that the COP position could be 10 mm away from the reversal point when slip is detected. This is due to finger pad compliance and fingertip rolling against the surface of the force sensor.

NF value for each trial, the goal of spanning the whole range of NF values across repetitions was achieved. The complete procedure lasted 15 minutes or less with naïve subjects.

2.4 Data Processing

For data processing and analysis, we considered the two force sensors independently. Indeed, the method described here considers only one force sensor at a time. Given that each force sensor was dedicated to a single finger, μ_{static} was analyzed independently for the thumb and the index finger. The force exerted by a finger normally to a single force sensor was denoted as NF. The force exerted by a finger tangentially to the force sensor was denoted as TF. These forces are illustrated in Fig. 1B.

We computed the center of pressure (COP) of the fingertip from the measured forces and torques. COP was defined as the point where the resultant interaction force between the fingertip and the force sensor was acting on the sensor. The x-y coordinates of COP on the force sensor were computed by using the following formula:

$$\mathrm{COP} = \left(-\frac{T_y}{\mathrm{NF}}, \frac{T_x}{\mathrm{NF}}\right) \tag{1}$$

where T_x and T_y denote torques measured about the x and y axes, respectively, which are tangential to the surface of the sensor (Fig. 1A). Measured force signals were low-pass filtered using a 4th-order Butterworth filter with a cut-off frequency of 75 Hz.

2.5 Data Analysis

We developed a method to compute μ_{static}, based solely on the forces and torques measured under a given fingertip. Fig. 2 presents a portion of a typical trial for the index finger of subject S03.

Fig. 2A shows the COP trajectory on the force sensor. Because vertical back-and-forth movements were made, we considered only the vertical component of the COP trajectory in the analysis (Fig. 2B). In support of this choice, we found that the discrepancy between the total and vertical amplitudes of the COP trajectory was less than 5 percent. We chunked the vertical component of the COP trajectory into several individual movements, using the extrema of the COP trajectory as separating points.

As mentioned earlier, computing μ_{static} requires identifying slip onset on each movement. To this end, we defined a “useful zone” in each movement, where slip is expected to occur (Fig. 2B). Due to varying fingertip morphologies between subjects and given that individual movements started from different vertical positions on the force sensor,

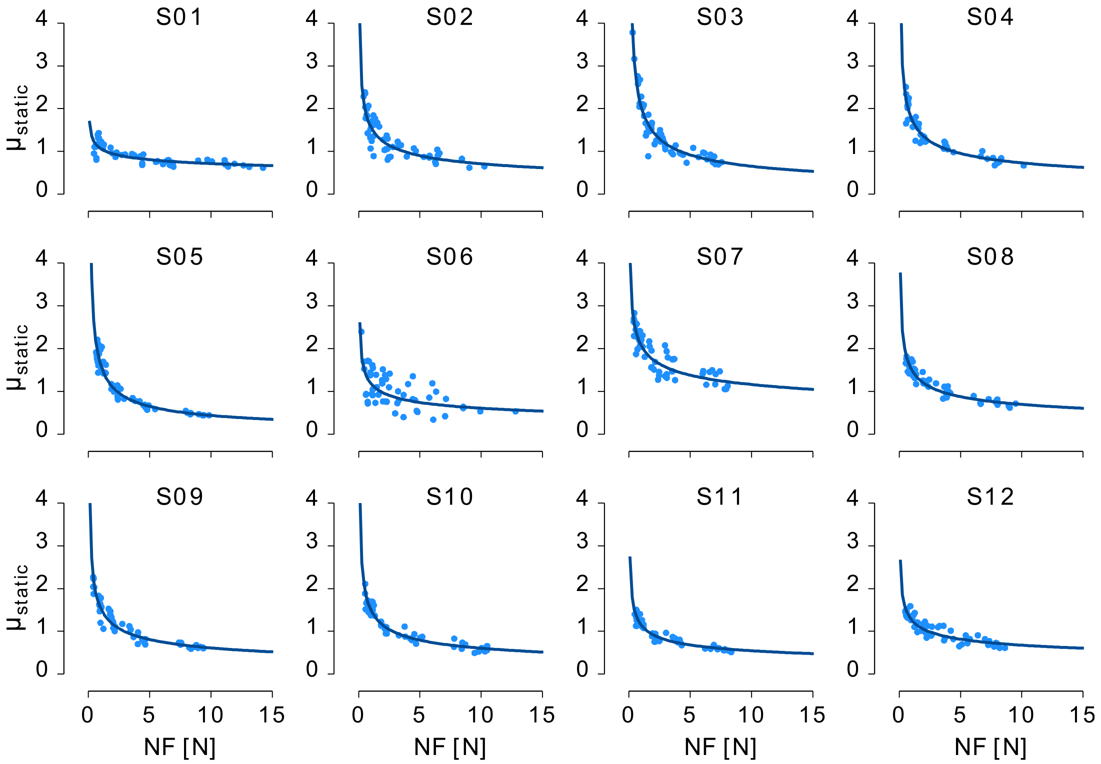

Fig. 3. *Relationship between* μ_{static} *and NF*. For each of the 12 naïve subjects (S01 to S12), μ_{static} data for the index finger were plotted against corresponding values of NF at slip onset (blue dots). A power law function was fitted to individual subject data (blue curve).

we set the threshold delimiting useful zones beyond and above half the range of the sensor, to guarantee that each zone would be sufficiently large to include the slip onset of the corresponding movement. This threshold was determined arbitrarily and was kept constant across all subjects and all normal force conditions.

Next, we searched for the slip onset in each useful zone by looking for the maximum TF/NF in each zone (red dots in Fig. 2E). TF/NF maxima provide good markers for slip onsets because the material covering the force sensors exhibits a static coefficient of friction that is larger than the dynamic one. As a result, the TF and TF/NF values decrease slightly at slip onset. Implementation of the overall procedure in MATLAB (MathWorks, Natick, MA, USA) and tools for visualizing the data are available in the supplemental material, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TOH.2016.2609921.

2.6 Statistical Analysis

For each subject, a negative power law was fitted to the data to quantify the relationship between μ_{static} and NF. This power law, which has been used in several previous studies [10], [11], [17], was expressed as:

$$\mu_{\mathrm{static}} = \mathrm{k}\,(\mathrm{NF})^{\mathrm{n}-1} \tag{2}$$

Fit parameters k and n were obtained by using an ordinary least-squares regression procedure. Paired t-tests were carried out to test for differences in the fit parameters between the two fingers and to assess the repeatability of the method.

3 RESULTS

Fig. 3 presents the measured values of μ_{static} and the corresponding normal force (NF) values for the 12 tested subjects. This figure clearly shows the relationship between μ_{static} and NF for all subjects. For high values of NF (> 5 N), μ_{static} had a constant low value. As NF decreased, μ_{static} increased dramatically, often reaching values above 2 for forces below 0.5 N.

A negative power function of the form $\mu_{\mathrm{static}} = \mathrm{k}(\mathrm{NF})^{\mathrm{n}-1}$ was fitted to the data to capture the relationship between μ_{static} and NF for each subject (solid lines in Fig. 3). Table 1 reports the values of parameters k and n, the coefficient of determination (R^2) of the fit, and the moisture levels for the thumb and index finger for all subjects. The R^2 values were large for all fits, with a mean (M) of 0.84 and standard deviation (SD) of 0.14, indicating that the power law correctly captured the effect of NF on μ_{static}.

To test whether data acquired for the thumb and index finger were different, we conducted paired t-tests on fit parameters k and n from both groups of data. Fit parameters were not significantly different for thumb versus index finger data ($\mathrm{t}(11) = 1.65$, $\mathrm{p} > 0.05$ for k; $\mathrm{t}(11) = 0.23$, $\mathrm{p} > 0.05$ for n). In addition, the correlations between thumb and index finger data were 0.85 and 0.84 for k and n, respectively. Therefore, measuring μ_{static} of only one of the two fingers can be considered as sufficient to capture the influence of NF on μ_{static} for a given subject.

For six of the twelve subjects, a second measurement session was performed a week after the first. To test the repeatability of the measurements from the two test sessions, we used paired t-tests conducted separately on the two fit parameters, with the measurement session as the

TABLE 1
Experimental Data

	Thumb				Index			
Subject	k	n	R^2	Moisture (M ± SD)	k	n	R^2	Moisture (M ± SD)
S01	1.26	0.76	0.80	30 ± 6	1.07	0.83	0.65	36 ± 5
S02	1.60	0.59	0.86	34 ± 3	1.56	0.66	0.77	58 ± 11
S03	2.05	0.55	0.90	76 ± 9	2.02	0.52	0.92	86 ± 13
S04	1.49	0.64	0.94	40 ± 5	1.75	0.63	0.90	65 ± 7
S05	1.69	0.54	0.94	61 ± 7	1.61	0.44	0.91	52 ± 4
S06	1.35	0.76	0.50	72 ± 8	1.18	0.72	0.42	75 ± 5
S07	2.05	0.69	0.93	38 ± 3	2.06	0.75	0.81	51 ± 2
S08	1.54	0.71	0.90	95 ± 6	1.50	0.67	0.90	114 ± 4
S09	1.48	0.61	0.94	99 ± 5	1.53	0.61	0.92	105 ± 8
S10	1.68	0.65	0.93	83 ± 7	1.49	0.61	0.92	93 ± 6
S11	1.15	0.71	0.81	62 ± 25	1.14	0.69	0.90	61 ± 14
S12	1.55	0.76	0.74	91 ± 11	1.27	0.73	0.83	95 ± 9

Fit parameters k and n, coefficient of determination (R^2) of the fits, and moisture level for the 12 subjects (M ± SD) for the thumb and index finger. Moisture measurements are provided in arbitrary units ranging from 20 to 120.

independent variable. No significant difference was found between fit parameters from the two sessions ($\mathrm{t}(5) = 0.98$, $\mathrm{p} > 0.05$ for k; $\mathrm{t}(5) = 0.98$, $\mathrm{p} > 0.05$ for n). Thus, results obtained by the proposed method were not significantly different across measurement sessions. In addition, the correlations between data from the two sessions were 0.84 and 0.61 for k and n, respectively.

4 DISCUSSION

4.1 Advantages of Our Method

In this paper, we propose a new method to measure μ_{static} at the fingertip-object contact. Our method allows μ_{static} to be measured quickly and accounts for the effect of the normal force (NF), which has already been highlighted by several previous studies [9], [10], [12]. During dexterous object manipulation, inertial forces can significantly influence the tangential force at the fingertip-object interface, hence affecting the minimal normal force that would prevent object drop and therefore the safety margin. Accordingly, it is important to measure μ_{static} for several normal forces before manipulation to estimate the safety margin continuously during manipulation.

Our method is applicable to subjects exhibiting skin moisture levels spanning the whole range of moisture measurable with the Corneometer (cf. skin moisture measurements in Table 1). It is also applicable to one or several fingers, provided that there is a single six-axis force and torque sensor dedicated to each finger contacting the object. Results obtained with this method are reproducible. Therefore, the relationship between μ_{static} and NF for a given subject can be measured before an experimental session and used during the entire subsequent session. Consequently, the experimenter can continuously estimate the minimal NF that would prevent slippage and thus continuously estimate the safety margin (i.e., the difference between the actual and minimal NF) during a dexterous manipulation experiment. Finally, this method works with normal forces spanning the whole range of forces used in tactile exploration [18], [19] and dexterous object manipulation [1], [5], [20], [21], namely from 0.5 N to above 8 N. Reference [10] reported that the fingertip skin μ_{static} becomes constant for NF values above 5 N. Given these advantages, our method is well suited for studies involving tactile exploration or dexterous object manipulation.

4.2 Comparison with Previous Methods

Our method only necessitates a single six-axis force and torque sensor to acquire data for different values of normal force. In comparison, several other methods used more complicated apparatuses [10], [13], [14], [22], [23].

Our method overcomes several limitations of the classical μ_{static} measurement method introduced by [4], in which subjects slowly release their grip until dropping the manipulandum. First, our method accounts for the dependence of μ_{static} on NF with no change in the apparatus, thereby allowing continuous estimation of the safety margin. Second, the intrinsic variability of the measurements is not a problem in our method, which is able to acquire numerous measurements rapidly, thereby reducing measurement error. Finally, our method does not require subjects to lift an object or release their grip slowly until the manipulandum is dropped. As a result, our method is easier to use for patients with motor impairments.

4.3 Limitations of Our Method

In addition to the aforementioned advantages, our method also has some limitations. First, our method requires that the material covering the force sensors exhibits a higher static than dynamic frictional coefficient. This is because the tangential force needs to decrease when the fingertip begins to slip, in order for our algorithm to detect slip onsets correctly.

The second limitation regards the moisture level of the subject's fingertip. Variations in fingertip skin moisture during object manipulation [24] and across subjects [25] have been shown to impact μ_{static} [10], [25]. In this study, we measured the average moisture level of subjects' fingertips. Some of the variability in our data might be explained by the variation in moisture levels across individual measurements. This is a possible explanation for the higher variability of μ_{static} exhibited by subject S06 in Fig. 3. We advise researchers to measure μ_{static} frequently and, if possible, to measure the fingertip moisture of each subject before and at different times during each data acquisition session.

Finally, our method was designed to measure the static coefficient of friction (i.e., at slip onset). Adapting our method to measure the dynamic coefficient of friction (i.e., during slippage) would require a complementary study. The latter measurement is not straightforward because the dynamic coefficient of friction depends on many factors, including the slipping speed and normal force [26].

4.4 Validity of the Negative Power Law

To capture the relationship between μ_{static} and NF, we used a negative power function that has been used in previous studies [10], [11], [17]. Reference [9] indicated that the parameter n must lie between 2/3 and 1, which was most often the case in our data (Table 1). The case where $\mathrm{n} = 2/3$ corresponds to a purely Hertzian contact. When $\mathrm{n} = 1$, the model simplifies to $\mu_{\text{static}} = \mathrm{k}\ (\mathrm{constant})$. This case is equivalent to Amontons' law, which states that the friction force (TF) is proportional to the normal force (NF). As $\mathrm{n} < 1$ for all subjects (Table 1), Amontons' law cannot be considered as valid for the fingertip-object contact at low normal force ($<$ 5 N). Our model better describes the reality in this case.

4.5 Influence of Tangential Force Rates

As previously stated, the inertial component of tangential force in dexterous object manipulation can vary significantly due to object's acceleration. In this study, we observed the tangential force rates during measurement of the relationship between μ_{static} and NF to be below 60 N/s. When tangential force rates during object manipulation are comparable to those applied during measurement, the measured relationship between μ_{static} and NF can be used to predict μ_{static} during object manipulation. By inspecting typical traces in previous studies, we found tangential force rates to be around 50 N/s for point-to-point movements [2] and around 10 N/s for oscillatory movements [5]. However, some tasks involve large levels of acceleration and therefore rapid variation of tangential forces, e.g. collision tasks where force rates can be above 500 N/s [27]. In this case, when tangential force rates are larger than the ones applied during measurement, the non-linear, visco-elastic properties of the fingertip skin might make the measured relationship between μ_{static} and NF invalid. This limitation is worth investigating in future studies.

5 CONCLUSION

Our method enables μ_{static} at the fingertip-object contact to be measured easily by using a six-axis force and torque sensor, while accounting for the dependence of μ_{static} on the normal force. Using our method, it is possible to estimate μ_{static} continuously and quickly during object manipulation and tactile exploration, provided that the material covering the force sensor exhibits a higher static than dynamic frictional coefficient. Under the assumption that the fingertip moisture level is constant, μ_{static} measured at the beginning of an experimental session remains valid during the course of the experimental session. Finally, the continuous estimation of μ_{static} during object manipulation enables continuous monitoring of the minimal NF to prevent object drop and, accordingly, of the safety margin (i.e., the difference between the actual and minimal NF values).

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Allan Barrea received the BS degree in engineering and the MS degree in electro-mechanical engineering from UCLouvain, Belgium, in 2011 and 2013, respectively. He is currently enrolled in the PhD program in engineering at UCLouvain. His research interests include biomechanics, psychophysics, haptics, neuroscience in the context of touch, and dexterous manipulation.

David Córdova Bulens received the BS degree in engineering and the MS in electro-mechanical engineering from UCLouvain, Belgium, in 2011 and 2013, respectively. He is currently enrolled in the PhD program in engineering at UCLouvain. His research interests include optimal control, biomechanics, and bimanual movements.

Philippe Lefèvre received the master's degree in electrical engineering and the PhD degree in engineering both from UCLouvain. He is a full professor of biomedical engineering in the School of Engineering at UCLouvain, Belgium. He is a member of the ICTEAM and IoNS Institutes. From 2010 to 2015, he was the head of the Department of Mathematical Engineering and the chair of the Program Committee in Biomedical Engineering at UCLouvain from 2007 to 2012. He supervised more than 20 PhD students. He did a sabbatical at the National Institutes of Health (NEI) from 2003 to 2004 and a postdoc at NIH from 1995 to 1997. His research interests cover the interaction between vision and the neural control of movement, dexterous object manipulation, and biomechanics of finger object interaction. He uses modelling, clinical, and behavioral approaches to investigate these topics.

Jean-Louis Thonnard received the BA and MA degrees in physical education and in physical therapy from UCLouvain, Belgium, in 1977 and 1979, respectively. He received the PhD degree in rehabilitation from UCLouvain in 1988. He has been a professor with UCLouvain since 2004. He was the head of the Physical Education and Rehabilitation Department, UCLouvain, between 2005 and 2008 and the head of the research division "System and Cognition" in the Institute of Neuroscience at UCLouvain between 2010 and 2016. He is interested in the sense of touch and its role in dexterous manipulation. More particularly, he is investigating the biomechanical properties of the fingertips and their role in tactile perception and dexterous manipulation.