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► **To cite this version:**

Robin Hager, Thomas Poulard, Antoine Nordez, Sylvain Dorel, Gaël Guilhem. Influence of joint angle on muscle fascicle dynamics and rate of torque development during isometric explosive contractions. *Journal of Applied Physiology*, 2020, 129 (3), pp.569-579. 10.1152/jappphysiol.00143.2019 . hal-03298460

HAL Id: hal-03298460

<https://hal.science/hal-03298460>

Submitted on 4 Aug 2021

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1 **Influence of joint angle on muscle fascicle dynamics and rate of torque**
2 **development during isometric explosive contractions**

3

4 **Running title: Muscle-tendon interactions and explosive strength**

5

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26

27 **Keywords:** explosive strength; muscle-tendon interactions; ultrafast ultrasound; muscle
28 activation; force-velocity properties

29 **ABSTRACT**

30 This study investigated how joint angle influences fascicle shortening dynamics of
31 gastrocnemius medialis (GM) during explosive contractions, and the resulting impact on rate
32 of torque development (RTD). Sixteen participants performed six sets of five maximal
33 explosive voluntary isometric plantar flexions at -20° , -10° , 0° (neutral position), 10° , 20° and
34 30° of ankle angle, and five no-load ballistic plantar flexions. RTD assessed over all time
35 windows (from 0 to 200 ms) was significantly lower in extreme plantar flexed ($\geq 20^\circ$) and
36 dorsiflexed (-20°) positions compared to -10° , 0° ($475 \pm 105 \text{ Nm}\cdot\text{s}^{-1}$) and 10° . At these neutral
37 positions, RTD was maximal and muscle fascicles mainly operated over the plateau of the
38 force-length relationship. At 0° , fascicle shortening velocity peaked at $9.26 \pm 2.85 \text{ cm}\cdot\text{s}^{-1}$ (i.e.,
39 28.2% of maximal shortening velocity measured during no-load ballistic condition). At 112
40 ms after RTD onset, fascicle force reached $208 \pm 78 \text{ N}$ (i.e., 85.6% of the theoretical
41 maximum force at the corresponding shortening velocity) and was thereafter comprised
42 within the 95% confidence interval of the force-velocity curve. This clearly indicates that
43 muscle force reached the maximal force that accounts for the fascicle shortening velocity.
44 These findings suggest that the dynamic behavior of muscle fascicles, and the associated
45 fascicle shortening velocity, may influence the rapid force-generating capacity mainly from
46 100 ms of RTD onset. The present study provides important information to better understand
47 the determinants of human muscle performance during explosive tasks.

48

49 **New & Noteworthy**

- 50 • Ankle angle influences the operating muscle fascicle lengths of gastrocnemius
51 medialis, and the rate of torque development during explosive isometric plantar
52 flexions.
- 53 • The rate of torque development peaks in neutral angles where muscle fascicles shorten
54 over the plateau of the force-length relationship.
- 55 • When fascicles operate over the plateau of the force-length relationship (neutral ankle
56 positions), the force-velocity properties represent a limiting factor for the rapid force-
57 generating capacity from 100 ms after the onset of explosive contractions.

58 INTRODUCTION

59 The ability of the human skeletal muscle to achieve maximal force production as
60 quickly as possible is important for actions that involve explosive tasks or rapid adjustments
61 in postural balance such as those encountered in sport-specific movement (1, 8, 37, 43). This
62 capacity to produce explosive force is classically evaluated through the rate of torque
63 development (RTD) achieved during a maximal voluntary isometric contraction (1, 30). RTD
64 can be measured using a relatively simple setting (i.e., a force or torque sensor) as the
65 variations of torque (or force) over various periods of time from the onset of torque (0 ms) to
66 50-200 ms, (19, 44). Thus, RTD is widely used as a performance index in various populations
67 (i.e., athletes, elderly, patients) and sports where the amount of time available for an increase
68 in force is limited (e.g., athletics, team sports, combat sports) (37, 43, 49).

69 It is well established that RTD depends primarily on the neural system's ability to
70 maximally and rapidly activate the available pool of motor units (15, 19). In particular, it has
71 been recently shown that the motor neuron recruitment speed and the maximal rate at which
72 motor neurons discharge action potentials in the initial phase of the contraction (0-50 ms)
73 dictate the variability in RTD (16). Alternatively, additional factors, such as muscle fiber-type
74 composition, architecture, muscle and tendon elastic properties have been suggested to
75 influence RTD (5, 37, 52, 53). In a recent study, Massey et al. (40) reported small correlations
76 between muscle-tendon unit relative stiffness and voluntary RTD, but no correlation with
77 absolute and relative tendon stiffness. This demonstrated that other factors than tissue
78 stiffness would influence RTD and confirmed the need for further experimental data to better
79 understand the roles of these variables during voluntary explosive contraction (22, 37, 40).

80 One possible explanation of the difficulty to infer the influence of tendon mechanical
81 properties on RTD is the fact that muscle and tendon inherently interact during contractions *in*
82 *vivo*. Using ultrasound, several studies demonstrated that muscle fascicle behaviour can be

83 largely uncoupled from that of the behaviour of the muscle-tendon unit during various human
84 movements thanks to the compliance of tendinous tissues (12, 20). As a basic illustration of
85 this process, muscle fascicles were reported to shorten while tendinous tissues lengthen during
86 isometric contractions of increasing intensity (29). This demonstrates that a non-isometric
87 contraction is performed at the fibre level, while the muscle-tendon length remains constant
88 (21, 29). These dynamic interactions between muscle and tendon may thus modify the range
89 of lengths over which muscle fibres operate. A recent study nicely demonstrated that absolute
90 knee extensor RTD was influenced by joint angle due to both alterations in neuromuscular
91 activation and changes in contractile response [i.e., twitch and octet evoked responses; (34)].
92 As recently shown for electrically-evoked contractions, the change in joint angle also
93 influences the initial fascicle length (41). In addition, joint angle could influence the apparent
94 stiffness of series elastic tissues and the interplay between these tissues and fascicles.
95 However, to our knowledge, no study has investigated fascicle dynamics (i.e., length changes)
96 during explosive isometric voluntary contractions. Such measurements may contribute to
97 determine the changes in operating fascicle lengths involved over time during voluntary
98 explosive contractions. Their comparison with force-length and force-velocity relationships
99 could thereby give very important information about their influence on RFD performance
100 (17). In addition, the influence of joint angle was not addressed for plantar flexors, while the
101 long Achilles tendon plays an important role (23, 25). If confirmed, such hypothesis may
102 contribute to bring new insights into the significant influence of joint angle on maximal and
103 explosive strength (14, 47).

104 The present study aimed to examine the behaviour of *gastrocnemius medialis* (GM)
105 muscle fascicle during a voluntary RTD test. Maximal explosive isometric contractions of
106 plantar flexor muscles were performed at various ankle positions (from -20° in dorsiflexion to
107 30° of plantar flexion). Given the significant changes in fascicle length reported during

108 isometric contractions in humans (21, 29, 45), our objectives were twofold: (i) to determine
109 the influence of ankle angle on the fascicle length shortening and RTD achieved during an
110 explosive contraction; (ii) to investigate how this dynamic behaviour of muscle fascicle and
111 its shortening velocity may influence RTD (by referring to the force-velocity relationship) in a
112 joint configuration that elicits fascicle shortening over the plateau of the force-length
113 relationship.

114

115 **METHODS**

116 *Participants*

117 Ten males and six females (age: 23.2 ± 2.7 years, height: 175.3 ± 6.4 cm, body mass: $70.2 \pm$
118 12.6 kg), with no history of ankle disorder or injury, participated in this study. All volunteers
119 were informed about the nature, aims and risks associated with the experimental procedure
120 before giving their written consent to participate. The study was approved by the local ethics
121 committee (2017-A03117-46) and conformed to the standards of the Declaration of Helsinki.

122

123 *Experimental design*

124 All participants attended one familiarization session and one testing session a few days later.
125 During these sessions, after a 10-minute standardized warm-up, participants performed 5
126 ballistic plantar flexions with no external load (load = 0 kg) on a specific ergometer composed
127 of a specific rotational footplate (Bio2M, Compiègne, France). Participants then performed
128 six sets of five repetitions of explosive voluntary isometric contractions to reach maximal
129 force of the plantar flexor muscles in a randomized order at various ankle angles (from -20° in
130 dorsiflexion to 30° in plantar flexion) on an Eracles-system mechatronic ergometer (Eracles-
131 Technology, Compiègne, France; Fig. 1). RTD and MVC peak torque were assessed on the
132 same repetitions to avoid fatigue occurrence. We performed pilot analyses that showed no

133 significant difference between these metrics assessed during the same contractions when
134 sufficient time was allowed to the participants were instructed to push “as fast and as hard as
135 possible” with sufficient time (5 s) to then achieve MVC torque plateau (37). We performed
136 pilot analyses that showed no significant difference in peak MCV torque between trials
137 performed in this condition and in a conventional MVC measurement. Therefore, we think
138 that this issue marginally influenced our results. At the end of the protocol, two passive
139 dorsiflexion cycles were performed on the same ergometer at $1^{\circ} \cdot s^{-1}$ to estimate triceps surae
140 moment arm (see moment arm section) and to subtract the passive torque to the raw torque in
141 order to obtain the active torque to build the active force-length relationship (see data
142 processing). During each explosive contraction performed at each ankle angle (Fig.1),
143 mechanical parameters (i.e., torque, displacement, velocity), muscle fascicle length and
144 velocity of GM, surface electromyography (EMG) activity of *gastrocnemius lateralis* (GL),
145 *soleus* (SOL) and *tibialis anterior* (TA) were simultaneously recorded.

146

147 ***Equipment and procedure***

148 *Voluntary isometric explosive contractions.* Voluntary isometric explosive contractions were
149 performed on an Eracles-system mechatronic ergometer (Eracles-Technology, Compiègne,
150 France) previously described (23). Participants were placed in prone position, with the knee
151 fully extended (0° : full knee extension) and firmly attached to the ergometer by harness. The
152 axis of right ankle rotation was aligned to the motor axis. The starting position of the ankle
153 was randomly set at various angles: -20° , -10° , 0° , 10° , 20° and 30° (0° : foot perpendicular to
154 tibia; positive positions in plantar flexion direction; Fig. 2). Participants were instructed to
155 contract “as fast and hard as possible” in order to reach maximal torque from a relaxed
156 condition (37) after a standardized 3-second countdown with a visual feedback of the force
157 trace and oral feedback of their RTD score measured from 0 to 200 ms after torque onset.

158 Five repetitions of 5-s duration interspaced by a 2-min rest period were performed per ankle
159 angle condition, and the 3 best trials were considered for analysis (see below). The residual
160 joint rotation during contractions was measured using a goniometer (Biometrics, Gometz-le-
161 Châtel, France) fixed to the ankle. Since the ergometer was rigid, potential change in ankle
162 angle was due mainly to slight heel movement on the platform. The pre-contraction torque
163 was consistently verified in order to avoid any pre-activation or counter-movement prior to
164 explosive contractions. In the case of pre-tension or countermovement, the trial was discarded
165 from the analysis.

166

167 *Passive torque.* The passive plantar flexor torque-angle relationship was assessed during the
168 tendon excursion method (3, 35) in dorsiflexion direction on the same ergometer and in the
169 same position as for voluntary isometric contractions. Footplate rotation was set at $1^{\circ} \cdot s^{-1}$ over
170 the maximal range of motion in plantar flexion and dorsiflexion for each individual (i.e., from
171 $42 \pm 8^{\circ}$ to $-27 \pm 9^{\circ}$ on average).

172

173 *Moment arm.* Length of the triceps surae moment arm was measured using the tendon
174 excursion method (3, 39) during the measure of passive torque, to determine fascicle force.
175 Displacement of fascicle insertion on deep aponeurosis was observed by ultrasound (32). The
176 length of the *triceps surae* moment arm was considered as the slope of the linear regression
177 between deep aponeurosis displacement (in cm) and change in ankle angle (-10° to 20° ; $r^2 =$
178 0.99 ± 0.04).

179

180 *No-load ballistic contraction.* In order to determine maximal fascicle shortening velocity
181 (V_{\max}), participants performed maximal dynamic plantar flexions with no external load on a
182 specific ergometer composed of a rotational footplate and a bench (Bio2M, Compiègne,

183 France) (33) as previously described and used (24, 25) . The starting position of the ankle was
184 set at -20° of dorsiflexion. Participants were instructed to contract “as fast as possible” from
185 rest over the whole range of motion (i.e., 50°). Participants performed five trials with a rest of
186 1’ between repetitions. When they thought they could achieve a faster movement, an
187 additional trial was performed, with a maximum of 10 trials to avoid fatigue. The fascicle
188 shortening velocity reached during RTD was expressed relatively to V_{\max} .

189

190 ***Data collection and processing***

191 *Mechanical data.* Joint angle, angular velocity and torque were recorded at 2000 Hz using an
192 analog-to-digital converter designed by our laboratory (Custom DT, INSEP, Paris, France).
193 Mechanical signals were analysed using custom-written scripts (Origin 9.1, OriginLab
194 corporation, USA). First, signals were low-pass filtered (150 Hz, zero-lag 4th order
195 Butterworth). Then, we determined the onset of contraction during RTD using the torque
196 signal according to the systematic approach proposed by Tillin et al. (51). The onset of torque
197 production was manually determined as previously described by Tillin et al. (49) before low-
198 pass filtering. First, recordings where the baseline (resting) torque was not stable (i.e., > 0.5
199 N.m the preceding 100 ms) were discarded. Second signals were checked with a consistent
200 scale (e.g. 500 ms vs. 1 N). Third, the investigator placed manually a dashed line on the apex
201 of the last peak/trough before the signal deflected from the baseline noise. RTD was
202 calculated as the rising torque divided by the time windows [i.e., a straight line: from 0 to 200
203 ms (RTD_{0-200}), from 0 to 50 ms (RTD_{0-50}) from 50 to 100 ms (RTD_{50-100}), and from 100 to
204 200 ms ($RTD_{100-200}$)]. Mean displacement of the heel was monitored using an electronic
205 goniometer (Biometrics, Gometz-le-Châtel, France). The mean displacement was measured at
206 respectively $1 \pm 1^\circ$, $1 \pm 1^\circ$, $1 \pm 2^\circ$, $2 \pm 2^\circ$, $2 \pm 2^\circ$ and $2 \pm 2^\circ$ at respectively 30° , 20° , 10° , 0° , -
207 10° and -20° . When detachment of the heel was above 5° , the trial was not considered. For

208 each set of five contractions performed at a given starting angle, the three trials resulting in
209 the highest RTD_{0-200} were averaged for further analysis. The peak torque corresponded to the
210 highest peak torque value obtained among the five explosive isometric contraction performed
211 in each ankle angle position. Maximal angular velocity during the no-load condition
212 corresponded to the averaged value measured from -10° to 20° of plantar flexion (25).

213

214 *Ultrasound.* An ultrafast ultrasound scanner (Aixplorer, Supersonic Imagine, Aix en
215 Provence, France) coupled with a linear transducer array (4-15 MHz, SuperLinear 15-4,
216 Vermon, Tours, France) was used to acquire ultrasonic raw data from the GM muscle at a
217 sampling frequency of 1000 Hz for RTD and 2000 Hz for the no-load condition. The
218 ultrasonic raw data were used to create B-mode images (depth = 30 to 50 mm, width = 55
219 mm; in order to visualize the whole muscle thickness for each participant) by applying
220 conventional beamforming through Matlab software (Version, The Mathworks, Natick, MA).
221 The ultrasound probe was placed on the skin surface at 30% of the distance between the
222 popliteal fossa area and the centre of the lateral malleolus. A specific cast was used during
223 contractions to keep the probe in the same location throughout the measurements. Changes in
224 GM fascicle length (Fig. 2A) and pennation angle were assessed in every frame over 500 ms
225 using the automatic tracking method proposed by Farris and Lichtwark (18) and low-pass
226 filtered (50 Hz) using a 3rd order Butterworth filter. Fascicle shortening was calculated in
227 every frame over the same time window used to determine RTD (i.e., 200 ms), over the whole
228 range of motion in the passive condition to build the fascicle force-length relationship.
229 Fascicle shortening velocity (Fig. 2C) was computed as the first-time derivative of fascicle
230 length. V_{max} was calculated as the peak obtained during the no-load condition (25). Total
231 plantar flexion force was calculated from the torque divided by the Achilles tendon moment

232 arm. Fascicle force was then calculated from the GM muscle force [i.e., 20.9% of total plantar
233 flexion force (13)], divided by the cosine of the pennation angle.

234

235 *Active force-length relationship.* According to the method proposed by Hoffman et al. (28),
236 the parallel elastic component was considered parallel to the contractile element only. Thus,
237 the individual fascicle force-length curve was determined by fitting passive fascicle torque
238 data to the following equation (28):

$$Passive\ force = Ae^{kL_f}$$

239 where A is constant, k is the stiffness of the curve and L_f the fascicle length.

240 To build the fascicle total force-length relationship, the peak fascicle force and the
241 corresponding fascicle length when GM fascicle force was maximal were extracted for each
242 ankle angle condition (30°, 20°, 10°, 0°, -10°, -20° of plantar flexion; Fig. 2D). For each
243 point, the x-coordinate corresponded to the fascicle length measured when GM fascicle force
244 was maximal. The y-coordinate corresponded to the peak fascicle force minus the passive
245 force measured at the same fascicle length on the passive force-length curve (28). The active
246 force-length relationship was fitted using the previously suggested methods (11, 28). A
247 Levenberg-Marquardt algorithm was used to calculate five parameters (Origin 9.1, OriginLab
248 corporation, USA): the maximal force, the fascicle length at the maximal force (i.e., optimal
249 fascicle length, L_0), the roundness, the skewness, and the width of the relationship. No
250 constraints were used, excepted when the fitted relationship resulted in non-physiological data
251 (see discussion section). The optimal fascicle length and maximal force were then used to
252 build the normalized force-length relationship for each individual and the whole sample of
253 participants.

254

255 *Force-velocity relationship.* Neutral ankle position (0°) is the most-commonly used condition
256 to assess plantar flexion MVC torque and RTD, and resulted in the highest RTD values.
257 Therefore, peak fascicle force elicited during MVC performed at 0° condition (F_{max}) was used
258 as the maximal theoretical force for each individual (i.e., F_0 of the force-velocity relationship;
259 Fig. 2E). This relationship was modelled using the hyperbolic equation (27):

$$V = b * (F_{max} - F) / (F + a)$$

260 where F is force, V is velocity, and a and b are constants.

261 This model was fitted to experimental data that included F_{max} measured during RTD
262 evaluation performed at 0° and V_{max} assessed during no-load ballistic contractions (Fig. 2E).
263 The values of coefficients a (202.0) and b (17.0) were determined using the following
264 equation:

$$a = k * F_{max}$$

$$b = k * V_{max}$$

265 where k is a constant.

266 The value of coefficient k (0.51) was determined from the mean force-velocity relationship
267 obtained in a previous study on participants with similar anthropometrical characteristics and
268 physical activity (24, 25). We determined the time point at which the mean fascicle force-
269 velocity data obtained during RTD testing crossed the lower limit of 95% confidence interval
270 of the mean force-velocity relationship.

271

272 *EMG.* Surface EMG activity was recorded using a wireless remote unit (Zerowire, Aurion,
273 Italy), on GL, SOL and TA muscles. The skin was shaved, gently abraded and cleaned with a
274 solution of ether, acetone and alcohol to minimize inter-electrode impedance. The bipolar,
275 silver/silver chloride, surface disc electrodes (Blue Sensor N-00-S/25, Medicotest, France)
276 were placed with a center distance of 2 cm. Electrodes were placed longitudinally with respect

277 to the underlying muscle fibre arrangement and located according to the Surface EMG for the
278 Non-Invasive Assessment of Muscles recommendation's (SENIAM) (26). EMG signals were
279 pre-amplified (input impedance: 20 MX; common mode-rejection ratio: 90 dB; gain: 1000;
280 bandwidth: 10–500 Hz), digitized and sampled at 2000 Hz. All EMG signals were first band-
281 pass filtered (high pass: 10 Hz, 3rd order Butterworth filter, low pass: 400 Hz, 3rd order
282 Butterworth, filtered forward–backward filtering for zero phase shifting). EMG signals
283 obtained during RTD was analysed as the root mean square (RMS) with a 10 ms moving
284 rectangular window to produce a RMS envelope. During MVC, RMS EMG was calculated
285 using a 500-ms moving rectangular windows. The maximal RMS EMG amplitude measured
286 during maximal isometric contraction performed at the corresponding tested plantar flexion
287 angle was selected as the reference to normalize EMG data at the same testing angle. GL and
288 SOL EMG RMS were averaged over different time windows: between 0 ms and 50 ms,
289 between 50 ms and 100 ms, between 100 ms and 200 ms and between 0ms and 200 ms.

290

291 *Statistical analysis*

292 All statistical analyses were performed with Statistica (StatSoft, Tulsa, Oklahoma, USA). All
293 data being normally distributed (Shapiro-Wilk's test), all results are expressed as means \pm s.d.
294 Statistical significance was set at $P < 0.05$. The potential effects of ankle angle (-20° , -10° , 0° ,
295 10° , 20° and 30°) on peak GM fascicle force, fascicle length corresponding to peak force,
296 fascicle length corresponding to the onset of RTD (in passive condition, before the onset of
297 the contraction), fascicle length changes over the first 200 ms, peak fascicle shortening
298 velocity and time to peak shortening velocity were determined by one-way ANOVAs (angle
299 effect) with repeated measures. The effects of ankle angle (-20° , -10° , 0° , 10° , 20° and 30°)
300 and time period (0-50, 50-100 and 100-200 ms) on RTD were tested by a two-way ANOVA
301 (angle \times time period) with repeated measures. Differences in muscle activation were tested for

302 each muscle (GL and SOL) using two two-way ANOVAs (time \times angle) with repeated
303 measures. The 95% confidence interval was calculated for the force-velocity relationship
304 (mean bias: 95%, mean difference: ± 1.96 s.d.). When the sphericity assumption in repeated
305 measures ANOVAs was violated (Mauchly's test), a Geisser-Greenhouse correction was
306 used. *Post-hoc* tests were performed by means of Newman-Keuls procedures for comparison
307 between time points.

308

309 **RESULTS**

310 *Effect of joint angle on RTD*

311 Figure 3A shows changes in torque during RTD evaluation for all tested angles over time.
312 The two-way ANOVA showed significant main effects of angle ($P < 0.001$), time period ($P <$
313 0.001) and time period \times angle interaction ($P < 0.001$) on RTD (Table 1). *Post-hoc* showed
314 that no significant effect was found on RTD₀₋₅₀ between -10° , 0° and 10° ($P = 0.29$). These
315 values were significantly higher than RTD₀₋₅₀ measured at -20° ($P < 0.03$) ($17 \pm 6\%$), which
316 was significantly higher than the values obtained at 20° and 30° ($33 \pm 16\%$ and $57 \pm 28\%$,
317 respectively; $P < 0.005$). We found no significant differences in RTD₅₀₋₁₀₀ between -10° , 0°
318 and 10° ($P = 0.83$), and these values were significantly higher than those obtained at -20° and
319 20° ($17 \pm 4\%$ and $20 \pm 6\%$, respectively; $P < 0.04$), which were significantly higher than
320 RTD₅₀₋₁₀₀ achieved at 30° ($28 \pm 13\%$; $P < 0.001$). RTD₁₀₀₋₂₀₀ measured at 0° , -10° and -20°
321 were significantly higher than the values obtained at 10° ($11 \pm 4\%$; $P = 0.02$), which was
322 significantly higher than the values obtained at 20° and 30° ($12 \pm 3\%$ and $33 \pm 3\%$; $P < 0.02$).

323

324 *Effect of joint angle on fascicle length and velocity changes during RTD evaluation*

325 At the two extreme ankle angle positions, GM fascicle operated from 3.6 ± 0.7 cm to 2.8 ± 0.6
326 at 30° and from 7.0 ± 1.2 cm to 5.8 ± 1.3 cm at -20° (Fig. 3). These fascicle length changes

327 were significantly different between all conditions (angle effect; $P < 0.05$), showing the
328 substantial effect of the ankle angle on this parameter. In all conditions, fascicle shortening
329 occurred mainly in the first 200 ms, corresponding to 0.67 ± 0.37 cm, 1.02 ± 0.38 cm, $1.22 \pm$
330 0.49 cm, 1.21 ± 0.48 cm, 1.06 ± 0.40 cm and 0.85 ± 0.33 cm for angles of -20° , -10° , 0° , 10° ,
331 20° and 30° , respectively. Fascicle shortening was significantly lower at -20° than in other
332 conditions ($P < 0.003$). Peak fascicle shortening velocity showed a significant angle effect (P
333 < 0.001), with a maximal value achieved at 0° (10.8 ± 3.8 cm.s⁻¹) and minimal at 20° ($6.7 \pm$
334 3.7 cm.s⁻¹; Table 1). Peak shortening velocity was significantly lower at -20° than at -10° , 0° ,
335 10° , 20° and 30° ($P < 0.001$).

336

337 ***RTD performance in relation with force-length relationship***

338 In addition to the effect on muscle fascicle length changes, we observed a significant effect of
339 angle on peak fascicle force ($P < 0.001$) reached during RTD evaluation. Values ranged
340 between 180 ± 49 N at 30° and 568 ± 177 N at -20° (Fig. 4). *Post-hoc* revealed that maximal
341 forces did not differ significantly between -20° , -10° (565 ± 129 N) and 0° (520 ± 114 N; $P =$
342 0.08 ; Fig. 4). Maximal fascicle forces produced at these angles were higher than values
343 obtained in plantar flexion positions at 10° , 20° and 30° ($P < 0.001$). The figure 4 allowed to
344 determine whether the average changes in fascicle length during RTD occurred over the
345 ascending limb, descending limb or the plateau of the force-length relationship. On average,
346 muscle fascicle operated over the ascending limb during RTD at 30° and 20° , while it was
347 over the descending limb at -20° . Changes in fascicle length during RTD performed at 10 and
348 -10° were mainly comprised between the ascending limb and the plateau at 10° and between
349 the descending limb and the plateau at -10° . Finally, the fascicles operated over the plateau
350 when RTD was performed at 0° .

351 The individual changes in length during RTD were analysed to further confirm these results
352 (Fig. 5). First, this individual analysis showed that the changes in fascicle length that occurred
353 during RTD at 30° and 20° corresponded to the ascending limb for all the participants.
354 Inversely, the changes in fascicle length during RTD performed at -20° corresponded to the
355 descending limb for all the participants excepted for 3/16 (i.e., participants # 4, 11 and 16) for
356 which muscle fascicles operated over the plateau in this condition. Second, at 10°, fascicle
357 length changes occurred over the ascending limb for 9/16 participants (#1, 2, 3, 4, 5, 10, 11,
358 14, 16), the plateau for 6/16 participants (#7, 8, 9, 12, 13, 15), and the descending limb for
359 1/16 participant (#6). In the same way, the changes in length during RTD at -10°
360 corresponded to the ascending limb for 1/16 participants (#11), the plateau for 7/16
361 participants (# 2, 3, 4, 5, 9, 10, 16) and the descending limb for 8/16 participants (#1, 6, 7, 8,
362 12, 13, 14, 15). Third, the changes in fascicle length during RTD at 0° corresponded to the
363 ascending limb for 1/16 participant (#11), the plateau for 11/16 participants (#1, 2, 3, 4, 5, 8,
364 9, 10, 12, 14, 16) and the descending limb for 4/16 participants (#6, 7, 13, 15).

365

366 ***RTD performance in relation with fascicle force-velocity relationship***

367 The 0° condition elicited a fascicle shortening range centred over optimal GM fascicle length
368 values commonly reported in voluntary contractions (i.e., ~5 cm, Fig. 2D). The average force-
369 velocity relationship of GM is displayed in Figure 6. The theoretical maximal fascicle force
370 and maximal fascicle shortening velocity obtained from this relationship reached 521 ± 115 N
371 and 33.3 ± 8.8 cm.s⁻¹, respectively. At 50 ms after the onset of RTD evaluation, the measured
372 fascicle force (51 ± 30 N) was low compared to the theoretical maximal force the individuals
373 were able to produce at the corresponding fascicle-shortening velocity (278 ± 61 N, Fig. 6).
374 Between 50 and 100 ms, the force increased up to 177 ± 73 N (i.e., 72.5% of the theoretical
375 maximum force at this corresponding specific shortening velocity) while the shortening

376 velocity continued to increase and reached a plateau corresponding to $9.26 \pm 2.85 \text{ cm}\cdot\text{s}^{-1}$ (i.e.,
377 28.2% of V_{max}). At 112 ms, fascicle force reached $208 \pm 78 \text{ N}$ (i.e., 85.6% of the theoretical
378 maximum force at this velocity) and was thereafter comprised within the 95% confidence
379 interval of the force-velocity relationship up to F_{max} .

380

381 **Muscle activity.** GL mean muscle activity showed no significant effect of angle ($P = 0.6$) and
382 time \times angle interaction ($P = 0.2$), with a significant effect of time ($P < 0.001$; Fig. 3D, Table
383 1). *Post-hoc* showed that GL mean activity between 50 and 100 ms was significantly higher
384 than activity measured 0 and 50 ms and between 100 and 200 ms ($P < 0.001$).

385 SOL mean muscle activity showed the significant effect of angle ($P < 0.001$), time ($P <$
386 0.001) and time \times angle interaction ($P = 0.001$, Table 1). *Post-hoc* showed that SOL activity
387 was significantly higher at -20° , -10° and 0° than at 20° and 30° ($P < 0.02$). SOL mean
388 activity between 0 and 50 ms was significantly lower than between 50 and 100 ms or between
389 100 and 200 ms ($P < 0.001$).

390

391 **DISCUSSION**

392 The present study aimed to determine the influence of joint angle on the plantar flexor
393 RTD and associated fascicle dynamics measured during an explosive isometric contraction. In
394 line with our hypothesis, the results revealed a significant shortening of GM fascicles during
395 explosive isometric contractions, which was significantly influenced by joint angle. RTD
396 measured over a 200-ms period reached higher values at 10° , 0° and 10° than in dorsiflexed ($-$
397 20°) and plantar flexed (20° and 30°) positions. This could mainly originate from the fact that
398 GM fascicles operate over the plateau of the force-length relationship in these neutral
399 conditions (i.e., centred on optimal fascicle length). At 0° , fascicle-shortening velocity
400 reached $\sim 28.2\%$ of V_{max} at 89 ms from RTD onset. This finding reflects that the substantial

401 fascicle shortening that occurs in the isometric condition causes a decrease in maximal
402 fascicle force-generating capacity, according to the force-velocity relationship.

403 Plantar flexor RTD values ($346 \pm 38 \text{ N.m.s}^{-1}$ and $417 \pm 137 \text{ N.m.s}^{-1}$ for RTD₀₋₅₀ and
404 RTD₀₋₂₀₀, respectively) were comprised within the ranges of RTD measures obtained during
405 ankle plantar flexions [i.e., from 200 to 610 Nm.s^{-1} (9, 46)]. In line with previous data
406 obtained on knee extensor muscles (34), our results show that the impact of ankle joint angle
407 on RTD follows an inverted 'U' relationship at any specific time point. To our knowledge, this
408 effect has never been reported for plantar flexors, while our results corroborate previous
409 studies focused on knee extensor muscles (2, 14). In the latter study, a change in ability to
410 produce force rapidly was associated with changes in muscle activation. These previous
411 findings are in accordance with the concomitant increase in EMG activity of SOL [i.e. main
412 contributor to planter flexor force (13)], and RFD observed in the present study at -20° , -10°
413 and 0° than 20° and 30° . However, our results showed no significant effect of ankle angle on
414 average GL EMG activity across different time windows (Table 1). It is important to note that
415 GM and antagonist activity were not measured, which precludes to strongly conclude on the
416 influence of joint angle on muscle activation during RTD evaluation.

417 We observed a significant fascicle shortening during explosive isometric contractions,
418 regardless of ankle position (Fig. 3 and 4). Such a non-isometric behaviour of the fascicle
419 provides an additional evidence of the decoupling between muscle fibres (which shorten) and
420 tendon (which stretches) observed during various motor tasks [i.e., walking, running,
421 jumping, single-joint dynamic contractions (21, 29)]. The significant effect of joint angle on
422 RTD can be interpreted with respect to the muscle fascicle shortening potential and the
423 associated muscle force-generating capacity, which depend on the initial muscle-tendon
424 length configuration (7, 28, 38).

425 The mean operating fascicle length during RTD₀₋₂₀₀ performed at 0° was comprised
426 between 5.87 ± 0.84 cm and 4.64 ± 0.99 cm, which strongly corresponds to the optimal length
427 condition to produce force for GM muscle [Fig. 4; (28)]. Although a substantial variability
428 was found between individuals, this finding was confirmed by individual analyses (Fig. 5). At
429 30° and 20°, muscle fascicles shortened over the ascending limb of the active force-length
430 relationship, thereby limiting force and RTD. The resulting RTD in these conditions was
431 significantly lower compared to the values elicited in neutral conditions where fascicles
432 operated over the plateau (Fig. 4; Table 1). In the same way, at -20° (dorsiflexed ankle
433 position), RTD values were lower than those obtained at 0° (Table 1). In this condition, GM
434 fascicle mainly operated over the descending limb of the force-length relationship. Therefore,
435 due to a decrease in the maximal force ability over the fascicle operating length, our results
436 strongly support that the force-length properties can contribute to limit the amount of RTD
437 achieved at 30°, 20° and -20°. Nevertheless, this mechanism should be considered together
438 with the potential impact of ankle angle on neural activation (17, 41). For intermediate angles
439 (10° and -10°), the fascicle shortening during RTD was between the ascending, descending
440 limb and the plateau. Therefore, the influence of the force-length relationship is more
441 mitigated for these conditions. Interestingly, while a trend was observed, RTD did not
442 significantly differ between 10°, 0° and -10°. As a whole, these results demonstrated that
443 using a neutral ankle position around 0° for RTD evaluation ensures a maximal force-
444 generating capacity in respect to the force-length relationship, and a minimal influence of the
445 force-length properties on the amount of produced muscle force. This finding is important
446 because it was the condition to further analyse the 0° condition by investigating the force
447 development in light of the force-velocity properties.

448 Our results enable the identification of different phases of RTD performed in this 0°
449 neutral condition. Firstly, from 0 to 50 ms, mean EMG activity (Table 1) and fascicle force

450 generated at the associated fascicle velocity was divergent from the maximal EMG activity
451 and the maximal force-velocity capacities of individuals. Therefore, in this phase, RTD may
452 be mainly related to the activation dynamics. Indeed, Del Vecchio et al. (16) showed that the
453 individual ability to produce force rapidly in this early phase of RTD is highly dependent on
454 motor unit recruitment and discharge rate. Secondly, from 50 to 100 ms, the mean fascicle
455 force generated at the associated velocity progressively approached the force-velocity
456 relationship (Fig. 6). During this phase, EMG activity was significantly higher than in the
457 other time windows. Thus, in this phase, explosive strength still depends on activation and
458 progressively on the force-velocity properties. Thirdly, after ~100 ms, the mean fascicle force
459 generated at the associated fascicle velocity measured during RTD matched with the maximal
460 force-velocity properties (Fig. 6).

461 These results confirm previous results obtained on knee extensor muscles (14). In the
462 latter study, the response to an evoked octet was reported as the primary determinant of force
463 development from 50 to 100 ms, suggesting that contractile properties of the muscle-tendon
464 unit may influence the force increase from 50 ms after the onset of contraction. Moreover, in
465 our study, fascicle force in the later part of RTD (after 200 ms) is strongly related to the
466 maximal isometric force-generating capacity as demonstrated by the force-velocity values
467 measured close to F_{max} . This result supports previous reports of an increasing influence of
468 maximal voluntary isometric torque on RTD measured over this later period of contraction (4,
469 19). The later putative intervention of contractile properties in plantar flexors may reflect the
470 influence of their pennate architecture as contractile forces are less directly transmitted to the
471 tendon than in less pennated muscles [e.g. knee extensors (48)]. Inversely, the gearing effect
472 allowed by fascicle pennation has been suggested to limit fascicle shortening velocity for
473 reaching a given muscle-tendon unit shortening velocity, which could increase RTD (6, 10).
474 How these two processes are involved in force rise remain to be elucidated.

475 The impact of fascicle dynamics on RTD could be influenced by the stiffness of the
476 elastic tissues (19, 36, 37, 41). Waugh et al. (53) showed that Achilles tendon stiffness could
477 account for up to 35% of the variability in RTD normalized to its peak value, while Kubo (31)
478 suggested that the link between changes in tendon properties and RTD may be divergent.
479 Mayfield, et al. (41, 42) showed a modest decrease in fascicle shortening velocity with
480 increasing the effective stiffness (manipulated by applying a rapid rotation of the foot at the
481 onset of contraction) during electrically-evoked RTD, thereby increasing force-generating
482 capacity. During voluntary contractions, the present protocol placed the elastic tissues in a
483 configuration where their passive stiffness increased when the ankle was in dorsiflexed
484 angles. The present study confirms that this rise in tendon stiffness in dorsiflexed positions
485 reduces fascicle shortening velocity (Table 1). However, although the decrease in fascicle
486 velocity is theoretically beneficial for producing high levels of force rapidly, mean RTD was
487 significantly lower at -20° over each time window compared to 0° . This finding suggests that
488 the impairment of the force-generating capacity during RTD in dorsiflexed ankle
489 configuration is mainly related to the fact that fascicles are forced to operate over the
490 descending limb of the force-length relationship. This result clearly shows the interplay
491 between tendon stiffness and fascicle mechanics that remain very difficult to dissociate *in vivo*
492 and may in turn substantially contribute to the observed variability between individuals.
493 Future research is required to find the best compromise between the mechanical properties of
494 both tendinous and contractile tissues, and thereby optimize fascicle dynamics for RTD
495 performance.

496 The fits applied to the active voluntary force-length relationships were done in the
497 same way than in previous published papers (11, 28). However, it should be kept in mind that
498 it requires the calculation of five parameters. For such fits, we cannot fully ascertain that the
499 real solution was found by optimization due to possible local minima. Thus, the fit should be

500 rather considered as an estimation about the theoretical force-length relationship. This should
501 not be considered as a main issue given that the parameters extracted from the fits were not
502 used in the present paper, excepted F_0 and L_0 for the average normalized force-length
503 relationship (Fig. 4B). In addition, for three participants (#11, 13 and 16, Fig. 5), the L_0 was
504 extrapolated in regards to the measured data points. Thus, the normalized force-length
505 relationship should be considered with caution. The force-velocity relationship was estimated
506 from Hill's model that was fitted on the basis of measured values of maximal force and
507 maximal shortening velocity. First, we assume that the fascicle velocity reached during no-
508 load ballistic plantar flexions is representative of the theoretical maximal velocity value (5).
509 Indeed, previous studies from our group have shown this method to be effective in assessing
510 the active V_{\max} that muscle fascicles can achieve *in vivo* (7, 23, 25). Second, the curvature
511 coefficients were taken from the mean values of a previous study (25). Ideally, the fascicle
512 force-velocity curvature coefficient could be individualized from data collected under
513 different loading conditions (25). The inclusion of concentric contractions at various
514 velocities would have also permitted to consider the intricate influence of both length and
515 velocity changes on RTD at intermediate shortening velocities using a 3-D force-length-
516 velocity relationship (50, 52). However, in the present study, it was not possible to add the
517 conditions required for this procedure due to the increased of fatigue due to this protocol.
518 Nevertheless, compared to the study by Hauraix et al. (25), participants had similar (i)
519 anthropometrical characteristics, (ii) maximal velocity (i.e., $30.8 \text{ cm}\cdot\text{s}^{-1}$ vs. $33.3 \pm 8.8 \text{ cm}\cdot\text{s}^{-1}$)
520 and (iii) maximal force (420 N vs. $520 \pm 115 \text{ N}$). Therefore, we are confident that our
521 approach is sufficiently robust to interpret the force and fascicle shortening velocity obtained
522 during isometric RTD testing in light of the mean force-velocity relationship.

523

524 **Conclusion**

525 The present study demonstrates that joint angle substantially influence the rate of torque
526 development, associated fascicle length changes and shortening velocity expressed during
527 explosive maximal isometric plantar flexions. Force-length properties mainly account for the
528 effect of ankle angle on RTD, which peaked around the neutral ankle positions where
529 fascicles operated over the plateau of the fascicle force-length relationship. After ~100 ms
530 from the onset of RTD, the fascicle force was very close to its maximal theoretical value
531 considering the associated shortening velocity (i.e., according to the force-velocity
532 relationship). While an initial phase is required to initiate the tendon stretch and maximally
533 activate the muscle, RTD is mainly influenced by muscle mechanics and the force-velocity
534 properties from 100 ms after RTD onset. This contribution of contractile properties to the
535 ability to generate force rapidly may also be modulated by the mechanical properties of elastic
536 tissues due to the inherent interplay between muscle and tendon *in vivo*. The present study
537 provides important information to better understand the determinants of human muscle
538 performance during explosive tasks. In the long term, it can be used to implement
539 individualized training programs and improve explosive strength.

540 **ACKNOWLEDGEMENTS**

541 The authors are grateful to Aurélien Vauquelin and Clémence Damay (Eraclès-Technology)
542 for the conception and design of the mechatronic ergometer resulting from a valuable
543 collaboration, Simon Avrillon and Enzo Hollville for their contribution during pre-
544 experiments and the participants who took part in the study.

545

546 **GRANTS**

547 R. Hager received a sponsorship funding from Actech. The Laboratory Sport, Expertise and
548 Performance is a partner of the French network ReFORM, recognized as a Research Centre
549 for the Prevention of Injury and Illness and the Protection of Athletes by the International
550 Olympic Committee (IOC). As a member of the IOC Medical Research Network, ReFORM
551 has received funding from the IOC to establish long-term research programmes on the
552 prevention of injuries and illnesses in sport for the protection of athlete health.

553

554 **DISCLOSURES**

555 No conflicts of interest, financial or otherwise, are declared by the authors.

556

557 **AUTHOR CONTRIBUTIONS**

558 R.H., A.N., S.D. and G.G. conception and design of research; R.H. and T.P. performed
559 experiments. R.H., T.P., A.N., S.D. and G.G. analysed data; R.H., T.P., A.N., S.D. and G.G.
560 interpreted results of experiments; R.H., A.N., S.D. and G.G. prepared figures; R.H. drafted
561 manuscript; R.H., A.N., S.D. and G.G. edited and revised manuscript; R.H., T.P., A.N., S.D.
562 and G.G. approved final version of manuscript.

563 **Table 1. Rate of torque development, peak fascicle velocity, and mean EMG activity in gastrocnemius lateralis and soleus muscles**
 564 **measured at different ankle angles.**

Ankle angle	-20° ^(a)	-10° ^(b)	0° ^(c)	10° ^(d)	20° ^(e)	30° ^(f)
RTD (Nm.s⁻¹)						
0-200 ms	320 ± 91 ^{cef}	354 ± 117 ^{ef}	389 ± 94 ^{aef}	329 ± 94 ^{ef}	265 ± 66 ^{abcdcf}	194.5 ± 53 ^{abcde}
0-50 ^{hi} ms	141 ± 61 ^{bcddef}	208 ± 127 ^{aef}	178 ± 105 ^{aef}	203 ± 113 ^{aef}	106 ± 53 ^{bdc}	81 ± 45 ^{bdc}
50-100 ^g ms	413 ± 136 ^{bcdcf}	496 ± 210 ^f	549 ± 178 ^{aef}	483 ± 168 ^f	388 ± 150 ^{cf}	280 ± 129 ^{abcde}
100-200 ^g ms	361 ± 128 ^{ef}	357 ± 128 ^{ef}	414 ± 98 ^{def}	317 ± 81 ^{cf}	284 ± 60 ^{abcf}	210 ± 59 ^{abcde}
Peak Fascicle velocity (cm.s⁻¹)	6.1 ± 3.4 ^{bcddef}	8.6 ± 4.0 ^a	10.8 ± 3.8 ^a	10.6 ± 3.0 ^a	9.8 ± 3.2 ^a	8.6 ± 3.4 ^a
Mean EMG GL (% RMS max)						
0-200 ms	69.7 ± 11.0	64.6 ± 24.6	62.3 ± 18.4	65.7 ± 21.0	62.2 ± 18.7	72.0 ± 17.1
0-50 ^h ms	67.2 ± 27.9	68.3 ± 37	58.6 ± 27.8	66.1 ± 27.1	53.1 ± 21.3	61.8 ± 25.0
50-100 ^{gi} ms	87.0 ± 19.7	78.6 ± 35.1	72.9 ± 23.2	75.5 ± 24.4	69.7 ± 24.0	76.9 ± 20.1
100-200 ^h ms	62.5 ± 22.3 ^g	57.8 ± 18.6 ^g	60.5 ± 19.2 ^g	62.7 ± 18.1 ^g	64.5 ± 17.3 ^{abc}	76.3 ± 16.6 ^{abc}
Mean EMG SOL (% RMS max)						
0-200 ms	57.4 ± 23.6	51.7 ± 27.1	50.7 ± 23.6	43.4 ± 19.0	36.8 ± 14.9	37.8 ± 18.8
0-50 ^{hi} ms	21.3 ± 12.5	16.9 ± 7.8	14.9 ± 8.2	13.3 ± 7.4	12.2 ± 6.8	14.4 ± 7.8
50-100 ^g ms	71.2 ± 33.5	78.6 ± 50.1	62.0 ± 32.1	52.9 ± 30.1	41.0 ± 19.5	40.5 ± 24.5
100-200 ^g ms	65.5 ± 22.3	59.2 ± 28.4	63.2 ± 31.4	53.9 ± 21.9	47.0 ± 18.9	48.2 ± 23.9

565

566

567 Values are mean ± SD (n = 16).

568 ^a, ^b, ^c, ^d, ^e and ^f: significantly different than -20°, -10°, 0°, 10°, 20°, and 30°, respectively [*P* < 0.05; two-way ANOVA, main effect: ankle angle (-
 569 20°, -10°, 0°, 10°, 20°, 30°)].

570 ^g, ^h and ⁱ: significantly different than RTD₀₋₅₀, RTD₅₀₋₁₀₀ and RTD₁₀₀₋₂₀₀, respectively [*P* < 0.05; one-way ANOVA, main effects: ankle angle (-
 571 20°, -10°, 0°, 10°, 20°, 30°) × time period (0-50, 50-100, 100-200 ms)].

572 MVC: maximal voluntary contraction; RMS: root mean square.

573

574

575 **FIGURES LEGENDS**

576

577 **Figure 1. Individual patterns of collected signals during RTD testing.** Plantar flexor
578 torque was recorded by a mechatronic ergometer triggered by a high-frame rate ultrasound
579 scanner. Fascicle length and pennation angle were measured on ultrasound images processed
580 using automatic tracking software. Fascicle length was differentiated ~~derived~~ to obtain
581 fascicle velocity. Electromyographic (EMG) activity of *gastrocnemius lateralis* and *soleus*
582 were recorded in time with ultrasound images and mechanical signals. The time
583 corresponding to the onset of torque development (first arrow) was manually determined
584 using the method proposed by (54).

585 **Figure 2. Methodological approach used to obtain individual force-length and force**
586 **velocity relationship. Force-length at MVC peak torque (D):** *Gastrocnemius medialis*
587 fascicle length (A) was recorded during RTD at different conditions (-20, -10, 0, 10, 20 and
588 30°) using ultrasound. Fascicle force (B) was calculated from torque recordings, moment arm
589 and pennation angle. Force-length at MVC peak torque (D) was built from the fascicle length
590 corresponding at peak fascicle force (black circle for peak at 0°, A) and associated fascicle
591 force (green circle for peak at 0°, B) minus the passive force produced at fascicle length
592 corresponding to peak fascicle force (31). The range of fascicle shortening at 0° plotted as a
593 green trace (green-black circle).

594 **Force-velocity relationship (E):** Fascicle velocity (C) was calculated from fascicle length
595 derivative. For the sake of clarity, only fascicle velocity at 0° during RTD (green line) and
596 during ballistic condition (dashed line) are presented here. From peak fascicle velocity (red
597 circle, C) and force values (green circle, B), the individual force-velocity relationship was
598 build (black trace in E). The curvature coefficient of the slope was defined using previous
599 mean data collected by our group on a similar sample of participants (27). Fascicle shortening
600 velocity during RTD was plotted as a rainbow trace, with the colour scale illustrating time
601 from 0 ms (red) to 600 ms (purple).

602 **Figure 3. Mean (n =16) Torque (A), *gastrocnemius medialis* fascicle length (B), fascicle**
603 **velocity (C) and GL RMS EMG time-courses (D) at various angles during RTD.** Mean
604 torque was presented without the effect of passive tension.

605 **Figure 4. Raw (A) and normalized (B) mean active force-length relationship** obtained
606 during maximal contractions performed at -20°, -10°, 0°, 10°, 20° and 30° of ankle angle
607 assuming the model B from Hoffman et al. [(29); n = 16)]. The force-length relationship was
608 normalized (B) using the maximal force (F_0) and the optimal fascicle length (L_0) obtained
609 using individual fits. Colour traces represents the time-course of force and fascicle length
610 changes that occurred during the evaluation of rate of torque development (RTD; i.e., from 0
611 N force to maximal values on the force-length relationship). The three black circles represent
612 the values achieved at 50, 100 and 200 ms during RTD. Fascicle forces values obtained at -
613 20°, -10° and 0° were significantly higher than values obtained at 10°, 20° and 30° [$P <$
614 0.001; one-way ANOVA, main effect: ankle angle (-20°, -10°, 0°, 10°, 20° and 30°)].

615 **Figure 5. Individual active force-length relationship** obtained during maximal contractions
616 performed at -20°, -10°, 0°, 10°, 20° and 30° of ankle angle assuming the model B from
617 Hoffman et al. 2012 for the 16 participants (P).

618 **Figure 6. Force-velocity relationship** (black line) with associated lower 95% confidence
619 interval. The curvature coefficient of the slope was defined using previous mean data
620 collected by our group on a similar sample of participants (n = 16) (27). Fascicle force and
621 shortening velocity measured at 0° of ankle angle during RTD was plotted as a rainbow trace,
622 with the color scale illustrating time from 0 ms (red) to 600 ms (purple). The three black
623 marks represents the mean fascicle length at 50, 100 and 200 ms from the onset of RTD
624 testing.

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768



Torque

50 Nm

L_F

1 cm

Pennation

4°

V_F

4 cm.s⁻¹

EMG GL

50% EMG MAX

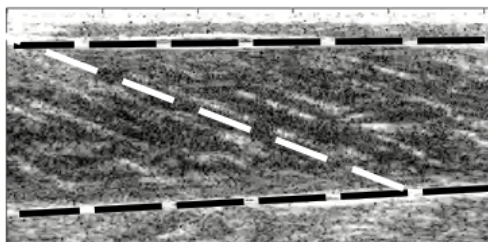
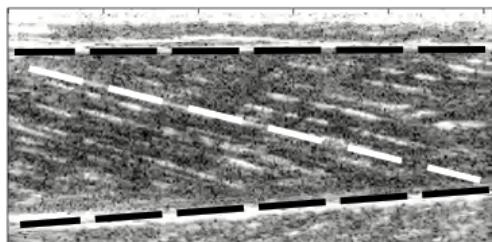
EMG SOL

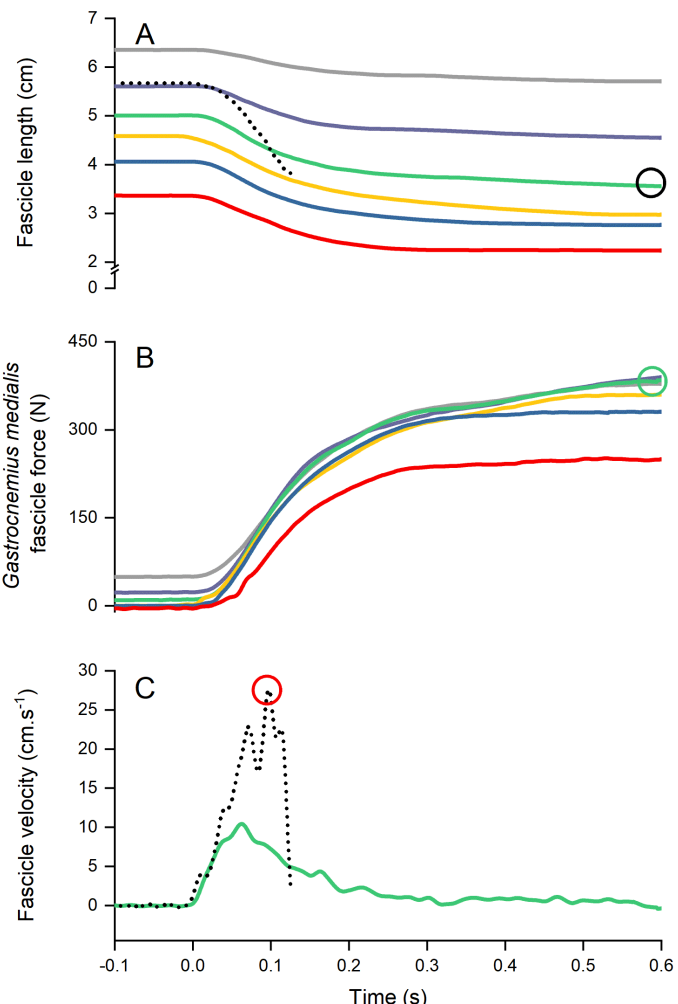
50% EMG MAX

RFD onset

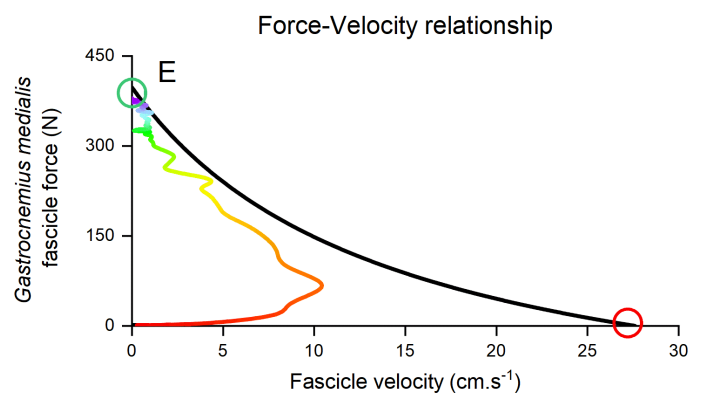
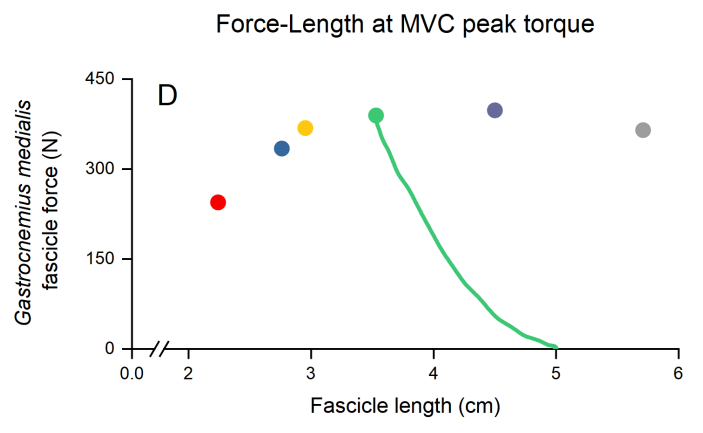
200 ms

50 ms





RFD conditions:
 ● -20° ● -10° ● 0° ● 10° ● 20° ● 30°
 Ballistic condition :
 —



Time (s)
 0.0 0.1 0.2 0.3 0.4 0.5 0.6

