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Short Communication

A new device to measure the three dimensional forces and torques in precision grip

O. WHITE*†, M. PENTA‡ and J.-L. THONNARD†

†Unité de Réadaptation et de médecine physique, Université catholique de Louvain, Avenue Mounier 53, B-1200 Bruxelles, Belgium
‡Institut d'éducation physique et réadaptation, Université catholique de Louvain, Place Pierre de Coubertin, 1-2, B-1348 Louvain-la-Neuve, Belgium

Fine prehension is ubiquitous in everyday skilled hand manipulations. The anticipatory nature of the control of normal grip forces exerted against tangential loads has been extensively used to provide insights into the working of neural control of movements. We designed a new versatile device to measure the three dimensional forces and torques during a broad panel of precision grip tasks. The instrument measures constraints exerted independently on two grip surfaces by the thumb and the opposing fingers. In addition, the device can be loaded to increase the weight and/or induce torques and can be easily integrated in a variety of experimental contexts. Its compactness improves its stability during movement and allows an ergonomic manipulation for impaired persons or children.

Keywords: Precision grip; Torque; Sensor; Strain gauge; Centre of pressure

1. Introduction

A precision grip occurs between the thumb and index finger during precise and skilled hand manipulations. In order to lift an object aloft without translational and/or rotational slips, the grip force applied normal to the grip surfaces must be large enough to counteract the destabilizing tangential forces and rotational torques acting on the fingertips [1]. Since the control of grip force is largely anticipatory [2], many behavioural paradigms can be imagined to address issues related to the control of movement in general.

The parallel co-ordination between grip forces (GF) and load forces (LF) applied to each contact surface of an object was initially studied by Johansson and Westling [1] during a motor task consisting in gripping, lifting and holding an object. Since then, the parallel change in GF and LF has been established as a general control strategy during prehension requiring grasp stability. For instance, studies reported that the GF was modulated with the fluctuations in inertial loads that arise from moving a grasped object in space as the object is accelerated and decelerated by the arm [3,4]. Another study showed that the GF modulated approximately in phase with changes in LF induced by whole body jumping [5]. This robust coupling between GF and LF emerges from a variety of grip configurations, like in multidigit grips [6] and for different forms of LF including those dependent on position, velocity and acceleration [7,8] as well as in normal or altered gravity conditions [9,10].

*Corresponding author. Email: olivier.white@uclouvain.be

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Most studies involving precision grip (i.e. not involving the whole hand) were limited to tasks in which LF were unidirectional, as in horizontal or vertical movements. However, in our daily activities, objects are often grasped such that multidirectional constraints are induced between the fingers, including torques [11,12]. The objective of this study is to design a new versatile instrument capable of measuring the three dimensional forces and torques under the thumb and index finger during a variety of manipulative tasks and experimental contexts.

2. Methods

2.1. Instrumented device

The device has a cylindrical shape of 80 mm diameter and 30 mm height (figure 1A). It is equipped with two lightweight (50 g each) force-torque sensors (Mini40 F/T sensor, ATI Industrial Automation, Garner, NC) mounted back-to-back in an aluminium frame (112 g). Each sensor measures the three orthogonal force (F_x, F_y, F_z) and torque (T_x, T_y, T_z) components along the corresponding axes intersecting the centre of the grasp surface. The sensing ranges for F_x, F_y and F_z are ± 40, ± 40 and ± 120 N with a 0.02, 0.02 and 0.06 N resolution, respectively. The sensing ranges for T_x, T_y and T_z are ± 2 N.m with a 1 N.mm resolution. The area of each sensor is 12.5 cm^2 and the distance apart is 30 mm. The basis weight of the instrument is 212 g and its centre of mass is located at the middle of the line joining the centre of both grip surfaces. The device can be loaded with six semi-rings that are either made of tungsten carbide (84 g each) or of Ertalon® (8 g each) for a loaded weight ranging from 260 g (with six Ertalon semi-rings) to 716 g (with six tungsten carbide semi-rings) (figure 1A). The semi-rings can be placed either symmetrically, so that its centre of mass is at the centre of the grasp surfaces, or asymmetrically, so that the centre of mass is off-centred from the centre of the grasp surfaces. When the centre of mass is off-centred, an adjustable torque can be applied by rotating the device at various angles relative to the direction of the eccentricity of the centre of mass ($\pm 90^\circ$ no torque, 0° maximal torque). A nylon opaque cover (22 g) gears the masses interlocking and hides the configuration so that its appearance is always visually the same.

2.2. Signal processing

The sensors are mounted back-to-back with sensor S2 rotated 22° around its Z-axis to avoid cable congestion while minimizing distance between the two surfaces. Since the common coordinate system is centred on S1 (figure 1B), the values measured by S2 are corrected according to:

$$\begin{pmatrix} F_x \\ F_y \\ F_z \\ T_x \\ T_y \\ T_z \end{pmatrix}_{S2,corrected} = \begin{pmatrix} \cos 22^\circ & \sin 22^\circ & 0 & 0 & 0 & 0 \\ \sin 22^\circ & -\cos 22^\circ & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos 22^\circ & \sin 22^\circ & 0 \\ 0 & 0 & 0 & \sin 22^\circ & -\cos 22^\circ & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} F_x \\ F_y \\ F_z \\ T_x \\ T_y \\ T_z \end{pmatrix}_{S2} \tag{1}$$

The total grip force (GF) was calculated as the average of the normal grip forces applied by the thumb and the fingers on each transducer. The force tangential to the grasp surface is a vector with two components:

$$\begin{pmatrix} F_{x,S} \\ F_{y,S} \end{pmatrix}, \tag{2}$$

where S denotes the sensor (S1 or S2). The total tangential force acting on the device is calculated as follows:

$$\vec{F}_{t,S} = (\vec{F}_{x,S1} + \vec{F}_{x,S2}) + (\vec{F}_{y,S1} + \vec{F}_{y,S2}). \tag{3}$$

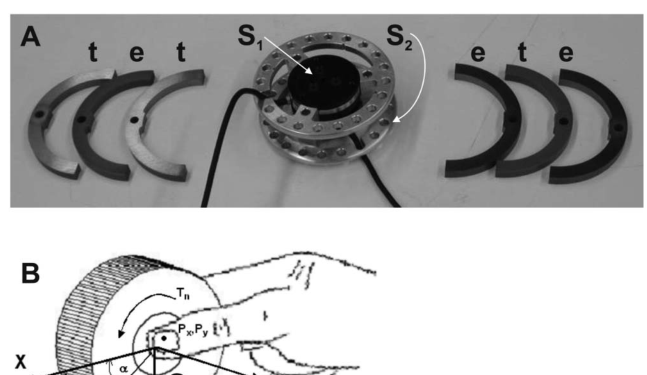

Figure 1. The instrumented device. (A) Fragmented view with three tungsten carbide (t) and three Ertalon® (e) semi rings. (B) The common coordinate system used to measure the load force (LF), the normal torque T_n around the Z-axis and the coordinates (P_x, P_y) of the centre of pressure.

Therefore, its magnitude (in N) and direction (in deg) with respect to the reference X-axis are:

$$LF = \left\| \vec{F}_{t,S} \right\| = \sqrt{\left(F_{x,S1} + F_{x,S2}\right)^2 + \left(F_{y,S1} + F_{y,S2}\right)^2} \quad (4)$$

$$\alpha = \frac{180}{\pi} \arctan\left(\frac{F_{y,S1} + F_{y,S2}}{F_{x,S1} + F_{x,S2}}\right) \quad (5)$$

In addition to the forces, torques can also be measured. The normal torque that tends to rotate a sensor around its Z-axis ($T_{n,S}$) is computed as the difference between the torque measured around the Z-axis ($T_{z,S}$) and the torque due to an off-centred grip, if any:

$$T_{n,S} = T_{z,S} - \left(F_{y,S} P_{x,S} - F_{x,S} P_{y,S}\right), \quad (6)$$

where ($P_{x,S}$,$P_{y,S}$) are the coordinates of the centre of pressure on each grasp surface, and are computed as:

$$\begin{pmatrix} P_{x,S} \\ P_{y,S} \end{pmatrix} = \begin{pmatrix} \frac{-T_{y,S}}{F_{z,S}} \\ \frac{T_{x,S}}{F_{z,S}} \end{pmatrix}. \quad (7)$$

The total normal torque (T_n) is calculated as the average of the normal torques applied to each sensor.

2.3. Data acquisition

The signals from both sensors are synchronized and digitized in a PXI-chassis (National Instruments©, Austin, TX). The controller is an AMD 333 MHz embedded processor that samples the signals at up to 1 kHz after an analog low pass second order Bessel filter at 235 Hz. The signals are then digitally low-pass filtered using a zero-phase digital filter (autoregressive, forward and backward filter, cut-off frequency: 15 Hz).

2.4. Experimental procedure

The new device has been tested in a grip-lift task comparable to those in previous studies (see for example [1]). An informed volunteer (male, 26 years old) was asked to grip the device, lift it 5 cm vertically off a table, hold it still in the air for 3 s, and then replace the object on the table. The procedure was repeated in two loading conditions: with or without generated torque. In both conditions, three semi-rings in tungsten carbide (heavy) and three in Ertalon® (light) were inserted in the body, leading to an equivalent mass of 510 g. In the symmetric load condition (torque = 0 N.mm), the heaviest rings filled the lower half-body, so that the centre of mass of the object and the point of application of GF were aligned with vertical. The asymmetric condition was obtained by rotating the symmetric configuration by 90° (torque = 23 N.mm). The participant was asked to apply a spontaneous GF during the task.

A force is defined by its magnitude and direction but it is often useful to identify its point of application, commonly called the centre of pressure, for example to investigate whether a slip occurs. Therefore in order to validate equation (7), we repeated the following procedure for each sensor. We applied continuous forces with a sharp pen along four equivalently spaced diameters (45° per section) of the circular area of the transducer, from one edge to the opposing edge. The diameters were grooved on brass surfaces covering the sensors.

3. Results

Two typical traces of fingertip forces and torques are presented in figure 2, either with a symmetric load (left panel) or with an asymmetric load generating a torque

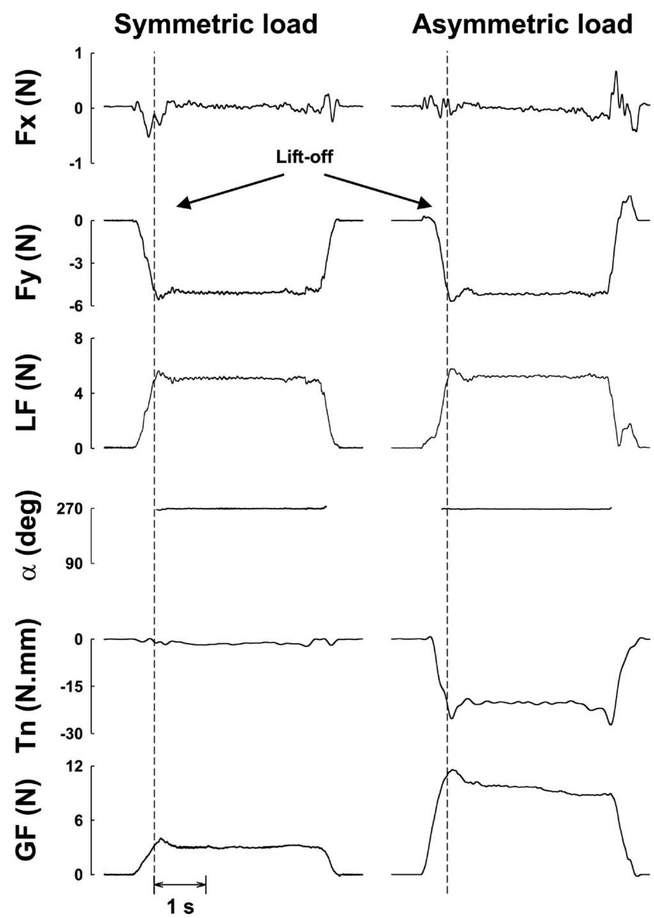

Figure 2. Typical traces of one grip lift trial in the symmetric (left panel) and asymmetric (right panel) load conditions (mass = 510 g). Presented over time are the horizontal (F_x) and vertical (F_y) components of the load force, the load force magnitude (LF) and direction (α), the normal torque (T_n) and the grip force (GF). The vertical dashed lines are aligned with lift-off. The direction of LF is not computed when LF = 0 N.

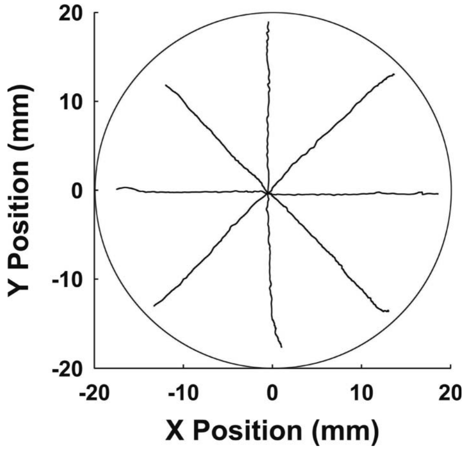

Figure 3. Reconstructed centre of pressure of a contacting force applied along four 45° spaced diameters on the transducer's plate (circle).

of -20.7 ± 1.11 N.mm around the Z-axis (right panel). In both conditions, the mass of the device is equal to 510 g (weight of 5 N). The total tangential load force (LF) is primarily due to its vertical component (F_y) because its horizontal component (F_x) was close to zero throughout the lift. Lift-off occurs when F_y reaches the device's weight (figure 2, vertical dashed lines). The direction of the tangential force vector (α) is equal to 270° after lift. While LF are the same in both conditions, a large torque tends to rotate the object about the Z-axis in the asymmetric load condition (right panel). Consequently, the GF increases in order to prevent a rotational slip.

Figure 3 depicts the centre of pressure in the 2D space of one sensor, calculated according to equations (6) and (7). The reconstructed point of application of the force followed very closely the exact diameter ($R^2 > 0.92$, SE < 0.8 mm). In addition, it is worth noting that the procedure to compute the centre of pressure is insensitive to an arbitrary profile of constraint applied on the transducer.

4. Conclusion

A new device has been developed for the measurement of 3D forces and torques to study the dynamics of precision grip. It avoids making assumptions about the direction of the load as required when using devices measuring forces along a single axis. The holes manufactured in its circumference allow an easy integration to external equipment, like robots or motors. This versatile instrument has already provided valuable results in parabolic flights [13], in a TMS study [14] and in weight-dropping tasks.

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