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4 **EFFECT OF OBJECT WIDTH ON MUSCLE AND JOINT FORCES**
5 **DURING THUMB-INDEX FINGER GRASPING**

6

7 Laurent VIGOUROUX¹; Mathieu DOMALAIN¹; Eric BERTON¹

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9 ¹Movement Sciences Institute, Etienne Jules Marey, UMR 6233, Mediterranean University,
10 Marseille, France.

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15 Corresponding author:

16 Laurent VIGOUROUX

17 Address: U.M.R. 6233 Institut des Sciences du Mouvement,
18 Faculté des Sciences du Sport,
19 Case postale 910,
20 163, avenue de Luminy
21 F-13288 Marseille Cedex 09 France

22 Phone: +33 (0)4 91 17 04 22

23 Fax: +33 (0)4 91 17 22 52

24 Email: laurent.vigouroux@univmed.fr

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

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28

29 **Abstract (196 words):**

30 The objective of this study was to identify the impact of modifying the object width on tendon
31 tensions and joint forces while gripping objects. The experimental protocol consisted to
32 maintain horizontally five objects of different widths (3.5, 4.5, 5.5, 6.5 and 7.5 cm) with a
33 thumb-index finger grip. Subjects were required to grasp spontaneously the object without
34 any consign of applied fingertip force (GF). A biomechanical model of thumb-index finger
35 pinch was developed to estimate tendon tensions and joint forces. This model included
36 electromyography, fingertip force and kinematics data as inputs. The finger joint postures and
37 the GF varied across the object widths. The estimated muscle forces also varied significantly
38 according to the object width. Interestingly, we observed that the tendon tension/GF ratios of
39 major flexors muscles remain particularly stable with respect to the width while other muscles
40 ratios differed largely. This may argue for a control strategy in which the actions of flexors
41 were preserved in spite of change in joint postures. The estimated joint forces tended to
42 increase with object width and increased in the distal-proximal sense. Overall, these results
43 are of importance for the ergonomic design of hand held objects and clinical problematic.

44

45 **Introduction**

46 Grasping objects or tools is a predominant daily life activity such as a loss of this
47 function is recognized as a major handicap (Armstrong & Chaffin1978; Engelberg, 1988;
48 Meagher, 1987; Wainstein & Nailor, 2006). Obviously, the characteristics of the object
49 grasped (width, load, shape) are predominant factors influencing the occurrence of
50 pathologies. Particularly, the object width modifies the joint postures and so changes the
51 muscle length, the muscle moment arms and finally, the muscle coordination what may lead
52 to more risked and/or fatiguing conditions (Chao et al., 1989; Cooney & Chao, 1977; Harding
53 et al., 1993).

54 Many ergonomic studies have focused on the determination of the optimal object
55 characteristics by selecting the width which maximizes the maximal grip force (MGF). Those
56 studies typically report an inverted U-shape relationship, the optimal grip width varying
57 around 5cm depending on the posture adopted, the number of fingers involved and the shape
58 of the object (Blackwell et al., 1999; Dempsey & Ayoub, 1996; Fathallah et al., 1991;
59 Fransson & Winkel, 1991). From an ergonomic point of view, submaximal grip forces have to
60 be taken into account for pathology prevention since during daily life objects are often
61 manipulated with less intensity than 100% of MGF. Some other studies focused on the motor
62 control of the external force spontaneously exerted ('grip force' GF) to hold an object
63 (Westling & Johansson, 1984). Few studies interested in the effect of width on GF.
64 Interestingly, in some conditions the width which minimizes GF differs from the one which
65 maximise MGF arguing for the including of GF concomitantly to MGF into the analysis
66 (Domalain et al., 2008).

67 Even if these studies contribute to the understanding of grip tasks and to the object
68 ergonomics, it remains crucial to understand how external forces (MGF and GF) are

69 transmitted into internal forces exerted on muscles, tendons and joints which are the structures
70 directly implicated in the pathologies. Indeed, because of finger postures and muscle
71 coordination reorganization, a higher external force does not necessarily traduce higher
72 internal forces and the other way round. As direct measurement of these variables is not
73 possible, some biomechanical models of hand and fingers were developed: Cooney & Chao
74 (1977) and Chao et al., (1976) used this type of model to estimate muscle forces exerted while
75 gripping an object with two fingers. Sancho-Bru et al. (2001) validated a biomechanical
76 model for power grip with different size but did not include the thumb into the analysis. The
77 most developed models used both mechanical data (external force, kinematics) and
78 physiological data (electromyography, EMG) to estimate physiologically realistic muscle
79 forces (Valero-Cuevas et al., 1998; Vigouroux et al., 2007).

80 In spite of this modeling possibility, nothing is known about the influence of the object width
81 on muscle/joint forces while gripping an object. This leads to ergonomic conceptions which
82 are currently focused on the external forces results only, without quantifying their impact on
83 the anatomical structures. The objective of this study was thus to investigate the effect of
84 object width on muscle forces and the joint forces. As a first step, the spontaneous grip of
85 object with an index/thumb fingers pinch grip was studied. A biomechanical model of
86 index/thumb was developed to determine internal forces. We hypothesized that even with the
87 possible reorganization of joint postures, object width would impact significantly muscle and
88 joint forces.

89 **Methods**

90 *Subjects*

91 Ten right-handed subjects participated in this study (age: 27.4 ± 3.9 years; height: 180.2 ± 4.0
92 cm; body mass: 76.6 ± 5.6 kg; hand size: 19.6 ± 0.6 cm; Mean \pm SD). None of the participant

93 had any history of trauma affecting the upper limbs. All subjects signed an informed consent
94 approved by the University guideline.

95 *Experimental set-up and procedure*

96 The participants were seated in a chair with the right elbow and the palm of the hand
97 supported by two clamps so that no effort was made by the muscles to stabilize the hand and
98 wrist. The shoulder was placed at 45° of flexion and abduction. The elbow was fixed at 80° of
99 flexion (full extension being 0°). The wrist was in neutral position (0° flexion and 0° of radio-
100 ulnar deviation) with forearm pronated. The thumb and index finger were positioned next to
101 the clamp so that they could move freely. **The task consisted in grasping objects of five**
102 **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).**
103 **The participants were instructed to maintain the object horizontally between their index and**
104 **thumb fingers during 6 seconds. Subjects were unaware of the characteristics of the objects**
105 **and no particular consign on how to grip was given. Also, no verbal or visual feedback was**
106 **given.** Positioning of the object was recorded using three reflective markers. Surfaces at digit-
107 object interface consisted of 8 mm diameter discs covered by fine grain sandpaper (80
108 grains/cm²) and participants' digits were cleaned with alcohol before the experiment. Three
109 trials were performed for each size object. One minute rest periods were provided between
110 each trial to avoid any effect of fatigue. The order of the conditions was randomized to avoid
111 any order effect.

112 *Fingertip force*

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

117 *EMG*

118 Surface EMG of five muscles (*abductor pollicis brevis* APB; *abductor pollicis longus* APL;
119 *Extensor digitorum communis*, EDC; *flexor pollicis longus* FPL, *First Radial Interosseous* RI)
120 were recorded at 2 kHz with a BIOPAC system (bandpass from 10Hz to 5 kHz; amplification
121 to 3db; common mode rejection ratio: >90dB) and the associated Acqknowledge 3.8.1
122 software. Skin of the subjects was abraded and cleaned before electrodes placement. 10 mm
123 width electrodes (EL503, Cerom) were used to record APL, EDC, FPL. As APB and RI were
124 small sized muscles, 4 mm Electrodes (EL254S, Cerom) were used to record their activities.
125 Placements of electrodes were made according to Basmajian and Blumstein (1989) and were
126 adjusted by palpation. Good positioning of the electrodes was ensured by testing functional
127 movements corresponding to the recorded muscle function. Concerning the FPL and APL
128 muscles, the positioning of the electrodes was made closed to the wrist at the beginning of the
129 muscle belly. At this location, FPL and APL are not covered by other surface muscles. EMG
130 signals were filtered off-line using a zero-lag Butterworth filter (order 4, bandpass from 20 to
131 400 Hz). Force and EMG acquisition tools were synchronized thanks to a rising edge trigger.

132 *Kinematic*

133 The 3D positioning of each thumb and index segment was recorded by a six cameras system
134 (Vicon 624 Motion System, Oxford Metrics, England). Three spherical micro-reflective
135 markers (4 mm diameter) were fixed on each segment using T-shape supports. Three markers,
136 placed on the metacarpal bones were used to define the dorsal hand plane reference system
137 (\mathcal{R}_{dhp}). Joint angles were computed from the 3D positioning of the segments for both thumb
138 and index finger models. The thumb and index were both considered as four segments
139 articulated by three joints. The interphalangeal joint of the thumb (IP), the distal and the
140 proximal interphalangeal joints of the index (DIP, PIP) were considered as 1 degree of

141 freedom (DoF) in flexion/extension. The metacarpophalangeal joints of the thumb and the
142 index (MP and MCP), the trapeziometacarpal joint of the thumb (TMC) were considered as 2
143 DoFs in flexion/extension and in adduction/abduction.

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

153 *Data analysis*

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

$$158 \quad e_m = \frac{\text{RMS}_m}{\text{RMS}_{m \max}} \quad (1)$$

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

163 *Biomechanical finger model*

164 The index and thumb musculo-skeletal systems were modeled as previously described (Chao
165 et al., 1989; Vigouroux et al., 2008; Vigouroux et al., 2009) and were used to compute muscle
166 forces. The index was mobilised by 7 muscles (*flexor digitorum profundus* FDP, *flexor*
167 *digitorum superficialis* FDS, *lumbrical* LU, *ulnar interosseus* UI, RI, EDC, *extensor*
168 *digitorum indicis* EDI) and the thumb by 10 muscles (FPL, *flexor pollicis brevis* FPB,
169 *opponents pollicis* OPP, APB, *adductor pollicis* oblique head ADPo, *adductor pollicis*
170 *transverse head* ADPt, APL, *extensor pollicis longus* EPL, *extensor pollicis brevis* EPB). The
171 model results in 9 equilibrium moment equations and 16 unknown muscle forces resumed as
172 follow:

$$173 \quad [R] \cdot \{T\} + \{L\} + \{F\} = \{0\} \quad (2)$$

174 where the 9×16 matrix $[R]$ is the moment arms matrix obtained from moment arms of
175 muscles and from the coefficients associated with the extensor mechanism (Vigouroux et al.,
176 2007; Vigouroux et al., 2009). The muscle moment arms were estimated from the finger joint
177 angles for each finger using the results of Chao et al. (1989). $\{T\}$ is the 16-elements vector
178 containing the unknown muscle forces. $\{L\}$ is the vector containing the passive moment over
179 MCP (Sancho-Bru et al., 2001) and TMC (see part below) due to the ligament and passive
180 joint structures. $\{F\}$ is the 9-elements vector representing moments of external force at each
181 degree of freedom of the index and thumb fingers. $\{F\}$ was computed from the joint angles,
182 the external fingertip forces and the segment lengths. The under-determined problem was
183 solved with an “optimization constrained by EMG” process (Vigouroux et al., 2007). This
184 optimization process used a muscle stress criterion to determine an optimal set of muscle
185 forces and included additional inequality constraints which account for the e_m of the muscles
186 recorded by EMG. Results of the optimization process were the muscle forces. Muscles forces

187 were normalized by the external fingertip force (muscle force-external force ratio) in order to
188 evaluate the action of muscles in regards to fingertip force. Using the nine equations of force
189 equilibrium the joint forces were computed for each joint. For this computing, all muscle
190 force intensities were considered as well as their respective unit force direction vector. This
191 was performed by using the anthropometric data of Chao et al. (1989) which described the
192 positioning of the tendons at each joint according to pulley and bones characteristics. The
193 intensity of each joint force was computed by considering both shear and normal components.

194 *Passive constraints*

195 During pulp pinch grip, the TMC joint is naturally positioned near its end range of motion to
196 provide the necessary stability at this joint (Napier, 1956). This leads to an important
197 participation of soft tissues (skin, ligaments, tendons, etc.) in the equilibrium of joint forces.
198 Thus, the results of Domalain *et al.* (2010) were used to determine the passive moment at the
199 TMC and were included into the Eq. 1 ($\{L\}$). The model of Domalain et al. (2010) is a
200 generic model which could be sensible to kinematic errors and individual properties. As the
201 amplitude of external force moments in the current gripping tasks were weak in regards to
202 maximal voluntary forces, the estimation error could thus represent a larger proportion. For
203 some subjects this resulted in TMC passive moments slightly superior than external force
204 moment. In this case, we decided to limit the passive joint moment to 90% of the external
205 joint moment. The passive constraints of IP, MP, DIP and PIP joints were neglected as these
206 joints were mobilized far from their end range of motion.

207 *Statistical analysis*

208 Results of each subject were averaged across the three trials. Normality of the results was
209 verified. Descriptive statistics are mean and standard deviation (\pm SD). Repeated-measure

210 Anovas were used to identify the effect of object size on external fingertip force, joint angles,
211 muscle forces, muscle force-external force ratio and joint forces. A level of $p < 0.05$ was
212 considered as significant.

213 **Results**

214 GF spontaneously applied on the object (Fig. 1) were significantly different with respect to
215 the object width ($F(4,36)=4.0$; $p < 0.05$). GF amounted to 6.2 ± 1.8 N for a 3.5cm object width,
216 5.7 ± 1.2 N for 4.5cm, 4.8 ± 1.7 for 5.5cm, 5.5 ± 1.0 N for 6.5cm and 6.0 ± 1.4 N for 7.5cm.

217 In thumb, IP flexion ($F(4,36)=1.6$; $p > 0.05$), MP flexion ($F(4,36)=1.7$; $p > 0.05$), MP Abduction
218 ($F(4,36)=1.6$; $p > 0.05$) and TMC abduction ($F(4,36)=0.22$; $p > 0.05$) did not varied significantly
219 with respect to the object width. IP mean flexion was $13.3^\circ \pm 12.5$, MP flexion averaged
220 $3.5^\circ \pm 9.1$. MP and TMC abduction averaged $15.9^\circ \pm 8.7$ and -8.2 ± 8.6 respectively. A
221 significant effect ($F(4,36)=18.3$; $p < 0.05$) was observed for TMC flexion which extend slightly
222 and progressively to $19.1^\circ \pm 4.8$, $17.1^\circ \pm 4.3$, $14.7 \pm 6.1^\circ$, $12.5^\circ \pm 5.8$, $11.1^\circ \pm 4.9$ for 3.5, 4.5, 5.5,
223 6.5 and 7.5cm respectively. Index posture changes significantly with object width. DIP
224 flexion ($F(4,36)=6.9$; $p < 0.05$) varied from $20.9 \pm 11.8^\circ$ with 3.5 cm, to $29.6 \pm 9.0^\circ$ with 7.5cm.
225 PIP flexion also varied significantly ($F(4,36)=6.5$; $p < 0.05$) from $22.1 \pm 14.0^\circ$ at 3.5cm,
226 $17.2 \pm 11.5^\circ$ at 4.5cm, $12.6 \pm 13.6^\circ$ at 5.5cm, $11.2 \pm 10.3^\circ$ at 6.5cm and $13.8 \pm 11.2^\circ$ at 7.5cm.
227 MCP abduction did not varied significantly ($F(4,36)=1.91$; $p > 0.05$) and averaged $-4.0^\circ \pm 9.4$.
228 MCP extend progressively ($F(4,36)=13.0$; $p < 0.05$) from $55.6 \pm 12.6^\circ$ at 3.5cm to $38.6 \pm 14.0^\circ$ at
229 7.5cm.

230 The figure 2 and 3 represents the muscle forces of index muscles and thumb muscles for a
231 5cm width object. The table 1 displays the mean muscle forces observed in each muscle with
232 respect to the object width. There is a significant effect of object width for FDP ($F(4,36)=2.7$;
233 $p = 0.05$), FDS ($F(4,36)=7.3$; $p < 0.05$), UI ($F(4,36)=4.4$; $p < 0.05$), EDC ($F(4,36)=2.6$; $p = 0.05$),

234 and EDI ($F(4,36)=3.5; p<0.05$). FDP, FDS and RI developed the highest force intensities for
235 the index finger. Concerning thumb muscles, a significant effect of object width on muscle
236 force was observed for ADPt ($F(4,36)=4.0; p<0.05$), ADPo ($F(4,36)=3.6; p<0.05$), APB
237 ($F(4,36)=4.8; p<0.05$), OPP ($F(4,36)=3.1; p<0.05$), EPL ($F(4,36)=4.2; p<0.05$) and EPB
238 ($F(4,36)=8.3; p<0.05$). FPL, FPB and APL presented no significant difference ($p>0.05$) with
239 respect to object width. The highest muscle forces were observed in FPL, OPP, ADPt and
240 EPL muscles for thumb.

241 The figure 4 represents the muscle force-external force ratio with respect to the object width.

242 The effect of object width was significant for FDS ($F(4,36)=8.2; p<0.05$), UI ($F(4,36)=4.5;$
243 $p<0.05$), EDC ($F(4,36)=3.1; p<0.05$), and EDI ($F(4,36)=3.7; p<0.05$). For EDI, EDC and FDS
244 the ratios increase with the increase in object width while for UI, we observed a decrease. No
245 significant effect of object width was observed for FDP, LU and RI muscle. Concerning the
246 thumb, the effect of object width on muscle force-external force ratio was significant for
247 ADPo ($F(4,36)=4.0; p<0.05$), ADPt ($F(4,36)=4.0; p<0.05$), APB ($F(4,36)=2.8; p<0.05$), OPP
248 ($F(4,36)=2.75; p<0.05$), EPL ($F(4,36)=7.0; p<0.05$), EPB ($F(4,36)=7.3; p<0.05$). EPL and
249 EPB muscle force-external force ratio increased with object width, APB decreased
250 progressively while OPP, ADPt and ADPo did not showed a simple evolution. No significant
251 effect appeared for FPL, FPB and APL.

252 Figure 5 presents the joint forces with respect to the object width. A significant effect of
253 object width was observed in PIP joint ($F(4,36)=4.0; p<0.05$). No significant effect was
254 observed in the TMC ($F(4,36)=1.9; p>0.12$) although a significant tendency was observed for
255 DIP joint ($F(4,36)=2.2; p=0.09$), MCP ($F(4,36)=2.47; p=0.06$), IP ($F(4,36)=0.3; p=0.8$), MP
256 ($F(4,36)=2.1; p=0.09$). Whatever the width and the finger, the finger joint force increased

257 from IP and DIP to MP and MCP. Mean joint forces ranged from 13.9N for the distal joints
258 (IP and DIP) to 76.5N for the proximal joints (MCP, TMC).

259 **Discussion**

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

265 As previously observed, the index finger adapted its posture (DIP flexion increased while PIP
266 and MCP extended) to the object width while the thumb postures changes in smallest
267 proportion (only TMC flexion slightly decreased with object width). The grip force used to
268 maintain the object was different with respect to the object width. It was well defined into the
269 literature that people use more force than necessary to grip and hold an object what is
270 generally defined as a “security margin” (Westling & Johansson, 1984). The current results of
271 grip force demonstrated that the security margin varied with respect to the object width in
272 spite of the similar weight, contact surfaces and friction characteristics. This phenomenon was
273 already observed into the literature but has still remained unexplained (Domalain et al. 2008).
274 In our study we showed an inverted U-shape relationship centered at 5.5 cm width which
275 differed from Domalain et al. (2008) who showed an increase from 3.5 cm to 9.5 cm. This
276 might be explained by the fact that in the current study we didn’t test a 9.5 cm width object
277 where the greatest differences were observed in Domalain et al. (2008). Moreover, we tested
278 smaller load (0.5kg) than in Domalain et al. (2008) (1kg, 1.5kg and 2.25kg) who observed the
279 largest effect with the largest load. Globally, this result showed that the central nervous
280 system (CNS) did not consider the intensity of GF and the value of security margin as an

281 absolute objective. The parameters the GF was adjusted to still remain unknown and are
282 probably numerous. However, the results of muscle and tendon forces indicate us that they
283 may be considered into the reflection.

284 The change in grip force and in finger postures resulted in significant changes in all muscles
285 excepted in EPL, APL, FPB for the thumb and RI, LI for the index finger. Similar effects
286 were observed in the muscle force/external force ratios excepted for the FDP muscle which
287 remained constant. When looking globally at these changes, one can observe an increase of
288 extensor muscle force-external force ratio in both index (EDC and EDI) and thumb (EPL and
289 EPB) with the increased width. This phenomenon could be associated to a strategy which
290 would consist in extending the posture of MCP and TMC to account for the increase of object
291 width. It was also observed that UI and APB decreased progressively their forces with the
292 increase of object width. Then the muscles acting on the opposite side of the finger-object
293 contact surface were less and less solicited. Even if extensor muscles and adductor/abductor
294 muscles acted as antagonist in the studied tasks, we hypothesized that their actions were
295 crucial to stabilize the joints and to position the joints in favorable conditions. The purpose of
296 such a strategy could be to first adapt a favorable joint posture in order that the finger tip was
297 placed ideally on the object and second that joint angles were favourable for the flexor muscle
298 action. This hypothesis is enforced by the fact that FPL and FDP were solicited in a constant
299 manner (stable muscle force-external force ratio) in spite of object width changes. This
300 suggests that angles, muscle coordination may be selected in order to keep these ratios
301 constant. FPL and FDP were indeed the only flexors acting on the distal joints. These muscles
302 were thus crucial for the success of the task. Then adapting the action of other muscles not
303 directly implicated in the task to preserve the action of FPL and FDP could be a strategy to
304 success the task whatever the object width.

305 Concerning the joint forces, no significant effect was observed except for the PIP joint. In
306 spite of no significant effect, a tendency was observed in DIP, MP and MCP. The values of
307 joint forces indeed increased progressively with the width but not significantly. It would be
308 interesting to test larger widths (8.5 and 9.5 cm) to confirm or infirm these tendencies.

309 Whatever the effect of object width, we observed a large increase of joint forces with the
310 proximity of the joints. DIP and IP joint forces were inferior to IP an MP joint forces which
311 are in turn inferior to MCP and TMC. This phenomenon could be explained by the action of
312 the muscle. More muscles act on proximal joints and create thus more compressive forces
313 than on distal joint crossed by fewer muscles. These considerations and the estimated values
314 may be taken into account for pathologies analysis such arthritis.

315 The use of biomechanical models is the single methods available to provide quantitative data
316 of internal forces. However, it should be noticed that the provided estimations of muscle and
317 joint forces could be source of errors due to error in kinematic analysis, EMG recording and
318 anthropometric data, under-determined problem (Valero-Cuevas et al., 2003; Vigouroux et
319 al., 2009). The results of 0N tension presented in LU and FPB muscles were probably witness
320 of this kind of errors. The results and conclusions of this study thus should be considered by
321 keeping in mind these limits. As a second limitation, it should be considered that the hand size
322 of the tested subjects averaged 19.6 ± 0.6 cm. During grasping, the hand size of the subjects
323 could modify the joint posture, the net joint moment, the lengths of bones and muscle moment
324 arms. Consequently, it is not known if our conclusions still valid for subject with larger or
325 smaller hands.

326 To resume this study detailed the effect of object width on external forces and internal forces.
327 It was showed that the changes of external forces (following a U inverted relationship) were
328 not necessarily followed by similar changes in muscle forces and joint forces. This suggested
329 coordination strategy to preserve the action of the muscles directly implicated in the success

330 of the task. From an ergonomics point of view, our results would suggest to limit the largest
331 objects in order to preserve extensor muscles. This argument becomes crucial when
332 considering that during grip (i.e. flexing) fatiguing exercise, extensor fatigued at the same rate
333 than the flexor muscles (Quaine et al., 2003). Moreover, our results suggested that gripping an
334 object with the fingertip may have a great impact on proximal joints due to muscle
335 compression. Further researches are needed to compare this impact when grip force is applied
336 at the level of proximal and middle phalanxes as during five digits grasping.

337

Accepted Version

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406 Table 1:

Muscle	3.5 cm width	4.5 cm width	5.5 cm width	6.5 cm width	7.5 cm width
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

407

408 Mean tendon tensions (N) across the ten subjects according to the object width. (*) indicates a
409 significant effect of object width ($p<0.05$). First part of the table presents the index muscles
410 while the last nine lines presents the thumb muscles.

411 **Figure legends**

412 Figure 1: Mean (SD) external forces (N) applied by the fingers on the object according to the
413 object width. A significant effect of object width was observed on the force intensity.

414 Figure 2: Schematic representation of tendon forces applied by the extrinsic muscles acting on
415 index and thumb finger during a 5.5cm width object.

416 Figure 3: Schematic representation of tendon forces applied by the intrinsic muscles acting on
417 index and thumb finger during a 5.5cm width object.

418 Figure 4: Mean muscle force-external force ratio (u.a) observed in flexor muscles (A),
419 extensor muscles (B), abductor muscles (C) and adductor muscles (D) according to object
420 width. Thumb muscles were drawn with grey dashed lines and index muscles with black lines.
421 To keep the figure clear, the SD was not drawn. The variability could be however appreciated
422 in Figure 1 and in Table 1 which represent the mean and SD of the two variables used to
423 compute the muscle force-external force ratio.

424 Figure 5: Mean (SD) joint forces in index joints (upper figure) and thumb joints (figure
425 below). The blocks represent the intensity of the joint forces computed from both shear and
426 normal components of the force. Distal joints (IP and DIP) were represented as a grey square
427 (■), middle joints (PIP, MP) with a black rhombus (◆) and proximal joints (TMC and MCP)
428 with a white triangle (▲).

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430 Figure 1:

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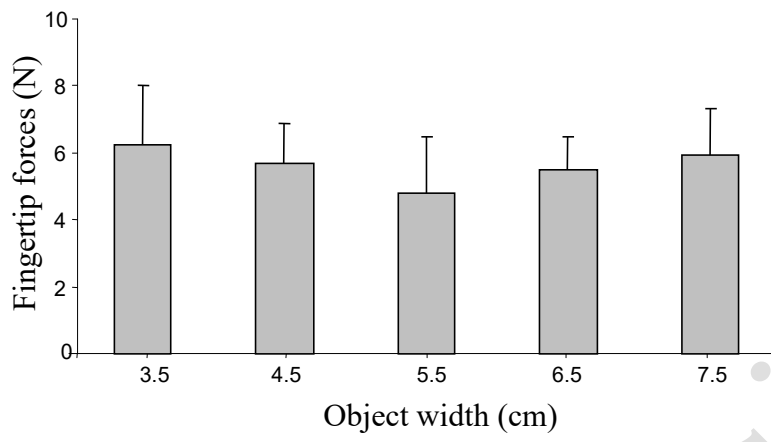
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Accepted Version

440 Figure 2:

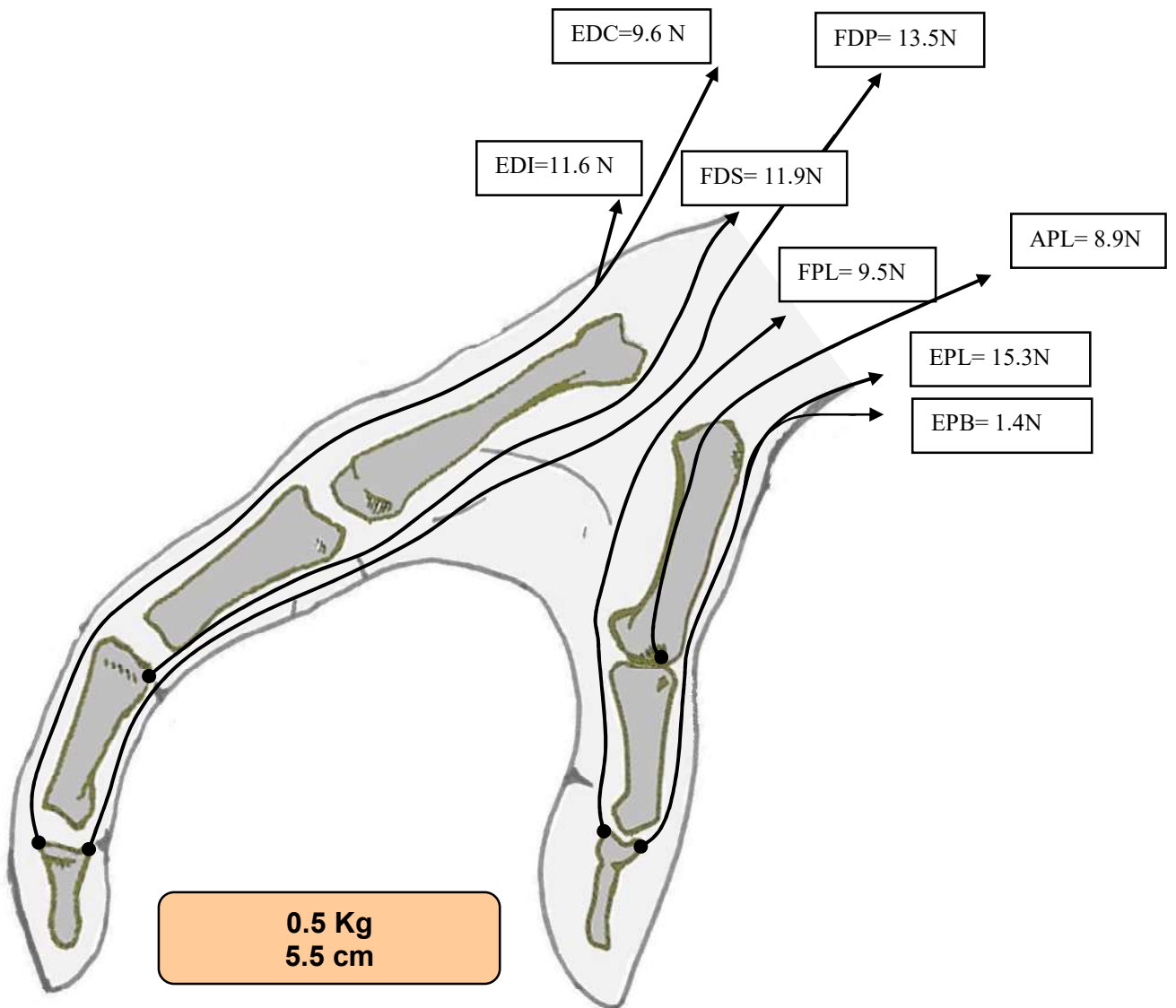
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446 Figure 3:

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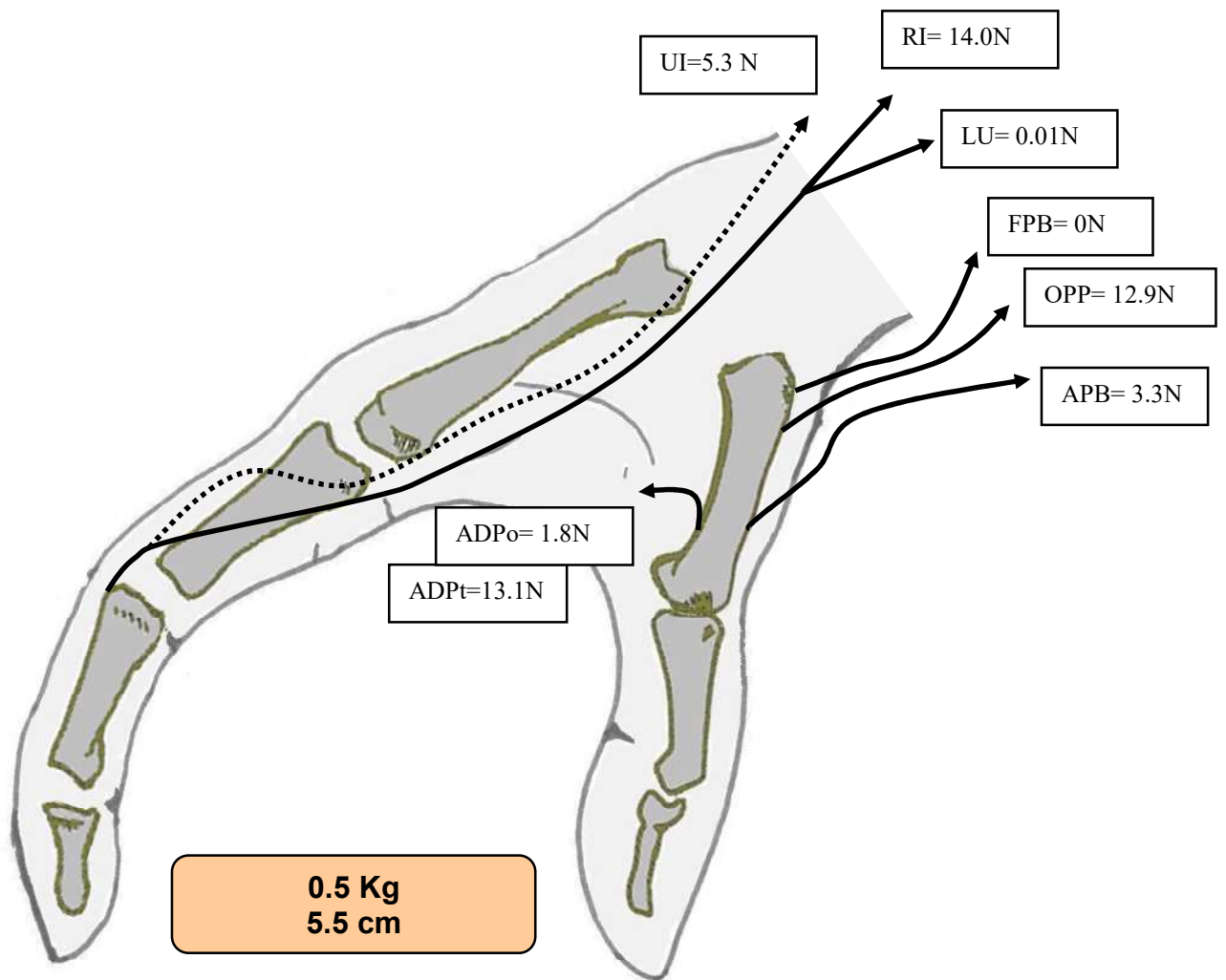
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465 Figure 4:

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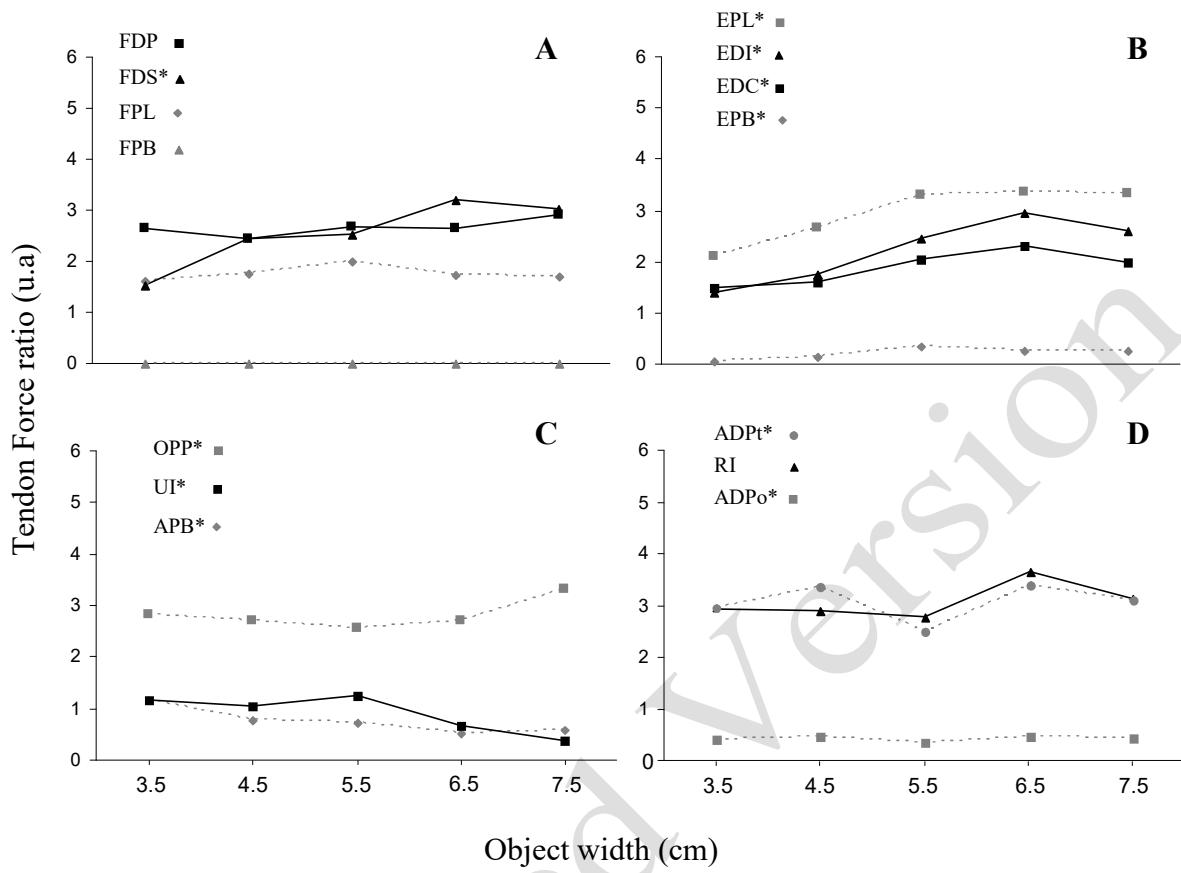
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479 Figure 5:

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