

Effect of Object Width on Muscle and Joint Forces During Thumb–Index Finger Grasping

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The objective of this study was to identify the impact of modifying the object width on muscle and joint forces while gripping objects. The experimental protocol consisted to maintain horizontally five objects of different widths (3.5, 4.5, 5.5, 6.5, and 7.5 cm) with a thumb–index finger grip. Subjects were required to grasp spontaneously the object without any instruction regarding the grip force (GF) to apply. A biomechanical model of thumb–index finger pinch was developed to estimate muscle and joint forces. This model included electromyography, fingertip force, and kinematics data as inputs. The finger joint postures and the GF varied across the object widths. The estimated muscle forces also varied significantly according to the object width. Interestingly, we observed that the muscle force/GF ratios of major flexor muscles remain particularly stable with respect to the width whereas other muscle ratios differed largely. This may argue for a control strategy in which the actions of flexors were preserved in spite of change in joint postures. The estimated joint forces tended to increase with object width and increased in the distal–proximal sense. Overall, these results are of importance for the ergonomic design of handheld objects and for clinical applications.

Keywords: modeling, hand, pinch grip, object ergonomic, joint force, muscle force

Grasping objects or tools is a predominant daily life activity such that a loss of this function is recognized as a major handicap (Armstrong & Chaffin 1978; Engelberg, 1988; Meagher, 1987; Wainstein & Nailor, 2006). Obviously, the characteristics of the object grasped (width, load, shape) are predominant factors influencing the occurrence of pathologies. Particularly, the object width modifies the joint postures and so changes the muscle length, the muscle moment arms, and, finally, the muscle coordination could lead to more risky and/or fatiguing conditions (Chao et al., 1989; Cooney & Chao, 1977; Harding et al., 1993).

Many ergonomic studies have focused on the determination of the optimal object characteristics by selecting the width that maximizes the maximal grip force (MGF). Those studies typically report an inverted U-shape relationship, the optimal grip width varying around 5 cm depending on the posture adopted, the number of fingers involved, and the shape of the object (Blackwell et al., 1999; Dempsey & Ayoub, 1996; Fathallah et al., 1991; Fransson & Winkel, 1991). From an ergonomic point of view, submaximal grip forces have to be taken into account for pathology prevention since during daily life objects are often manipulated with less intensity than 100% of MGF. Some other studies focused on the motor

control of the external force spontaneously exerted (“grip force” [GF]) to hold an object (Westling & Johansson, 1984). Few studies have been interested in the effect of width on GF. Interestingly, in some conditions, the width that minimizes GF differs from the one that maximizes MGF, thus arguing for the including of GF concomitantly to MGF into the analysis (Domalain et al., 2008).

Even if these studies contribute to the understanding of grip tasks and to the object ergonomics, it remains crucial to understand how external forces (MGF and GF) are transmitted into internal forces exerted on muscles, tendons, and joints, which are the structures directly implicated in the pathologies. Indeed, because of finger postures and muscle coordination reorganization, a higher external force does not necessarily traduce higher internal forces and vice versa. As direct measurement of these variables is not possible, some biomechanical models of hand and fingers were developed: Cooney & Chao (1977) and Chao et al. (1976) used this type of model to estimate muscle forces exerted while gripping an object with two fingers. Sancho-Bru et al. (2001) validated a biomechanical model for power grip with different size but did not include the thumb in the analysis. The most developed models used both mechanical data (external force, kinematics) and physiological data (electromyography [EMG]) to estimate physiologically realistic muscle forces (Valero-Cuevas et al., 1998; Vigouroux et al., 2007).

In spite of this modeling possibility, nothing is known about the influence of the object width on muscle/joint forces while gripping an object. This leads to

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ergonomic conceptions that are currently focused on the external forces results only, without quantifying their impact on the anatomical structures. The objective of this study was thus to investigate the effect of object width on muscle forces and the joint forces. As a first step, the spontaneous grip of object with an index/thumb fingers pinch grip was studied. A biomechanical model of index/thumb was developed to determine internal forces. We hypothesized that even with the possible reorganization of joint postures, object width would significantly impact muscle and joint forces.

Methods

Subjects

Ten right-handed subjects participated in this study (age: 27.4 ± 3.9 years; height: 180.2 ± 4.0 cm; body mass: 76.6 ± 5.6 kg; hand size: 19.6 ± 0.6 cm; mean \pm *SD*). None of the participants had any history of trauma affecting the upper limbs. All subjects signed an informed consent approved by the university guidelines.

Experimental Setup and Procedure

The participants were seated in a chair with the right elbow and the palm of the hand supported by two clamps so that no effort was made by the muscles to stabilize the hand and wrist. The shoulder was placed at 45° of flexion and abduction. The elbow was fixed at 80° of flexion (full extension being 0°). The wrist was in neutral position (0° flexion and 0° of radio-ulnar deviation) with forearm pronated. The thumb and index finger were positioned next to the clamp so that they could move freely. The task consisted in grasping objects of five different widths (3.5, 4.5, 5.5, 6.5, and 7.5 cm). The weight of the five objects was equal (0.5 kg). The participants were instructed to maintain the object horizontally between the thumb and index finger for 6 s. Subjects were unaware of the characteristics of the objects and no particular instruction on how to grip was given. In addition, no verbal or visual feedback was given. Positioning of the object was recorded using three reflective markers. Surfaces at digit-object interface consisted of 8 mm diameter discs covered by fine-grain sandpaper (80 grains/cm²) and participants' digits were cleaned with alcohol before the experiment. Three trials were performed for each size object. The data of each condition were then averaged across the three trials. One minute rest periods were provided between each trial to avoid any effect of fatigue. The order of the conditions was randomized to avoid any order effect.

Fingertip Force

A six-axial force sensor (Nano-25, ATI Industrial Automation, Garner, NC) was embedded in the objects to record the grip force and the moments applied to the object. The force and moments signals were recorded at 100 Hz using National Instrument acquisition products (NI-PCI 6220, USA and a customized Labview program).

EMG

Surface EMG of five muscles (abductor pollicis brevis [APB]; abductor pollicis longus [APL]; extensor digitorum communis [EDC]; flexor pollicis longus [FPL], first radial interosseus [RI]) were recorded at 2 kHz with a BIOPAC system (band pass from 10 Hz to 5 kHz; amplification to 3 dB; common mode rejection ratio: >90 dB) and the associated Acqknowledge 3.8.1 software. Skin of the subjects was abraded and cleaned before electrode placement. Electrodes of 10 mm in width (EL503, Cerom) were used to record the APL, EDC, and FPL muscles. As APB and RI are small muscles, 4 mm electrodes (EL254S, Cerom) were used. Locations of the electrodes followed the recommendation of Basmajian and Blumenstein (1980). Notably, electrodes for FPL and APL muscles were located at the wrist side of the muscle belly: at this location, FPL and APL are not covered by other surface muscles. Accurate positioning of the electrodes was ensured by testing functional movements corresponding to the recorded muscle function. The EMG signals were filtered off-line using a zero-lag Butterworth filter (order 4, band pass from 20 to 400 Hz). Force and EMG acquisition tools were synchronized thanks to a rising edge trigger.

Kinematics

The 3D positioning of each thumb and index segment was recorded by a six-camera system (Vicon 624 Motion System, Oxford Metrics, England). Three spherical microreflective markers (4 mm in diameter) were fixed on each segment using T-shape supports. Three markers, placed on the metacarpal bones were used to define the dorsal hand plane reference system (R_{dhp}). Joint angles were computed from the 3D positioning of the segments for both thumb and index finger models. The thumb and index were both considered as four segments articulated by three joints. The interphalangeal joint of the thumb (IP), the distal and the proximal interphalangeal joints of the index (DIP, PIP) were considered as 1 degree of freedom (*df*) in flexion/extension. The metacarpophalangeal joints of the thumb and the index (MP and MCP), the trapeziometacarpal joint of the thumb (TMC) were considered as 2 *df* in flexion/extension and in adduction/abduction.

The angle of IP, MP, DIP, PIP, and MCP were defined as rotation between distal and proximal segments using reference systems placed on the metacarpal bones, the proximal phalanges, and the distal phalanges. The TMC joint angles were defined as the rotation between thumb metacarpal and the trapezium bone reference system (R_t). The positioning of R_t was determined from Cooney et al. (1981), who reported that R_t is rotated by 46° of flexion, 35° of abduction, and 82° of supination with respect to R_{dhp} . Angles were extracted from the rotation matrix using the Z, Y, X, Euler's sequence (i.e., flexion, abduction, supination) with fixed axes situated on the proximal segment to follow the method of Cooney et al. (1981). Abduction and flexion have positive values.

Data Analysis

Averaged fingertip forces and finger postures were calculated within a 750 ms window centered on the force plateau. Joint moments were then computed for input of biomechanical model. Within this time interval, muscle excitation levels for each muscle (e_m , with $m = \text{APB, APL, EDC, FPL, RI}$) were computed:

$$e_m = \frac{\text{RMS}_m}{\text{RMS}_{m \max}} \quad (1)$$

where RMS_m was the EMG root mean square value computed for each test (Basmajian & De Luca, 1985). The term $\text{RMS}_{m \max}$ corresponded to the largest root mean square value recorded during additional maximal voluntary tasks performed in the same posture in various external force directions (flexion, extension, adduction, and abduction of the thumb and index fingers).

Biomechanical Finger Model

The index and thumb musculoskeletal systems were modeled as previously described (Chao et al., 1989; Vigouroux et al., 2008, 2009) and were used to compute muscle forces. The index was mobilized by seven muscles (flexor digitorum profundus [FDP], flexor digitorum superficialis [FDS], lumbrical [LU], ulnar interosseus [UI], RI, EDC, extensor digitorum indicis [EDI]) and the thumb by nine muscles (FPL, flexor pollicis brevis [FPB], opponens pollicis [OPP], APB, adductor pollicis oblique head [ADPo], adductor pollicis transverse head [ADPt], APL, extensor pollicis longus [EPL], extensor pollicis brevis [EPB]). The model results in nine equilibrium moment equations and 16 unknown muscle forces summarized as follows:

$$[\mathbf{R}] \times \{\mathbf{T}\} + \{\mathbf{T}\} + \{\mathbf{F}\} = \{\mathbf{0}\} \quad (2)$$

where the 9×16 matrix $[\mathbf{R}]$ is the moment arms matrix obtained from moment arms of muscles and from the coefficients associated with the extensor mechanism (Vigouroux et al., 2007, 2009). The muscle moment arms were estimated from the finger joint angles for each finger using the results of Chao et al. (1989). The term $\{\mathbf{T}\}$ is the 16-element vector containing the unknown muscle forces, $\{\mathbf{L}\}$ is the vector containing the passive moment over MCP (Sancho-Bru et al., 2001) and TMC (see below) due to the ligament and passive joint structures, and $\{\mathbf{F}\}$ is the 9-element vector representing moments of external force at each degree of freedom of the index finger and thumb. Vector $\{\mathbf{F}\}$ was computed from the joint angles, the external fingertip forces, and the segment lengths. The under-determined problem was solved with an “optimization constrained by EMG” process (Vigouroux et al., 2007). This optimization process used a muscle stress criterion to determine an optimal set of muscle forces and included additional inequality constraints that account for the e_m of the muscles recorded by EMG. Results of the

optimization process were the muscle forces. Muscles forces were normalized by the external fingertip force (muscle force–external force ratio) to evaluate the action of muscles in regards to fingertip force. Using the nine equations of force equilibrium, the joint forces were computed for each joint. Thus, all muscle force intensities were considered as well as their respective unit force vector (determined by pulley and bones characteristics). This was performed by using the anthropometric data of Chao et al. (1989), which described the positioning of the tendons at each joint. The total intensity of each joint force was computed by considering both shear and normal components.

Passive Constraints

During pulp pinch grip, the TMC joint is naturally positioned near its end range of motion to provide the necessary stability at this joint (Napier, 1956). This leads to an important participation of soft tissues (skin, ligaments, tendons, etc.) in the equilibrium of joint forces. Thus, the results of Domalain et al. (2010) were used to determine the passive moment at the TMC and were included into Equation 1. Given the exponential behavior of passive structure stiffness, the model of Domalain et al. (2010) is highly sensitive to precision of joint angles and individual maximal amplitude estimation. Because our “light” experimental task resulted in little joint moments, the estimated passive moment represented in few cases a rather large proportion of the total joint moment. For this reason we arbitrarily limited the passive joint moment to 90% of the external joint moment. This limitation was required with 2 of our 10 subjects.

The passive constraints of IP, MP, DIP, and PIP joints were neglected, as these joints were mobilized far from their end range of motion.

Statistical Analysis

Descriptive statistics are mean and standard deviation ($\pm SD$). Normality of the results was verified. Repeated-measures ANOVAs were used to identify the effect of object size on external fingertip force, joint angles, muscle forces, muscle force–external force ratio, and joint forces. A level of $p < .05$ was considered as significant.

Results

The GFs spontaneously applied on the object (Figure 1) were significantly different with respect to the object width ($F_{(4,36)} = 4.0$; $p < .05$). The GFs amounted to 6.2 ± 1.8 N for a 3.5 cm object width, 5.7 ± 1.2 N for 4.5 cm, 4.8 ± 1.7 for 5.5 cm, 5.5 ± 1.0 N for 6.5 cm, and 6.0 ± 1.4 N for 7.5 cm.

In thumb, IP flexion ($F_{(4,36)} = 1.6$; $p > .05$), MP flexion ($F_{(4,36)} = 1.7$; $p > .05$), MP Abduction ($F_{(4,36)} = 1.6$; $p > .05$), and TMC abduction ($F_{(4,36)} = 0.22$; $p > .05$) did not vary significantly with respect to the object width. The

IP mean flexion was $13.3 \pm 12.5^\circ$, MP flexion averaged $3.5 \pm 9.1^\circ$. MP and TMC abduction averaged $15.9 \pm 8.7^\circ$ and $-8.2 \pm 8.6^\circ$ respectively. A significant effect ($F_{(4,36)} = 18.3$; $p < .05$) was observed for TMC flexion, which extend slightly and progressively to $19.1 \pm 4.8^\circ$, $17.1 \pm 4.3^\circ$, $14.7 \pm 6.1^\circ$, $12.5 \pm 5.8^\circ$, and $11.1 \pm 4.9^\circ$ for 3.5, 4.5, 5.5, 6.5, and 7.5 cm respectively. Index posture changes significantly with object width. Muscle DIP flexion ($F_{(4,36)} = 6.9$; $p < .05$) varied from $20.9 \pm 11.8^\circ$ with 3.5 cm, to $29.6 \pm 9.0^\circ$ with 7.5 cm. Muscle PIP flexion also varied

significantly ($F_{(4,36)} = 6.5$; $p < .05$) from $22.1 \pm 14.0^\circ$ at 3.5 cm, $17.2 \pm 11.5^\circ$ at 4.5 cm, $12.6 \pm 13.6^\circ$ at 5.5 cm, $11.2 \pm 10.3^\circ$ at 6.5 cm, and $13.8 \pm 11.2^\circ$ at 7.5 cm. Muscle MCP abduction did not vary significantly ($F_{(4,36)} = 1.91$; $p > .05$) and averaged $-4.0 \pm 9.4^\circ$. Muscle MCP extended progressively ($F_{(4,36)} = 13.0$; $p < .05$) from $55.6 \pm 12.6^\circ$ at 3.5 cm to $38.6 \pm 14.0^\circ$ at 7.5 cm.

Figures 2 and 3 show the muscle forces of index muscles and thumb muscles for a 5-cm-wide object. Table 1 displays the mean muscle forces observed in

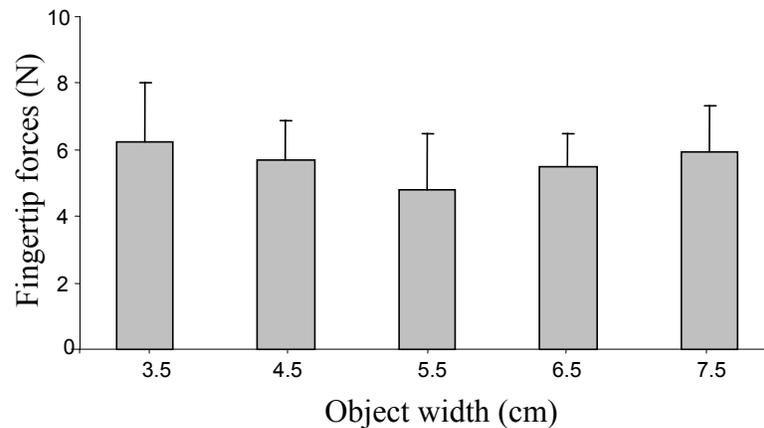


Figure 1 — Mean (*SD*) external forces (newtons) applied by the fingers on the object according to the object width. A significant effect of object width was observed on the force intensity.

Table 1 Mean muscle forces (in newtons) across the 10 subjects according to the object width

Muscle	Width of the Object				
	3.5 cm	4.5 cm	5.5 cm	6.5 cm	7.5 cm
FDP *	16.9 ± 6.7	14.0 ± 4.1	13.5 ± 7.9	14.5 ± 4.8	18.0 ± 9.6
FDS *	9.6 ± 4.4	13.6 ± 5.9	11.9 ± 7.0	17.8 ± 8.4	17.6 ± 5.7
LU	0.1 ± 0.02	0.1 ± 0.03	0.01 ± 0.03	0.00 ± 0.01	0.0 ± 0.0
RI	17.5 ± 7.9	16.5 ± 10.6	14.0 ± 7.8	20.7 ± 14.4	20.3 ± 15.1
UI *	6.4 ± 7.6	5.2 ± 7.7	5.3 ± 6.2	3.3 ± 7.5	1.7 ± 3.4
EDC *	8.4 ± 5.5	8.5 ± 5.2	9.6 ± 5.3	12.6 ± 7.6	12.0 ± 6.4
EDI *	7.3 ± 10.0	9.0 ± 8.8	11.6 ± 9.3	16.2 ± 12.3	15.5 ± 10.6
FPL	10.3 ± 5.4	10.5 ± 5.5	9.5 ± 5.0	9.6 ± 4.6	10.6 ± 5.0
FPB	0.1 ± 0.03	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.01
OPP *	18.3 ± 7.4	15.7 ± 6.8	12.9 ± 7.0	15.0 ± 6.5	20.3 ± 7.8
APB *	6.8 ± 2.8	4.5 ± 2.1	3.3 ± 1.6	2.9 ± 1.8	3.2 ± 1.9
ADPo *	2.6 ± 1.3	2.7 ± 1.3	1.8 ± 1.4	2.7 ± 1.3	2.7 ± 1.3
ADPt *	18.7 ± 9.5	19.1 ± 9.4	13.1 ± 10.1	19.4 ± 9.6	19.3 ± 9.2
APL	9.5 ± 3.8	8.5 ± 3.0	8.9 ± 3.1	8.8 ± 3.1	9.5 ± 3.4
EPL *	13.5 ± 6.6	14.9 ± 6.3	15.3 ± 6.3	18.5 ± 6.8	20.2 ± 8.4
EPB *	0.3 ± 0.9	0.7 ± 0.9	1.4 ± 0.9	1.4 ± 0.8	1.5 ± 0.9

Note. *Indicates a significant effect of object width ($p < .05$). The top portion of the table presents the index finger muscles, whereas the bottom portion presents the thumb muscles.

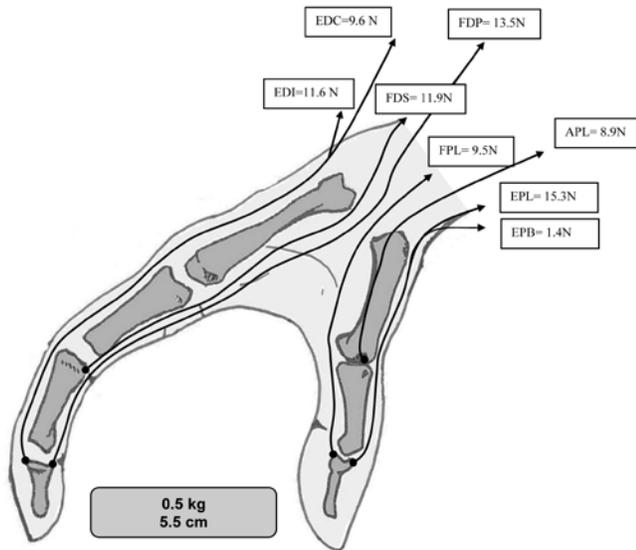


Figure 2 — Schematic representation of muscle forces applied by the extrinsic muscles acting on thumb and index finger during a 5.5-cm-wide object.

each muscle with respect to the object width. There is a significant effect of object width for FDP ($F_{(4,36)} = 2.7$; $p = .05$), FDS ($F_{(4,36)} = 7.3$; $p < .05$), UI ($F_{(4,36)} = 4.4$; $p < .05$), EDC ($F_{(4,36)} = 2.6$; $p = .05$), and EDI ($F_{(4,36)} = 3.5$; $p < .05$). Muscles FDP, FDS, and RI developed the highest force intensities for the index finger. Concerning thumb muscles, a significant effect of object width on muscle force was observed for ADPt ($F_{(4,36)} = 4.0$; $p < .05$), ADPo ($F_{(4,36)} = 3.6$; $p < .05$), APB ($F_{(4,36)} = 4.8$; $p < .05$), OPP ($F_{(4,36)} = 3.1$; $p < .05$), EPL ($F_{(4,36)} = 4.2$; $p < .05$), and EPB ($F_{(4,36)} = 8.3$; $p < .05$). Muscles FPL, FPB, and APL presented no significant difference ($p > .05$) with respect to object width. The highest muscle forces were observed in FPL, OPP, ADPt, and EPL muscles for thumb.

Figure 4 shows the muscle force–external force ratio with respect to the object width.

The effect of object width was significant for FDS ($F_{(4,36)} = 8.2$; $p < .05$), UI ($F_{(4,36)} = 4.5$; $p < .05$), EDC ($F_{(4,36)} = 3.1$; $p < .05$), and EDI ($F_{(4,36)} = 3.7$; $p < .05$). For EDI, EDC, and FDS, the ratios increase with the increase in object width, whereas for UI, we observed a decrease. No significant effect of object width was observed for FDP, LU, and RI muscles. Concerning the thumb, the effect of object width on muscle force–external force ratio was significant for ADPo ($F_{(4,36)} = 4.0$; $p < .05$), ADPt ($F_{(4,36)} = 4.0$; $p < .05$), APB ($F_{(4,36)} = 2.8$; $p < .05$), OPP ($F_{(4,36)} = 2.75$; $p < .05$), EPL ($F_{(4,36)} = 7.0$; $p < .05$), EPB ($F_{(4,36)} = 7.3$; $p < .05$). For EPL and EPB, the muscle force–external force ratio increased with object width; APB decreased progressively, whereas OPP, ADPt, and ADPo did not show a simple evolution. No significant effect appeared for FPL, FPB, and APL.

Figure 5 presents the joint forces with respect to the object width. A significant effect of object width

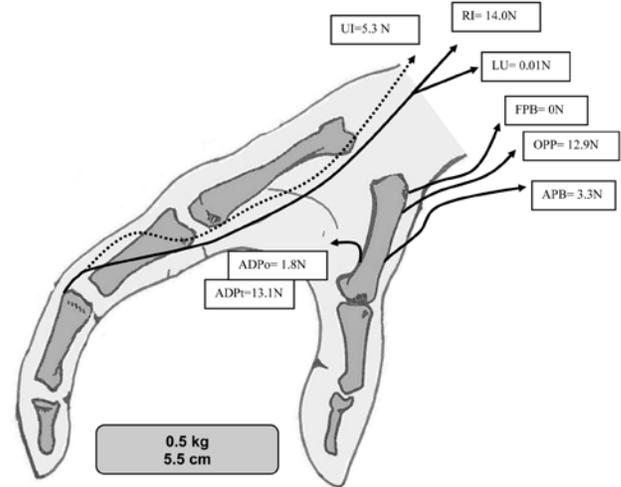


Figure 3 — Schematic representation of muscle forces applied by the intrinsic muscles acting on thumb and index finger during a 5.5-cm-wide object.

was observed in the PIP joint ($F_{(4,36)} = 4.0$; $p < .05$). No significant effect was observed in the TMC ($F_{(4,36)} = 1.9$; $p = .13$) and IP ($F_{(4,36)} = 0.3$; $p = .8$) although a significant tendency was observed for the DIP joint ($F_{(4,36)} = 2.2$; $p = .09$), MCP ($F_{(4,36)} = 2.47$; $p = .06$), and MP ($F_{(4,36)} = 2.1$; $p = .09$). Whatever the width and the finger, the finger joint force increased from IP and DIP to MP and MCP. Mean joint forces ranged from 13.9 N for the distal joints (IP and DIP) to 76.5 N for the proximal joints (MCP, TMC).

Discussion

This study aimed to explore the effect of the object width on the muscle forces and joint forces while gripping spontaneously an object. The understanding of the internal constraints caused by changes in object width could have a great impact first for the ergonomics field, to shape objects and tools which prevent pathology and fatigue, and second for the clinical field, to improve surgical and rehabilitation programs.

As previously observed, the index finger adapted its posture (DIP flexion increased while PIP and MCP extended) to the object width whereas the thumb postures changed in smallest proportion (only TMC flexion slightly decreased with object width). The grip force used to maintain the object was different with respect to the object width. It was well defined in the literature that people use more force than necessary to grip and hold an object, and that is generally defined as a “security margin” (Westling & Johansson, 1984). The current results of grip force demonstrated that the security margin varied with respect to the object width in spite of the similar weight, contact surfaces, and friction characteristics. This phenomenon was already observed in the literature but has still remained unexplained (Domalain et al. 2008). In our study, we showed an inverted U-shape relationship

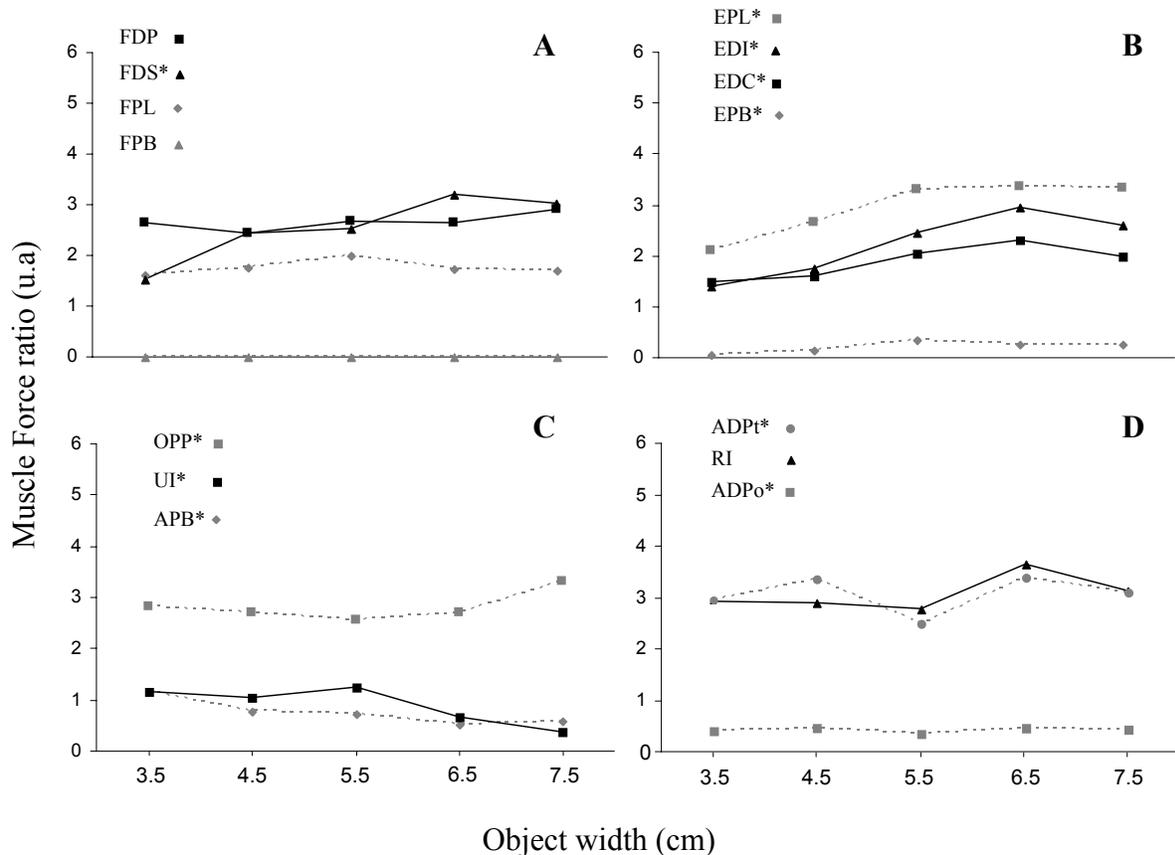


Figure 4 — Mean muscle force–external force ratio (u.a) observed in flexor muscles (A), extensor muscles (B), abductor muscles (C), and adductor muscles (D) according to object width. Thumb muscles were drawn with gray dashed lines and index muscles with black lines. To keep the figure clear, the *SD* values were not included. The variability could be, however, appreciated in Figure 1 and in Table 1, which represent the mean and *SD* of the two variables used to compute the muscle force–external force ratio.

centered at 5.5 cm width, which differed from Domalain et al. (2008), who showed an increase from 3.5 cm to 9.5 cm. This might be explained by the fact that in the current study we did not test a 9.5-cm-wide object, where the greatest differences were observed in Domalain et al. (2008). Moreover, we tested a smaller load (0.5 kg) than in Domalain et al. (1, 1.5, and 2.25 kg), who observed the largest effect with the largest load. Globally, this result showed that the central nervous system did not consider the intensity of GF and the value of security margin as an absolute objective. The parameters the GF was adjusted to still remain unknown and are probably numerous. However, the results of muscle forces indicate to us that they may be considered into the reflection. The change in grip force and in finger postures resulted in significant changes in all muscles excepted in EPL, APL, FPB for the thumb, and RI and LU for the index finger. Similar effects were observed in the muscle force–external force ratios, except for the FDP muscle, which remained constant. When looking globally at these changes, one can observe an increase of extensor muscle force–external

force ratio in both index (EDC and EDI) and thumb (EPL and EPB) with the increased width. This phenomenon could be associated to a strategy that would consist of extending the posture of MCP and TMC to account for the increase of object width. It was also observed that UI and APB progressively decreased their forces with the increase of object width. Then the muscles acting on the opposite side of the finger–object contact surface were less and less solicited. Even if extensor muscles and adductor/abductor muscles acted as antagonist in the studied tasks, we hypothesized that their actions were crucial to stabilize the joints and to position the joints in favorable conditions. The purpose of such a strategy could be to first adapt a favorable joint posture in order that the fingertip was placed ideally on the object and second that joint angles were favorable for the flexor muscle action. This hypothesis is enforced by the fact that FPL and FDP were solicited in a constant manner (stable muscle force–external force ratio) in spite of object width changes. This suggests that angles, muscle coordination may be selected to keep these ratios constant. Muscles

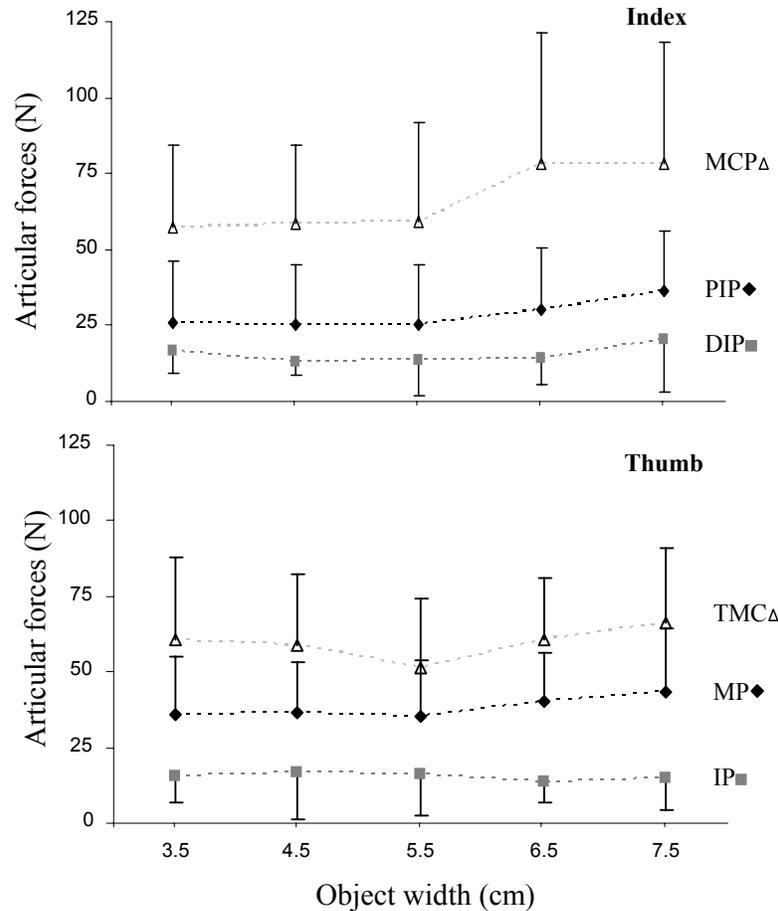


Figure 5 — Mean (*SD*) joint forces in index joints (upper figure) and thumb joints (figure below). The blocks represent the total intensity of the joint forces computed from both shear and normal components of the force. Distal joints (IP and DIP) were represented as a gray square (■), middle joints (PIP, MP) with a black rhombus (◆), and proximal joints (TMC and MCP) with an open triangle (△).

FPL and FDP were indeed the only flexors acting on the distal joints. These muscles were thus crucial for the success of the task. Then adapting the action of other muscles not directly implicated in the task to preserve the action of FPL and FDP could be a strategy to success in the task whatever the object width.

Concerning the joint forces, no significant effect was observed except for the PIP joint. In spite of no significant effect, a tendency was observed in DIP, MP, and MCP. The values of joint forces indeed increased progressively with the width but not significantly. It would be interesting to test larger widths (8.5 and 9.5 cm) to confirm or negate these tendencies. Whatever the effect of object width, we observed a large increase of joint forces with the proximity of the joints. DIP and IP joint forces were inferior to PIP and MP joint forces, which are in turn inferior to MCP and TMC. This phenomenon could be explained by the action of the muscle. More muscles act on proximal joints and create thus more compressive forces than on distal joint crossed by fewer muscles. These considerations and the estimated values may be

taken into account in the analysis of such pathologies as arthritis.

The use of biomechanical models is the only method available to provide quantitative data of internal forces. However, it should be noted that the provided estimations of muscle and joint forces could be a source of errors due to error in kinematic analysis, EMG recording, anthropometric data, and the solving of the under-determined problem (Valero-Cuevas et al., 2003; Vigouroux et al., 2009). The results of 0 N of tension presented in LU and FPB muscles were probably examples of this kind of error. The results and conclusions of this study thus should be considered by keeping in mind these limits. As a second limitation, it should be considered that the hand size of the tested subjects averaged 19.6 ± 0.6 cm. During grasping, the hand size of the subjects could modify the joint posture, the net joint moment, the lengths of bones, and muscle moment arms. Consequently, it is not known if our conclusions are still valid for subjects with especially large or small hands.

To summarize, this study detailed the effect of object width on external forces and internal forces. It was shown that the changes of external forces (following an inverted-U relationship) were not necessarily followed by similar changes in muscle forces and joint forces. This suggested a coordination strategy to preserve the action of the muscles directly implicated in the success of the task. From an ergonomics point of view, our results would suggest limiting the largest objects to preserve extensor muscles. This argument becomes crucial when considering that during grip (i.e., flexing) fatiguing exercise, extensors fatigued at the same rate as the flexors (Quaine et al., 2003). Moreover, our results suggested that gripping an object with the fingertips may have a great impact on proximal joints due to muscle compression. Further research is needed to compare this effect when grip force is applied at the level of proximal and middle phalanges, as during five-digit grasping.

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