

Adaptive control of grip force to compensate for static and dynamic torques during object manipulation

F. Crevecoeur, T. Giard, J.-L. Thonnard and P. Lefèvre

J Neurophysiol 106:2973-2981, 2011. First published 21 September 2011; doi:10.1152/jn.00367.2011

You might find this additional info useful...

This article cites 30 articles, 16 of which can be accessed free at:

<http://jn.physiology.org/content/106/6/2973.full.html#ref-list-1>

Updated information and services including high resolution figures, can be found at:

<http://jn.physiology.org/content/106/6/2973.full.html>

Additional material and information about *Journal of Neurophysiology* can be found at:

<http://www.the-aps.org/publications/jn>

This information is current as of December 8, 2011.

Adaptive control of grip force to compensate for static and dynamic torques during object manipulation

F. Crevecoeur,^{1,*} T. Giard,^{2,3,*} J.-L. Thonnard,² and P. Lefèvre^{2,3}

¹Centre for Neuroscience Studies, Queen's University, Kingston, Canada; and Institutes of ²Neuroscience and ³Information and Communication Technologies, Electronics and Applied Mathematics, Université Catholique de Louvain, Belgium

Submitted 21 April 2011; accepted in final form 15 September 2011

Crevecoeur F, Giard T, Thonnard JL, Lefèvre P. Adaptive control of grip force to compensate for static and dynamic torques during object manipulation. *J Neurophysiol* 106: 2973–2981, 2011. First published September 21, 2011; doi:10.1152/jn.00367.2011.—Manipulating a cup by the handle requires compensating for the torque induced by the moment of the mass of the cup relative to the location of the handle. In the present study, we investigated the control strategy of subjects asked to perform grip-lift movements with an object with center of mass located away from the grip axis. Participants were asked to lift the manipulandum with a two-fingers precision grip and stabilize it in front of a visual target. Subjects showed a gradual and slow adaptation of the grip-force scaling across trials: the grip force tended to decrease slowly, and the temporal coordination between grip-force and load-torque rates displayed gradually, better-coordinated patterns. Importantly, this adaptation was much slower than the stabilization of the same parameters measured either when no torque came into play or after previous adaptation to the presence of a torque. In contrast, the maximum rotation induced by the torque was controlled efficiently after only few trials, and an unexpected decrease in the tangential torque produced significant overcompensation. An unexpected increase in torque produced a consistent opposite effect. This shows that the compensation for the dynamic torque was based on an anticipatory, dynamic counter-torque produced by the arm and wrist motor commands. The comparatively slow stabilization of grip-force control suggests a specific adaptation process engaged by the presence of the torque. This paradigm, including tangential torques, clearly constitutes a powerful tool to extract the adaptive component of grip control during object manipulation.

cutaneous feedback; motor adaptation; motor prediction; tangential torques

WITH THE THUMB OPPOSING THE index, humans have the ability to grasp and manipulate objects. More specifically, this grip permits modulation of the force developed to hold objects stable in our hands. Indeed, the force required to hold an object depends on many factors, including the object weight, the mechanical and frictional properties of the skin/object interface, and the inertial constraints induced when the object is accelerated. Several studies have characterized the sensorimotor control of precision grip and shown that in general, the grip force exhibits a predictive compensation for the load constraints induced by the interaction with the object. Such anticipatory scaling is known to be based on internal models, prior knowledge of the object properties, and cutaneous feedback of

the mechanical properties of the fingertip/object interface (André et al. 2010; Augurelle et al. 2003; Crevecoeur et al. 2010; Danion and Sarlegna 2007; Flanagan and Wing 1993, 1995, 1997; Johansson and Westling 1984; Westling and Johansson 1984; Witney et al. 2004).

Many studies have focused on the tight coupling between the grip force and the load force when the latter is the only constraint that comes into play. However, in most situations encountered on daily bases, manipulating an object also implies the anticipation of static and inertial torques. A typical example is when we grasp a cup by the handle, a clear objective is to minimize the swinging of the cup to avoid spilling the content. In such a situation, the torque induced by the moment of the object center of mass relative to the grip axis must be taken into account to maintain a stable grip. Several strategies have been reported in studies examining multidigit grasp configurations. In general, the central nervous system is capable of coordinating the force distribution under the fingers and control the moment arm induced by the spatial distribution of finger locations to compensate for external torques (Lukos et al. 2007; Santello and Soechting 2000; Shim et al. 2006; Zatsiorsky et al. 2002). In the context of bidigital precision grip with the thumb and index finger, previous results showed that the grip-force modulation also compensates for tangential torques and scales as a function of torque variations (Goodwin et al. 1998; Kinoshita et al. 1997; Wing and Lederman 1998). In particular, although categorical changes in movement and grip-force parameters following practice have been reported earlier (Wing and Lederman 1998), there has been, to date, no investigation of the trial-by-trial adaptation of grip force and movement control in the presence of constraints that tend to rotate the object.

To investigate this issue, the present paper addresses the control of grip-lift movements of an object producing tangential torques at the finger/object interface. Our results enhance that the anticipation of inertial torques is based on a dynamic counter-torque applied by the arm and wrist motor commands. In addition, our results unravel an adaptive control of grip force that is directly attributable to the presence of a torque, suggesting a particular role of sensory feedback of torque constraints for the central control of grip force.

METHODS

Subjects. Twenty-nine healthy human subjects between 23 and 46 yrs participated in this study after giving written, informed consent. The experimental protocol was approved by the Ethics Committee of the Université Catholique de Louvain (Belgium). The subjects were separated in four groups corresponding to the four following experiments. The first two experiments involved the manipulation of an

* F. Crevecoeur and T. Giard contributed equally to this work.

Address for reprint requests and other correspondence: P. Lefèvre, Institutes of Neuroscience and Information and Communication Technologies, Electronics and Applied Mathematics, Université Catholique de Louvain, 4 Ave. Georges Lemaître, 1348 Louvain-la-Neuve, Belgium (e-mail: philippe.lefevre@uclouvain.be).

object with center of mass away from the grip axis, inducing torques at the finger/object interface (*experiments 1* and *2*). The third experiment sought to dissociate the effect of the torque from the effect of the high level of grip force developed by the subjects tested during the first experiment. More details about this control experiment are given hereafter (Experiment 3 below). In all experiments, subjects were instructed to use a two-fingers grasp. The grip aperture was 4.5 cm, and the force sensors were covered by brass. Each experiment consisted of a series of grip-lift movement with comfortable intertrial duration (10 s to 1 min). Subjects were encouraged to take breaks as often as needed to avoid fatigue. A fourth experiment was conducted to estimate the minimum grip force required to avoid slippage in each experimental condition.

Experiment 1. Subjects ($n = 8$) were required to perform grip-lift movements with the right hand by using precision grip. The start of each trial was cued by a visual target placed 20 cm above the starting position. The geometry of the manipulandum was not symmetrical, and subjects could clearly see the off-centered mass prior to the experimental run. The off-centered mass was a cylinder of 100 g, placed 10 cm away from the grip (Fig. 1), and the total mass of the manipulandum, including the 100-g cylinder, was 430 g. Subjects were asked to perform a series of 60 grip-lift movements toward the aforementioned visual target. After the 60th trial, the subjects were blindfolded, and the experimenter replaced the off-centered mass by a cylinder with identical shape but reduced mass (40 g). This procedure was intended to produce an unexpected change in static and inertial torques. Then, visual feedback was recovered, and the subjects performed another series of 60 grip-lift trials with the 40-g off-centered mass.

Experiment 2. This experiment addressed the interaction between the absolute torque level and the previous exposure to the presence of a torque in the adaptation of grip-force parameters. Subjects ($n = 8$) performed the same task as did the subjects involved in the first experiment, except that they started to manipulate the manipulandum equipped with the 40-g off-centered mass. After the 60th trial, the 40-g cylinder was replaced by the 100-g cylinder, following identical procedures as in the first experiment. Reversing the order allowed us to compare the adaptation with the control of static and dynamic torques with and without previous exposure to another torque level. In *experiments 1* and *2*, only the off-centered mass was changed, inducing a change in torque but also a small change in net mass (14%). This design was retained to preserve the overall shape of the manipulandum.

Experiment 3. The grip force, which subjects developed initially to hold the manipulandum with the 100-g off-centered mass, was substantially higher than the range commonly reported when studying the grip load-force coupling. It was thus necessary to compare the effect observed in the presence of a torque with subjects' behavior without

torque but with similar force recruitment. To do so, we defined an equivalent mass: a mass for which subjects would produce similar levels of grip force but without torque. We followed a theoretical approach based on the computation of the tensor of tangential constraints at the finger-object interface. We computed the force density on the contact surface with and without off-centered mass. By using a classical argument of linear addition, the force-density tensors corresponding to a centered mass only or a torque only were summed to estimate the overall force-density tensor. Then, we defined the equivalent mass as a centered mass, which would produce an identical, integrated square norm of force density as the one computed in the presence of a torque. We approximated the finger-object contact surface as a disc of radius 9.3 mm, compatible with experimental observations (André et al. 2011). Knowing that the total mass of the manipulandum (including the off-centered mass) was 430 g, we estimated that the equivalent mass was ~ 1.6 Kg. The details of the computation are provided in APPENDIX. The subjects involved in this control experiment ($n = 6$) were asked to perform a series of 60 grip-lift movements with the equivalent mass.

Experiment 4. This experiment was designed to examine the minimum grip force required in each configuration of the manipulandum tested in *experiments 1–3* (100 g off-centered, 40 g off-centered, and with the equivalent mass). Participants ($n = 7$) were asked to hold the manipulandum stationary in a precision grip for more than 5 s and then release the grip gradually until slipping occurred, either in rotation when an off-centered mass was present or in translation with the equivalent mass. Each subject performed 10 grip-release trials with each configuration (30 in total).

Data collection and analysis. The custom manipulandum (ESAGLM, Arsalis, Louvain-la-Neuve, Belgium) was equipped with two, three-dimensional force and torque sensors (Mini40 Force/Torque transducers, ATI Industrial Automation, Apex, NC). We collected the tangential and normal forces at the interface between the fingers and the manipulandum, as well as the tangential torques generated by the off-centered mass along the grip axis. The grip force was defined as the mean of the normal components measured by each sensor. The load force was the sum of the tangential constraints measured on each sensor. The analyses reported hereafter focus on the vertical component of the load force. The load torque was also defined as the sum of the tangential torques relative to the grip axis on the right and left sensors. Each signal was collected at 800 Hz and digitally low-pass filtered with a fourth-order zero-lag Butterworth filter with cut-off frequency set to 20 Hz.

The position of the manipulandum was measured with a motion-tracking device (Codamotion, Charnwood Dynamics, Leicestershire, UK), collecting the position of infrared markers placed on the manipulandum, as illustrated in Fig. 1. From the position of the three markers, we computed the location of the center of the spherical structure, corresponding to the center of the grip axis. The vertical coordinate and velocity of this point are considered hereafter. Regarding the angle induced by the torque, the movements were projected into the vertical plane orthogonal to the grip axis, and the angle was computed from the change in orientation of the vector joining the grip axis to the off-centered mass. The position of the markers was sampled at 200 Hz and digitally low-pass filtered with a fourth-order zero-lag Butterworth filter with 20 Hz cut-off frequency.

The movement onset (t_o) and end (t_f) were determined when the vertical velocity exceeded or dropped below 1% of its peak value computed on each individual trial. The tangential torque recorded from the sensors was corrected to take into account the actual torque relative to the fingertips' center of pressure, according to procedures described in other studies (André et al. 2010; Kinoshita et al. 1997). The center of pressure was also used to address possible compensation for the external torque by adjusting the finger configuration within the allowed grip surface. Indeed, the 40-mm diameter of force sensors leaves some room for adjustments of finger location. The time derivatives of force and torque signals were also extracted from numerical

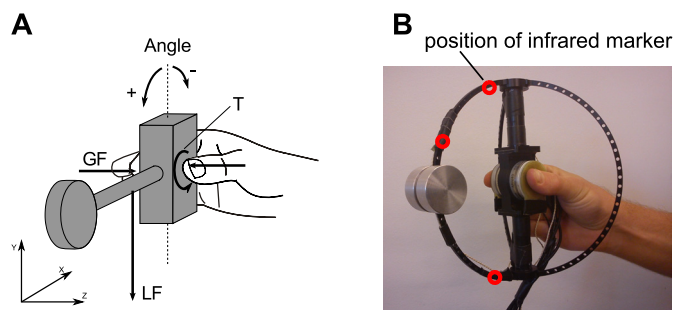


Fig. 1. A: schematic representation of the instrumented object equipped with an off-centered mass that moved the center of mass away from the grip axis. The study focuses on the grip force (GF), the load force (LF), the tangential torque measured along the grip axis (T), and the angle induced by the static and dynamic torques. B: picture of the manipulandum with schematic representation of the position of the infrared markers used for motion tracking.

differentiation. The static grip force was the average grip force in a time window from $t_f + 1$ s to $t_f + 2$ s. The presence of an effect across the trials was addressed by means of classical one-way ANOVA. The characterization of learning curves for the grip force was based on exponential fits computed on pooled subjects' data vs. the trial number (n) as follows

$$GF(n) = a_0 + a_1 \exp(a_2 n) \quad (1)$$

This equation was fitted to the maximum and static values of the grip force (GF in Eq. 1) across each individual trial. The significance of the exponential fit was based on whether the estimated 95% confidence interval of a_2 included 0. The data and fits presented below show the maximum and static values of grip force normalized for each subject to their individual means across the last 10 trials performed with the 100-g off-centered mass for *experiments 1* and *2* and to the last 10 trials for *experiment 3*. This normalization procedure was used for illustration purpose, as it partially reduces the intersubjects' variability. However, the estimates of adaptation rates were identical when the fits were computed on raw grip-force parameters. The comparison of two populations was based on the nonparametric Wilcoxon rank sum test. The coordination of forces and torques was based on cross-correlation of the derivative of force and torque signals.

The minimum grip force necessary to hold the manipulandum stationary was estimated as follows (*experiment 4*). When an off-centered mass was present, the mean and SD of the tangential torque were computed in a 1-s time window preceding the initiation of grip-force release. Then, we determined the time when the load torque dropped below the mean $- 2$ SD for at least 200 ms. The grip force at the beginning of this 200-ms time window was averaged across the 10 repeats to estimate the grip force at slipping. The procedure used to determine the minimum grip force with the equivalent mass was identical, except that the mean and SD of the load force were considered instead of the tangential torque.

RESULTS

Experiment 1. A typical example is illustrated in Fig. 2. The movement exhibited standard kinematics with single-peak, bell-shaped velocity profiles (Fig. 2, position and velocity). Some subjects (three of eight) presented a significant decrease in peak velocity across the first 60 trials based on linear regressions, but there was no consistent tendency across subjects. Three individual subjects showed a significant increase in peak velocity across the second series (*trials 61–120*). However, pooled subjects' data revealed no significant variation of the velocity peak, neither within each series of 60 trials with the two different off-centered masses nor across the 120 consecutive trials ($F < 0.85$, $P > 0.87$, ANOVA). The peak

inertial external torque presented no significant tendency across trials within each series of lifting movements ($F < 0.45$, $P > 0.5$, ANOVA). There was no migration of the center of pressure across trials within each series of lifting movements ($F < 0.6$, $P > 0.5$, ANOVA). Across all subjects, the average location of center of pressure was within a radius of 7.5 mm, relative to the center of the force sensors. Thus movement kinematics, grip configuration, and tangential torque tended to be stable across trials, which is critical to interpret changes in grip-force production as gradual adaptation to the tangential torque.

Most subjects reported that it was quite hard to hold the object with the 100-g off-centered mass. Indeed, they developed very high levels of grip force ranging from 42 N to 58 N across the subjects (average across *trials 2–5*). These values are presented in Fig. 3A, along with the values measured at the end of the first series (average across *trials 57–60*) and the last four trials with the 40-g off-centered mass (average across *trials 117–120*). The maximum grip force presented a highly significant decrease across the two series of trials, from *trial 1* to *60* with the 100-g off-centered mass and from *trial 61* to *120* with the 40-g off-centered mass ($F > 3.36$, $P \ll 0.001$, ANOVA). The static grip force presented a highly significant decrease during the first series of 60 trials ($F = 6.07$, $P \ll 0.001$, ANOVA) and did not show significant evolution across the second series ($F = 1.19$, $P = 0.17$, ANOVA). Besides the results of the ANOVA analyses, all exponential fits computed on the grip-force parameters were significant (maximum and static grip force during the first and second series). These fits are plotted in Fig. 3, *B* and *C*, for data normalized for each individual subject to their maximum and static values averaged across *trials 51–60*. Interestingly, the time constants ($1/|a_2|$, see Eq. 1) were higher in the first series than in the second series: the estimated time constant for the maximum and static grip force during the first series included 42 and 39 trials, respectively (*trials 1–60*, 100-g off-centered mass), and five and eight trials during the second series for the maximum and static grip-force values, respectively (*trials 61–120*, 40-g off-centered mass).

As other evidence for a gradual, rather slow adjustment of grip force, we computed the cross-correlation among the grip-force rate, load-force rate, and load-torque rate during the first grip-lift series (*trials 1–60* with the 100-g off-centered mass). Fig. 4A shows grip-force, load-force, and load-torque profiles normalized to their peak values for the first and last trials,

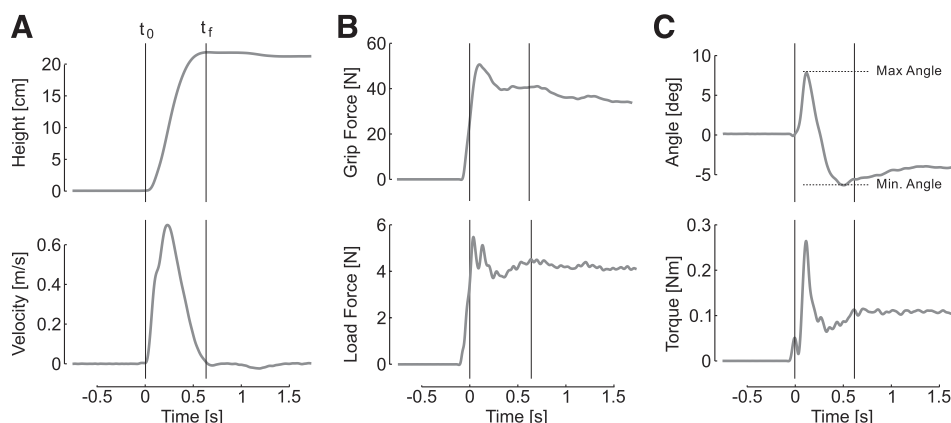


Fig. 2. Representative traces of 1 grip-lift trial. A: position and velocity profiles as a function of time. B: grip-force and load-force traces. C: change in angle and tangential torque during the lifting movement. The vertical lines illustrate the estimated movement onset (t_0) and end (t_f). The maximum and minimum angles are illustrated.

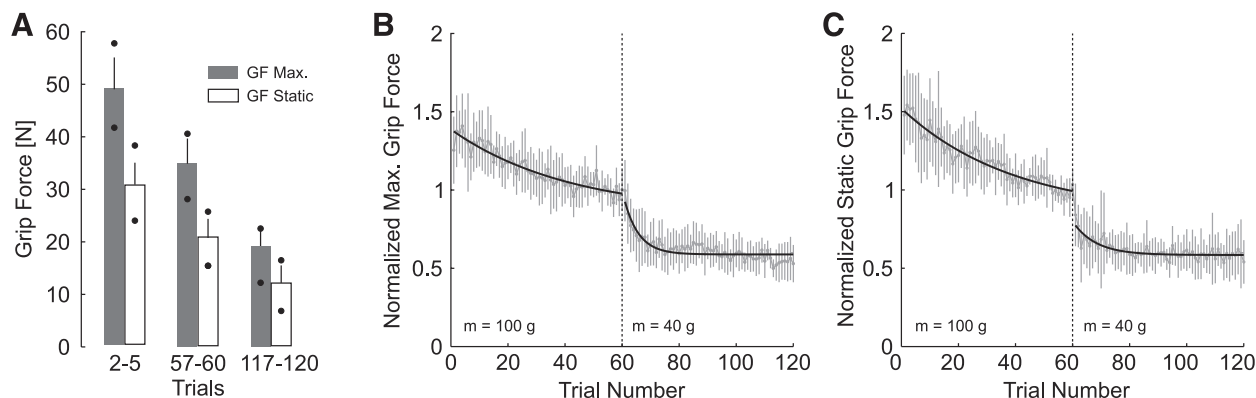


Fig. 3. *A*: raw values of maximum and static grip force at the beginning of the experiment, at the end of the first series of 60 trials, and at the end of the second series. The bars indicate 1 SD, and the dots are the minimum and maximum values across subjects. *B*: time course of the maximum grip force across trials (mean $\pm$ SD across the 8 subjects). *C*: time course of the static grip force across trials (mean $\pm$ SD). For each individual subject, the values were normalized to the last 10 trials of the series with 100-g off-centered mass (see METHODS, *Data collection and analysis*). *B* and *C*: the black lines represent the first-order exponential fits.

executed by one representative subject in this series. Fig. 4*B* shows the derivative of the signals plotted in Fig. 4*A*. *Time zero* corresponds to the estimated t_0 . These plots clearly show a better-coordinated pattern at the end of the first series, which we quantified by looking at the peak cross-correlation among the derivatives of the grip-force, load-force, and load-torque profiles. The peak correlation between the grip-force rate and the load-torque rate presented significant variation ($F = 1.85$, $P < 0.001$, ANOVA) and increased significantly across trials ($P < 0.001$, linear regression; Fig. 4*C*). There was no significant effect of the trial number on the peak correlation, neither between the grip-force and load-force rates nor between the load-force and load-torque rates ($F < 1.19$, $P > 0.1$, ANOVA). The grip-force rate lagged the load-force rate by 26 ± 23 ms and led the load-torque rate by 51 ± 42 ms (mean $\pm$ SD across subjects). Time lags did not show significant variation across trials ($F > 0.9$, $P > 0.6$, ANOVA).

Importantly, although grip force was gradually (and relatively slowly) adjusted to the tangential torque in both dynamic and static phases, the tilt of the manipulandum was controlled successfully by subjects from the first trials. There was no

significant evolution of the maximum angle of the manipulandum within each series of grip-lift trials with the two different off-centered masses (Fig. 5*A*). There was a significant variation of the maximum angle between the first and second series, which can be directly attributed to the change in off-centered mass. However, the minimum swing angle also varied significantly between the end of the first series and the beginning of the second series ($P < 0.01$, Wilcoxon rank sum test; Fig. 5*B*). The examination of the peak acceleration and velocity before the end of the first series (10 last trials with 100-g off-centered mass) and the beginning of the second series (10 first trials with 40-g off-centered mass) revealed no significant changes in peak acceleration and peak velocity, suggesting a limited impact of the change in net mass in the kinematics of the lifting movement ($P > 0.13$, Wilcoxon rank sum test). Thus the change in angle provides evidence that subjects dynamically varied the torque applied on the object to counter the inertial torque induced by the acceleration of the off-centered mass. The change in minimum angle at the beginning of the second series reveals that the counter-torque was applied in anticipation of the inertial torque.

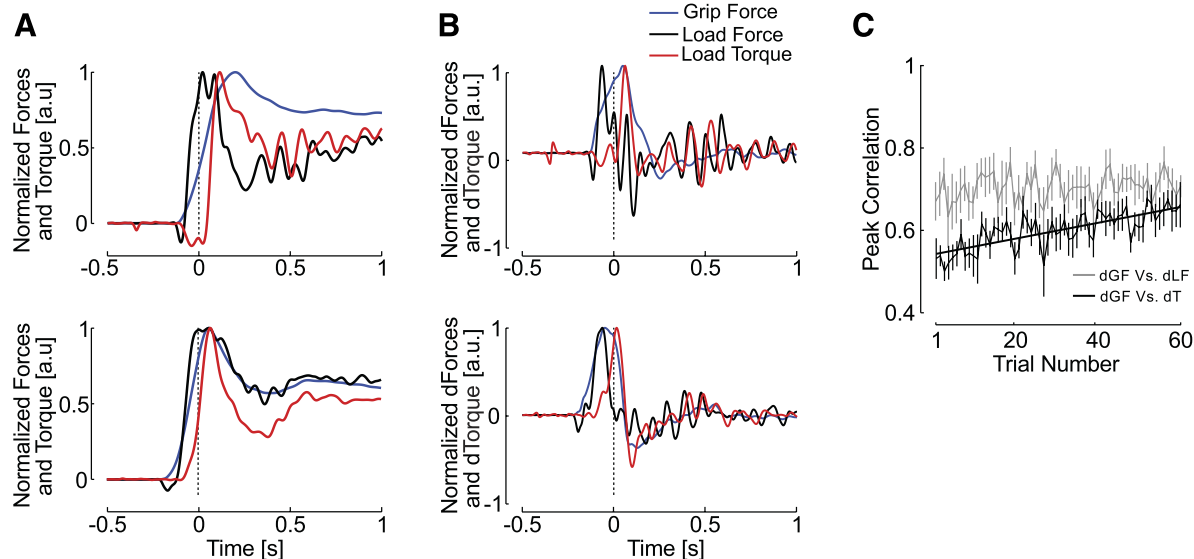


Fig. 4. *A*: grip force, load force, and load torque normalized to their maximum values for the first (*top*) and last (*bottom*) trial of 1 representative subject with the 100-g off-centered mass. *B*: time derivatives (*d*) of the signals plotted in *A*, normalized to their peak values. *C*: peak cross-correlation between the grip-force rate and the load-force rate (gray) and between the grip-force rate and the load-torque rate (black). The mean $\pm$ SE across the 8 subjects is represented for clarity.

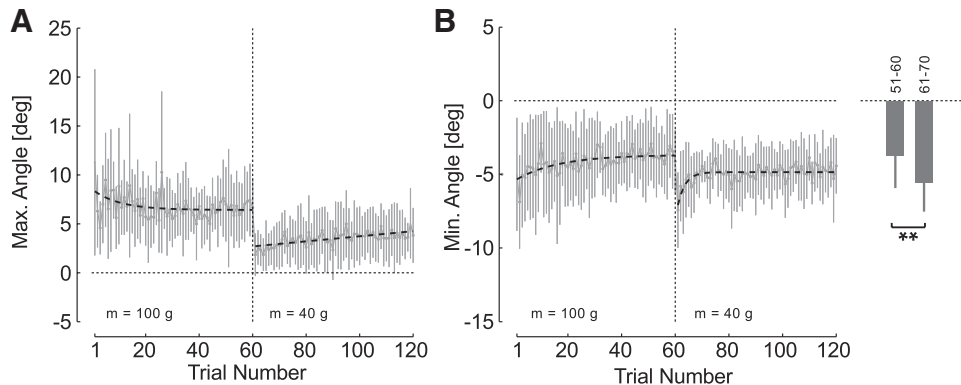


Fig. 5. A: maximum swing angle across trials; B: minimum swing angle (means $\pm$ SD). The dashed traces correspond to the first-order exponential fits, which were not significant, but give the general tendency. B, inset: comparison between the last 10 trials of the first series and the first 10 trials of the second series. **Significantly different at $P < 0.01$.

Experiment 2. Overall, the results of this experiment were qualitatively similar to those of *experiment 1*. The rotation of the manipulandum was well controlled, whereas grip-force adjustments exhibited adaptation across trials. The absolute grip-force values tended to be smaller at the beginning of each series than in *experiment 1* but gradually decreased toward values comparable with the ones observed in *experiment 1* after adaptation (compare Figs. 3A with 6A). The maximum grip force presented a significant effect across trials in the first series ($F = 2.85$, $P < 0.001$, ANOVA). The analysis of variance failed to reveal significant variation of maximum grip force for the second series (100-g off-centered mass). The static values of grip force presented significant evolution across trials in the first and second series ($F > 1.75$, $P < 0.005$). Besides ANOVAs, the exponential fits computed on normalized pooled subjects' data were significant in the four series ($P < 0.05$). The estimated time constants in the first series were 13 and 10 trials for the maximum and static values, respectively (40 g), and 11 and nine trials for maximum and static values in the second series. Compared with *experiment 1*, adaptation in the second series in both cases is clearly facilitated by the prior manipulation performed in the first series.

As shown in Fig. 7, the maximum and minimum angle displayed little to no variation across trials in each series ($F < 1.2$, $P > 0.13$, one-way ANOVA). The change in angle at the transition was compatible with our hypothesis that participants dynamically anticipated the inertial torque: the maximum angle (Fig. 7A) in the first trial of the second series (100 g after 40 g) exhibited a dramatic increase, due to the unexpected change in off-centered mass ($P < 0.01$, Wilcoxon rank sum test; com-

parison between *trials 60* and *61*). The minimum angle (Fig. 7B) also increased, suggesting that the anticipative counter-torque could not compensate for the unexpected higher torque (Fig. 7B, inset, $P < 0.05$).

Experiment 3. This control experiment investigates grip-force adaptation when no torque comes into play but with a mass intended to produce high levels of grip force. Figure 8A shows that the subjects developed peak and static grip force, which were comparable with the level measured during the first experiment: subjects' average maximum grip force across *trials 2–5* ranged between 30 N and 51 N. This control experiment critically emphasizes that peak and static values of the grip force also present a highly significant decrease when the force recruitment approaches the one observed in *experiment 1*, even in the absence of torque (Fig. 8, B and C; $F > 2.28$, $P < 0.001$, ANOVA). The exponential fits were also significant (normalized data; Fig. 8, B and C). However, the estimated time constants were substantially shorter in this case: the results were 11 and nine trials for the peak and static values of the grip force, respectively. This suggests a fourfold-faster adaptation process than when a tangential torque is present, despite similar force recruitment at the beginning of the two series. Thus the decrease in peak and static grip force observed in the presence of the torque in *experiment 1* (first series) is partially due to the high level of grip force required, but the slow decrease rate may be mostly attributed to the presence of the tangential torque (*experiment 1*, first series, vs. *experiment 3*). The tangential torque also clearly influenced the stabilization of the peak grip-force level. Indeed, Figs. 3A and 8A show

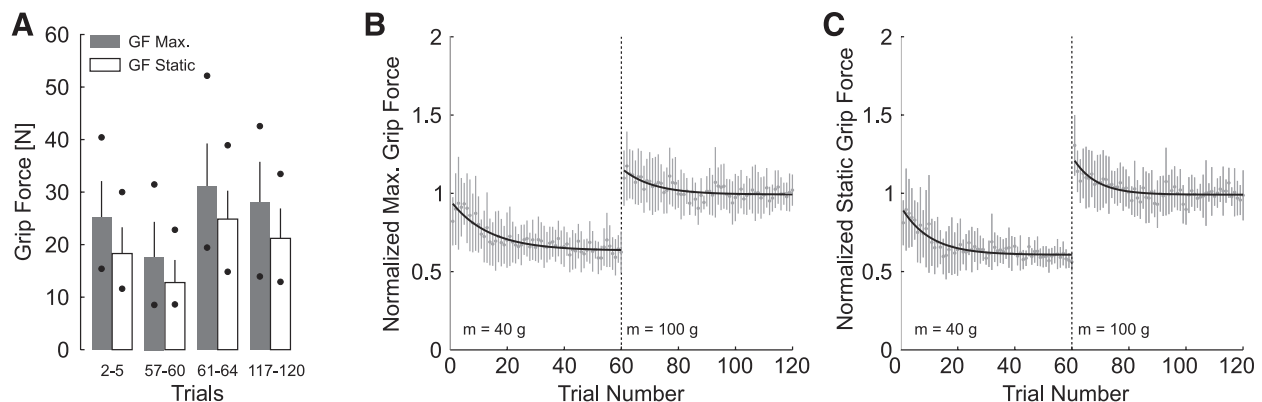
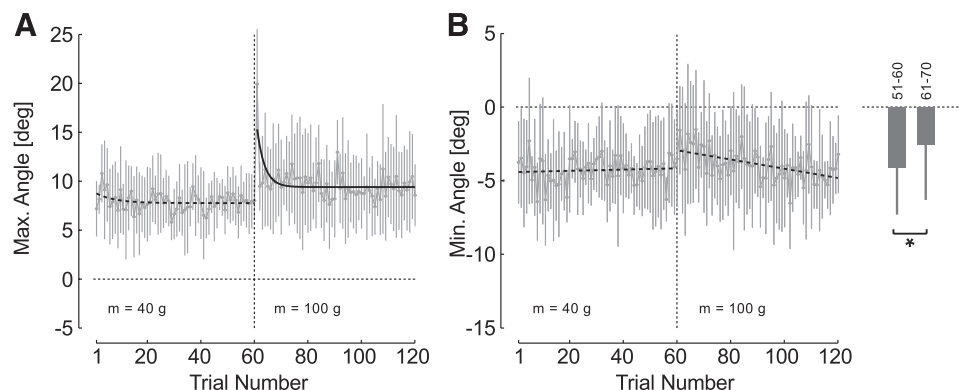


Fig. 6. Same plots as Fig. 3 for the second experiment. A: raw values of grip force; the bars indicate 1 SD, and the dots are the minimum and maximum values across subjects. B: normalized maximum grip forces as a function of the trial number (mean $\pm$ SD across subjects). We used the same normalization procedure that consisted in normalizing relative to the last 10 trials of the series performed with the 100-g off-centered mass. C: same as B with the static grip force.

Fig. 7. Same as Fig. 5 for the second experiment with 40-g off-centered mass manipulated in the first series, followed by the 100-g off-centered mass. **A**: maximum angle across trials (mean $\pm$ SD across subjects). Dashed trace indicates nonsignificant tendency from the exponential fit. Solid trace indicates that the increase induced by the unexpected change in mass enforced a significant exponential trend. **B**: minimum angle across trials. **B, inset**: comparison between the last 10 trials of the first series and the first 10 trials of the second series. *Significantly different at $P < 0.05$.



that the maximum grip force stabilized to lower values in *experiment 3* than in *experiment 1*.

Experiment 4. The minimum grip force to hold the manipulandum stable before slipping was 16.7 ± 3 N with the 100-g off-centered mass; 8.5 ± 2.6 N with the 40-g off-centered mass; and 16.8 ± 2.8 N with the equivalent mass (mean $\pm$ SD across subjects). In all, these results enhance the following important points. First, the theoretical approach used to estimate the equivalent mass based on an approximation of the local constraints at the skin-object interface is validated by this experiment, as we found strikingly similar mean values of grip force at slipping onset in the two conditions (100-g off-centered and equivalent mass). Second, this experiment suggests that subjects used a greater safety margin when tangential torques come into play, as the static grip force in *experiment 1* with 100-g off-centered mass stabilized at $\sim 123\%$ of the minimum estimated above (20.5 N), and the static grip force in *experiment 2* with the same mass stabilized at the same level (125%, 21 N). In contrast, the subjects manipulating the equivalent mass stabilized at 16.9 N. This result suggests that different values for safety margins must be considered with caution. Indeed, the grip force developed by subjects involved in *experiment 3* was $\sim 100\%$ of the measured slip force, which is too close to the minimum grip force required, reported above. Such a small safety margin is likely due to the fact that different subjects were involved in different experiments. However, as similar slip forces were found for the 100-g off-centered mass and for the equivalent mass, a direct comparison of force levels developed by subjects in each condition can be done. Such a comparison reveals that the grip forces developed with the 100-g off-centered mass were significantly

greater than those measured with the equivalent mass ($P < 0.05$, one-tail Wilcoxon rank sum test).

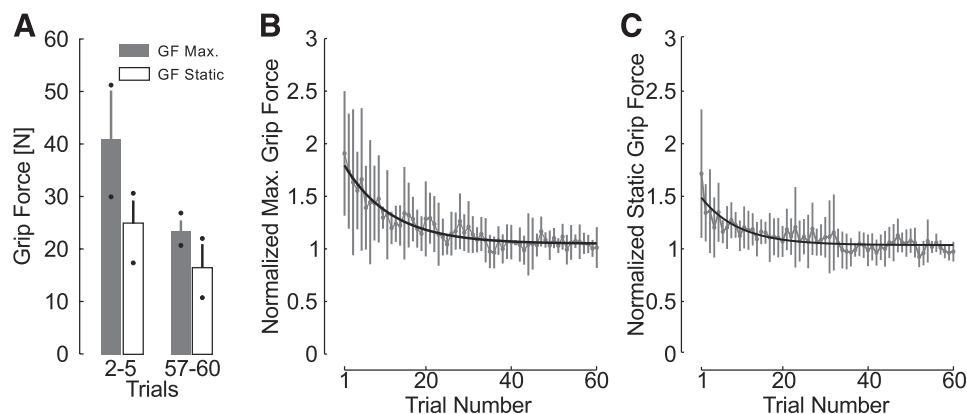
The grip force developed to hold the manipulandum with 40-g off-centered mass revealed even higher safety margins with reproducible measurements across *experiments 1* and *2*. With this mass, we observed stabilization of the static grip force at 143% of the slip force in *experiment 1* (12.5 N) and at 150% (12.8 N) in *experiment 2*.

DISCUSSION

The results clearly demonstrate the two following facts. First, the anticipatory compensation for inertial torque involves a dynamic application of a counter-torque by the arm motor commands in addition to the grip-force modulation. Second, the grip-force adjustment stabilizes slowly, whereas the dynamic swinging of the manipulandum produced by the inertial torque is compensated almost immediately. Notably, we demonstrated that the torque played a critical role in the grip-force adaptation process. Indeed, previous exposure facilitates the adaptation of grip-force scaling (*experiment 2*), and the stabilization observed for similar levels of force, but without any torque, was appreciably faster (*experiment 3*).

Our results are compatible with previous findings on grip-force adjustment to the presence of static or inertial torques (Goodwin et al. 1998; Kinoshita et al. 1997; Wing and Lederman 1998). Wing and Lederman (1998) reported changes in some parameters between the first and last movement consisting in the horizontal transport of an object designed to produce inertial torques during the acceleration phase (the center of mass was below the grip axis). The authors reported a decrease in baseline grip force and an increase in grip-force rate. How-

Fig. 8. Same plot as Fig. 3 for the third experiment. **A**: raw values of grip force. **B**: evolution of the maximum grip force across trials normalized to the 10 last trials. **C**: evolution of the static grip force across trials normalized to the 10 last trials. SD across the subjects is represented.



ever, Wing and Lederman (1998) did not observe a strong effect on the grip-force peak, which could be attributed to the differences in protocol (hold and transport vs. grip-lift in the present study). Goodwin and colleagues (1998) addressed the grip-force modulation in a "grip-tilt" task, isolating the changes in torque in a paradigm equivalent to the grip-lift task when focusing on the grip-force modulation with the load force. In general, these previous studies enhanced a tight coupling between the grip force and the load torque. The present study replicates this relationship and importantly, also focuses on the compensation for inertial torque by looking at the control of the swing of the manipulated object. This original contribution allowed us to enhance the dynamic application of a counter-torque and the comparatively slow decrease of the grip-force parameters with a detailed analysis of the effects of torque and force recruitments on adaptation rates.

The variation in minimum angle after changing the off-centered mass clearly provides evidence for an anticipatory application of a counter-torque during the dynamic phase of the lifting movement. Indeed, if that minimum angle corresponded to an overcompensation for the maximum angle, based on a feedback-control mechanism, we would not observe such a sudden change in minimum angle. In *experiment 1* (decrease in external torque), the change in minimum angle reflects that the actual torque was smaller than the counter-torque applied by the subjects in an anticipative way. Indeed, the first trial with the 40-g off-centered mass should be considered as a catch trial, unraveling the anticipatory application of a dynamic counter-torque. The second experiment (increase in external torque) confirmed this result: the minimum angle expanded after increasing the off-centered mass, showing that the anticipatory compensation for inertial torque was not sufficient to stabilize the manipulandum against the torque induced by the 100-g off-centered mass. In particular, this result emphasizes that the compensation for tangential torque was not solely based on the stiffening of the grip.

Another strategy to compensate for the presence of a torque was emphasized recently when the grip configuration is not constrained to a two-fingers grasp configuration: a coordinated distribution of forces applied by the fingers when using multidigit grasp (Santello and Soechting 2000; Shim et al. 2006; Zatsiorsky et al. 2002) and the control of the position of the fingers on the manipulated object (Fu et al. 2010; Lukos et al. 2007, 2008) can induce a moment in the grip that compensates for external torques. This strategy efficiently allowed subjects to minimize the roll angle of the manipulated object without dramatically increasing the grip force as in the present study. Importantly, Lukos and colleagues (2007, 2008) emphasized that the control of digit placement was an important component of the control of the grasp movement. Here, the object configuration and the constrained position of the fingers on the sensors limited the possibility to vary the moment of the grip from the location of the fingers' contact points. Altogether, these and previous findings show that object manipulation relies on strategies, including spatial control of digit placements and modulation of arm and wrist motor commands, in addition to the grip-force modulation.

The present study seems in contradiction with previous results on adaptation rates of grip force and movement control (Flanagan et al. 2003): grip-force modulation rapidly anticipated vertical loads proportional to horizontal velocity (rate less than five trials), although movement control stabilized

much later (rate >25 trials). In the present experiment, we observed an opposite tendency with fast, stable movement control, whereas the peak grip force stabilized more slowly, indicative of the slower adaptation of the predictive component. Although there is no clear theoretical context capable of reconciling the two studies, we may speculate that the present experiment inverted the complexity of the predictor/controller components: compensating for a torque is a very common situation for arm motor commands (e.g., a cup, a hammer, a racket, etc., all produce torques), whereas the use of a two-fingers grasp with such tools is highly unusual. In contrast, linear loads used by Flanagan and colleagues (2003) are quite usual for precision grip control, whereas a vertical force proportional to horizontal velocity is a less common situation. However, additional investigations are needed to further elucidate whether tangential torques can be at the origin of such differences between the adaptation rates of prediction and control components.

One implication for the motor control theory is that the sensorimotor strategies underlying object manipulation could be considered in a more general way. One classical view states that the prediction of inertial constraint output by an internal forward model is processed by a grip controller, which modulates the grip force accordingly (Kawato 1999). When there is no torque, the arm motor commands that move the object and the arm motor commands that contribute to maintaining the grip could hardly be dissociated, since both produce forces aligned with the direction of motion. In the present paradigm, the arm motor commands that anticipate the inertial constraints were uncovered by changing the off-centered mass, revealing that in addition to the grip-force modulation, a dynamic counter-torque was applied to compensate for the inertial torque. Nonetheless, it is known that the central nervous system uses internal models of interaction torques to control multijoint dynamics in various contexts, including voluntary reaching, rapid motor responses, or postural stance (Gribble and Ostry 1999; Hollerbach and Flash 1982; Hsu et al. 2007; Kurtzer et al. 2008). The present study suggests that skillful object manipulation is part of a global control scheme based on internal models of joint interaction dynamics, which extends to the presence of a manipulated object.

A second main implication is that the shape of the torsional constraints at the finger-object interface is taken into account for the grip-force adjustment. Indeed, the fingertips are innervated with peripheral encoders of mechanical events (Birznieks et al. 2001; Johansson and Flanagan 2009; Witney et al. 2004) and torques in particular (Birznieks et al. 2010), conveying critical cutaneous feedback. Kinoshita and colleagues (1997) showed that the grip force accounts for the presence of both tangential torque and tangential force. However, the effect of each factor could hardly be dissociated, since increasing both tangential torque and force increases the resulting constraints at the finger/object interface. Thus on one hand, the peripheral apparatus encoding rotational constraints exists, but little was known as to whether this information impacted the central control of grip force as linear loads of similar amplitude. On the other hand, our study provides behavioral evidence for different adaptation rates, with or without tangential torque, despite similar force recruitment (*experiments 1* and *3*), as well as an interaction between the level of the torque and a previous exposure to an off-centered mass in the adaptation process

(experiments 1 and 2). Afferent feedback from fingers and arm muscles may also provide information about the torque. However, we showed by looking at angle control that adaptation to kinematics control was fast and could therefore hardly interfere with grip-force adjustments. Altogether, this suggests that the specific pattern of local skin deformation, in addition to the intensity of the deformation, is a pivotal component of sensorimotor control of precision grip.

Why this adjustment evolved slowly across trials remains unanswered. Even with 40 g manipulated first, a time constant of 13 trials suggests that the steady level is reached after about 40 trials, in agreement with Fig. 6. It is, however, clearly due to the presence of a torque that interacts with the level of force required to hold the object stable and produced a level of static grip force after adaptation, which was quite high relative to the minimum grip force required to hold the manipulandum stationary (>120%). Several factors can be at the origin of such a slow decrease. First, we should acknowledge that the use of a two-digits grasp with such levels of force is highly unusual and possibly alters the learning. Another possible origin for such a slow decrease is that the norm of local constraints induced by the tangential torque at the finger/object interface increases as a function of the distance to the center of pressure, whereas the pressure under the fingers decreases as a function of the same distance (Monzée et al. 2003). Thus close to the boundary of the contact surface between the fingertips and the object, the fact that lower pressure counteracts higher constraint density could induce more microslips, encouraging subjects to maintain an excessive level of grip force and slowing down the learning. Importantly, our results emphasize that the classical grip-lift paradigm, extended to the presence of an off-centered mass, may provide a powerful mean to address the adaptive sensorimotor control of grip with obvious applications in clinical, developmental, and fundamental studies.

APPENDIX

The local force on the surface of an object subject to mechanical constraint is equal to the force-density tensor multiplied by the vector normal to the contact surface. To model the contact surface between the object and the fingers, we consider a disc in the plane generated by the x and y dimensions (Fig. 9). Under this assumption, the force-density constraint and normal vector are functions of x and y only. Let $\underline{\sigma}(x,y)$ be the 3×3 matrix representing the force-density constraint. The vector normal to the surface is $\underline{\tau}(x,y) = [0 \ 0 \ 1]^T$. If the center of mass is on the grip axis, then the force will have components only in the y dimension. Thus the only parameter of $\underline{\sigma}(x,y)$ to be determined is the ratio between the force along the y axis and the z coordinate of the normal vector. We call σ_{yz} this parameter (Fig. 9). Now, we must take into account that the integration of the local forces on one contact surface must be equal to one-half of the weight of the object, assuming that the object is static and that the weight is equally distributed across the two fingers. For a mass M and a contact area A , we must solve the following equation

$$\int_A \sigma_{yz} dA = \frac{-Mg}{2} \quad (2)$$

with g representing the gravity. It gives directly

$$\sigma_{yz} = \frac{-Mg}{2A} \quad (3)$$

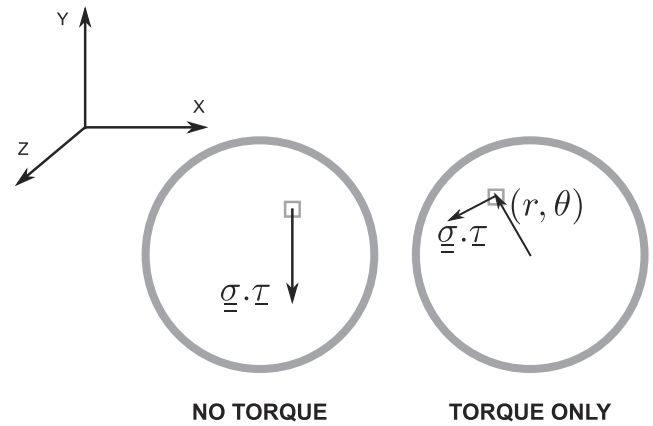


Fig. 9. Representation of the local forces on the contact surface between the manipulandum and the fingertips. The *left* plot shows that when there is no torque, the local force is parallel to the direction of the weight (vertical). The integral of this local force on the 2 sensors must be equal to the weight. The *right* plot shows that in the presence of a torque only, the local constraint on the point (r, θ) is orthogonal to the vector joining (r, θ) with the center of the contact surface and proportional to r by a factor α . This local constraint produces a moment relative to the center of the contact surface. The integral of local moments across the contact surface on the 2 sensors must be equal to the torque induced by the off-centered mass. X , Y and Z are the coordinates of the reference frame, $\underline{\sigma}$ is the tensor of force density, and $\underline{\tau}$ is the vector normal to the contact surface.

Let us now assume that a tangential torque equal to T is applied to the contact surface. We further assume that the local force at (x,y) is orthogonal to the vector (x,y) and proportional to the distance from the center of the disc by a factor α (Fig. 9). Again, we must integrate the moment of the local forces relative to the center of the disc and make it equal to one-half of the torque. The integral is computed in polar coordinates as follows

$$\iint_A \alpha r^3 dr d\theta = \frac{T}{2} \quad (4)$$

which gives

$$\alpha = \frac{T}{AR^2} \quad (5)$$

We now use a simple argument of linear addition to estimate the force-density tensor, taking into account the total mass and torque by using Eqs. 3 and 5 expressed in Cartesian coordinates. We find

$$\underline{\sigma}(x,y) = \begin{bmatrix} 0 & 0 & -\frac{T}{AR^2}y \\ 0 & 0 & \frac{T}{AR^2}x - \frac{Mg}{2A} \\ -\frac{T}{AR^2}y & \frac{T}{AR^2}x - \frac{Mg}{2A} & 0 \end{bmatrix} \quad (6)$$

The equivalent mass is defined as follows: we need to find a mass, for example, M_E , such that the integrated square of the norm of the force-density constraint for this mass, without torque, gives the same number as the same quantity computed with the tensor given in Eq. 6. The integrated square of the norm of the force-density constraint in the presence of a torque (Eq. 6) gives

$$\int_A \|\underline{\sigma}(x,y) \cdot \underline{\tau}(x,y)\|^2 dA = \frac{2\pi T^2}{4A^2} + \frac{M^2 g^2}{4A} \quad (7)$$

We now have to solve

$$\frac{2\pi T^2}{4A^2} + \frac{M^2 g^2}{4A} = \frac{M_E^2 g^2}{4A}$$

which gives

$$M_E = \sqrt{\frac{2\pi T^2}{Ag^2} + M^2}$$

This expression was used with the parameters given in METHODS, Experiment 3, to estimate the equivalent mass used in *experiment 3*.

ACKNOWLEDGMENTS

The authors thank R. Delépine for the fruitful pilot study, T. Dasnoy for his help in the data acquisition of *experiments 1* and *3*, and J. R. Flanagan for helpful comments about an earlier version of this work.

GRANTS

Support for F. Crevecoeur was provided by grants from the Canadian Institute of Health Research (CIHR) and from Fonds Spécial de la Recherche (FSR, Belgium). Support for this work was provided by PROgramme for the Development of Scientific EXperiments (PRODEX) program grants, Fonds National de la Recherche Scientifique, Action de Recherche Concertée (Belgium), and the European Space Agency of the European Union. This paper presents research results of the Belgian Network Dynamical Systems, Control and Optimization, funded by the Interuniversity Attraction Poles Programmes, initiated by the Belgian State, Science Policy Office.

DISCLOSURES

The scientific responsibility for this work rests with its authors.

AUTHOR CONTRIBUTIONS

Author contributions: F.C., T.G., J-L.T., and P.L. conception and design of research; F.C. and T.G. performed experiments; F.C. and T.G. analyzed data; F.C., T.G., J-L.T., and P.L. interpreted results of experiments; F.C. and T.G. prepared figures; F.C. and T.G. drafted manuscript; F.C., T.G., J-L.T., and P.L. edited and revised manuscript; F.C., T.G., J-L.T., and P.L. approved final version of manuscript.

REFERENCES

- André T, Lefèvre P, Thonnard JL. Fingertip moisture is optimally modulated during object manipulation. *J Neurophysiol* 103: 402–408, 2010.
- André T, Lévesque V, Hayward V, Lefèvre P, Thonnard JL. Effect of skin hydration on the dynamics of fingertip gripping contact. *J R Soc Interface* 8: 1574–1583, 2011.
- Augurelle AS, Smith AM, Lejeune T, Thonnard JL. Importance of cutaneous feedback in maintaining a secure grip during manipulation of hand-held objects. *J Neurophysiol* 89: 665–671, 2003.
- Birznieks I, Jenmalm P, Goodwin AW, Johansson RS. Encoding of direction of fingertip forces by human tactile afferents. *J Neurosci* 21: 8222–8237, 2001.
- Birznieks I, Wheat HE, Redmond SJ, Salo LM, Lovell NH, Goodwin AW. Encoding of tangential torque in responses of tactile afferent fibres innervating the fingerpad of the monkey. *J Physiol* 588: 1057–1072, 2010.
- Crevecoeur F, Thonnard JL, Lefèvre P. Sensorimotor mapping for anticipatory grip force modulation. *J Neurophysiol* 104: 1401–1408, 2010.
- Danion F, Sarlegna FR. Can the human brain predict the consequences of arm movement corrections when transporting an object? Hints from grip force adjustments. *J Neurosci* 27: 12839–12843, 2007.
- Flanagan JR, Vetter P, Johansson RS, Wolpert DM. Prediction precedes control in motor learning. *Curr Biol* 13: 146–150, 2003.
- Flanagan JR, Wing AM. Modulation of grip force with load force during point-to-point arm movements. *Exp Brain Res* 95: 131–143, 1993.
- Flanagan JR, Wing AM. The role of internal models in motion planning and control: evidence from grip force adjustments during movements of hand-held loads. *J Neurosci* 17: 1519–1528, 1997.
- Flanagan JR, Wing AM. The stability of precision grip forces during cyclic arm movements with a hand-held load. *Exp Brain Res* 105: 455–464, 1995.
- Fu QS, Zhang W, Santello M. Anticipatory planning and control of grasp positions and forces for dexterous two-digit manipulation. *J Neurosci* 30: 9117–9126, 2010.
- Goodwin AW, Jenmalm P, Johansson RS. Control of grip force when tilting objects: effect of curvature of grasped surfaces and applied tangential torque. *J Neurosci* 18: 10724–10734, 1998.
- Gribble PL, Ostry DJ. Compensation for interaction torques during single- and multi-joint limb movement. *J Neurophysiol* 82: 2310–2326, 1999.
- Hollerbach MJ, Flash T. Dynamic interactions between limb segments during planar arm movement. *Biol Cybern* 44: 67–77, 1982.
- Hsu WL, Scholz JP, Schoner G, Jeka JJ, Kiemel T. Control and estimation of posture during quiet stance depends on multi-joint coordination. *J Neurophysiol* 97: 3024–3035, 2007.
- Johansson RS, Flanagan JR. Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nat Rev Neurosci* 10: 345–359, 2009.
- Johansson RS, Westling G. Roles of glabrous skin receptors and sensory motor memory in automatic-control of precision grip when lifting rougher or more slippery objects. *Exp Brain Res* 56: 550–564, 1984.
- Kawato M. Internal models for motor control and trajectory planning. *Curr Opin Neurobiol* 9: 718–727, 1999.
- Kinoshita H, Backstrom L, Flanagan JR, Johansson RS. Tangential torque effects on the control of grip forces when holding objects with a precision grip. *J Neurophysiol* 78: 1619–1630, 1997.
- Kurtzer IL, Pruszynski JA, Scott SH. Long-latency reflexes of the human arm reflect an internal model of limb dynamics. *Curr Biol* 18: 449–453, 2008.
- Lukos J, Ansuini C, Santello M. Choice of contact points during multidigit grasping: effect of predictability of object center of mass location. *J Neurosci* 27: 3894–3903, 2007.
- Lukos JR, Ansuini C, Santello M. Anticipatory control of grasping: independence of sensorimotor memories for kinematics and kinetics. *J Neurosci* 28: 12765–12774, 2008.
- Monzée J, Lamarre Y, Smith AM. The effects of digital anesthesia on force control using a precision grip. *J Neurophysiol* 89: 672–683, 2003.
- Santello M, Soechting JF. Force synergies for multifingered grasping. *Exp Brain Res* 133: 457–467, 2000.
- Shim JK, Park J, Zatsiorsky VM, Latash ML. Adjustments of prehension synergies in response to self-triggered and experimenter-triggered load and torque perturbations. *Exp Brain Res* 175: 641–653, 2006.
- Westling G, Johansson RS. Factors influencing the force control during precision grip. *Exp Brain Res* 53: 277–284, 1984.
- Wing AM, Lederman SJ. Anticipating load torques produced by voluntary movements. *J Exp Psychol Hum Percept Perform* 24: 1571–1581, 1998.
- Witney AG, Wing A, Thonnard JL, Smith AM. The cutaneous contribution to adaptive precision grip. *Trends Neurosci* 27: 637–643, 2004.
- Zatsiorsky VM, Gregory RW, Latash ML. Force and torque production in static multifinger prehension: biomechanics and control. I. Biomechanics. *Biol Cybern* 87: 50–57, 2002.