

# Higher muscle fiber conduction velocity and early rate of torque development in chronically strength trained individuals

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1 **TITLE PAGE**

2 **Higher muscle fiber conduction velocity and early rate of torque development in**  
3 **chronically strength trained individuals**

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15 **Short title**

16 Explosive torque neuromuscular assessment

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22 **Key words:** Explosive force contractions; Motor unit Conduction Velocity; Motor unit  
23 recruitment; Neuromuscular assessment; Size principle

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29 **ABSTRACT**

30 Strength trained individuals (ST) develop greater levels of force when compared to untrained  
31 subjects. These differences are partly of neural origin and can be explained by training  
32 induced changes in the neural drive to the muscles. In the present study we hypothesize a  
33 greater rate of torque development (RTD) and faster recruitment of motor units with greater  
34 muscle fiber conduction velocity (MFCV) in ST when compared to a control cohort. MFCV  
35 was assessed during maximal voluntary isometric explosive contractions of the elbow flexors  
36 in eight ST and eight control individuals. MFCV was estimated from high-density surface  
37 electromyogram recordings (128 electrodes) in intervals of 50 ms starting from the onset of  
38 the EMG. The rate of torque development (RTD) and MFCV were computed and normalized  
39 to their maximal voluntary torque (MVT) values. The explosive torque of the ST was greater  
40 than in the control group in all time intervals analyzed ( $p < 0.001$ ). The absolute MFCV values  
41 were also greater for the ST than controls at all time intervals ( $p < 0.001$ ). ST also achieved  
42 greater normalized RTD in the first 50 ms of contraction ( $887.6 \pm 152$  vs.  $568.5 \pm 148.66$   
43  $\%MVT \cdot s^{-1}$ ,  $p < 0.001$ ) and normalized MFCV before the rise in force when compared to  
44 controls. We have shown for the first time that ST can recruit motor units with greater MFCV  
45 in a shorter amount of time when compared to untrained subjects during maximal voluntary  
46 isometric explosive contractions.

47

48 **New & Noteworthy**

49 Strength trained individuals show neuromuscular adaptations. These adaptations have been  
50 partly related to changes in the neural drive to the muscles. Here, we show for the first time  
51 that during the initial phase of a maximal isometric explosive contraction, strength trained  
52 individuals achieve higher levels of force and recruit motor units with greater conduction  
53 velocities.

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57

## 58 INTRODUCTION

59 The human neuromuscular system has the ability to develop high forces in short time  
60 intervals (1). It takes approximately 150 ms to reach high levels of force (>70% maximal  
61 voluntary force) during a single-joint maximal voluntary isometric explosive contraction (7,  
62 16, 30, 50). Explosive force is commonly measured during specific time intervals from the  
63 contraction onset or characterized by the slope of the joint torque-time curve (i.e., the rate of  
64 torque development, RTD) during the first 200 ms of force generation (1). Over the past  
65 decades there has been an increasing interest in the determinants of explosive force  
66 especially in relation to the implications for enhancing athletic performance and for the  
67 prevention of falls and injuries (1, 6, 30, 35, 42, 46, 50). Moreover, the RTD has been  
68 identified as an important parameter to detect changes in neuromuscular function in addition  
69 to the maximal voluntary force (35).

70

71 At the neuromuscular level, RTD is associated to the neural drive to muscles during the very  
72 early phase (first ~50 ms) of the contraction (9, 12, 14, 30, 47). The neural drive to muscles  
73 is the ensemble of motor neuron action potentials that reach the muscle per unit time (24).  
74 During rapid 'ballistic' contractions, the size principle of motor unit recruitment is maintained  
75 (11) but the motor unit recruitment thresholds decrease and discharge rates increase  
76 compared to slow-force contractions (12).

77

78 There is a strong association between the neural activity during the early phase of muscular  
79 contraction (0-50 ms) and explosive force (1, 30, 46, 47, 50). The greater RTD in the first 50  
80 ms of the contraction observed in power athletes is partly associated to a greater EMG  
81 amplitude with respect to controls (50). Moreover, twelve weeks of isometric explosive  
82 training significantly increase the neural responses during explosive contractions when  
83 compared to isometric strength training (6). However, the specific neural adaptations in  
84 chronically strength/power trained individuals are largely unknown. The current evidences

85 from cross-sectional studies that compared trained individuals vs. a control cohort (29, 50)  
86 relies on EMG features that are separated from the neural drive to the muscle (19, 54, 55).

87

88 At the motor unit level, short-term ballistic training increased motor unit discharge rate of the  
89 first four detected motor unit action potentials during isometric ballistic contractions (10).

90 Similarly, six week of strength training increased the motor unit discharge rate during  
91 contractions at forces below 30% of maximum (57). It can be hypothesized that chronic

92 strength training involving explosive tasks may also results in a faster recruitment of larger,  
93 fast-twitch motor units. A faster motor unit recruitment would increase the explosive force of

94 a muscle because the size of the motor unit (i.e. the recruitment threshold (33)) is associated  
95 to the motor unit mechanical properties (peak force, force rise-time) (32, 52). However, direct

96 or indirect data on motor unit recruitment strategies in chronically resistance trained  
97 individuals are lacking (15). Recently, Methenitis and colleagues reported significant

98 associations between MFCV and rate of force development in strength trained individuals  
99 (39). However, the estimates of MFCV were obtained during electrical stimulation of

100 individual muscle fibers (39) thus the time course of MFCV (when the muscle fibers are  
101 activated by the central nervous system) is unknown.

102

103 There are methodological limitations in the identification of individual motor unit activities in  
104 time intervals of 20-50 ms during explosive force contractions. However, it is possible to

105 indirectly assess the properties of active motor units by measuring their average muscle fiber  
106 conduction velocity (MFCV). MFCV is a size principle parameter (4) since muscle fibers of

107 high threshold motor units have greater diameters than those of lower threshold motor units  
108 (4, 37, 54). There is a biophysical relation between MFCV and fiber diameter (41, 43) that

109 has been demonstrated at the individual muscle fiber level (31). Moreover, we have recently  
110 shown that the increase in the average MFCV during increasing-force contractions is

111 strongly associated with the increase in single motor unit conduction velocities when related

112 to the progressive recruitment of motor units (55). It has also been shown that MFCV can be  
113 reliably estimated from EMG signals in intervals as short as ~25 ms (23, 25, 37, 53).

114

115 Therefore, estimates of MFCV may provide an indirect analysis of motor unit recruitment (4,  
116 54, 55). Moreover, the time-course of MFCV during maximal voluntary isometric explosive  
117 contractions is unknown. In this study, we measure for the first time MFCV during explosive  
118 voluntary force contractions in chronically ST individuals when compared to untrained  
119 subjects. We hypothesized a greater early RTD in ST individuals that would be accompanied  
120 with a higher MFCV during isometric explosive force contractions.

121

## 122 **MATERIALS AND METHODS**

### 123 *Participants*

124 Sixteen healthy, non-smoking young men volunteered for this study which was approved by  
125 the University of Rome Ethical Advisory Committee and conducted according to the  
126 Declaration of Helsinki. The volunteers signed an informed consent, completed a standard  
127 health questionnaire, and were screened for their habitual physical activity. None had any  
128 previous history of neuromuscular disorders. Volunteers included those involved in regular  
129 strength training programs (strength training group (ST), n = 8, age, 22.2 ± 2.5 years; body  
130 mass, 85.2 ± 8.3 kg; height 181.2 ± 9.3 cm) and control individuals who were only involved  
131 in light to moderate aerobic activity (control group, n = 8, age, 23.4 ± 3.1 years; body mass,  
132 73.2 ± 7.5 kg; height 177.3 ± 7.5 cm). All volunteers were students from the department of  
133 Human Movement Sciences, University of Rome 'Foro Italico', Rome, Italy. Before the first  
134 familiarization session, the volunteers were asked to report their physical activity habits. ST  
135 volunteers were required to be in a strength-training program that targeted strength and  
136 power for at least three years and for a minimum of three times per week. The training  
137 programs were classical models of progressive strength training for enhancing muscle  
138 strength and power that targets all major upper and lower muscle groups. The training  
139 protocols performed by the ST cohort closely matched the guidelines reported in (2) for

140 enhancing strength and power. The individuals from the ST cohort also performed national  
141 and international competitions that involved explosive tasks, such as volleyball (4 subjects),  
142 javelin throw (1), boxing (1), karate (1). Controls were required to be involved in moderate to  
143 light aerobic exercise less than twice per week and were not involved in any form of regular  
144 strength or power training. All subjects were instructed to avoid strenuous exercise and  
145 caffeine, respectively 48 and 24-hour prior to their visit to the laboratory.

146

#### 147 *Study overview*

148 Participants visited the laboratory on two occasions, one week apart. During the first visit,  
149 they performed a familiarization test to become acquainted with the experimental protocol.  
150 The familiarization session included elbow flexion maximal voluntary isometric contractions  
151 (MVC) and maximal voluntary isometric explosive contractions of their dominant arm (self-  
152 reported). During the second visit, the volunteers performed the experimental session with  
153 concurrent recordings of force (MVC and isometric explosive force contractions) and high-  
154 density surface electromyography (HDsEMG).

155

#### 156 **Measurements**

##### 157 *Force Recording*

158 Both the familiarization and measurement sessions were conducted using an isokinetic  
159 dynamometer (KinCom Dynamometer, Chattanooga, TN) with the elbow of the dominant  
160 limb flexed to 90°. The reliability and feasibility of this dynamometer has been described  
161 previously (27) and used in previous studies that assessed maximal RTD (1). The chair  
162 configuration was established during the familiarization session and replicated in the main  
163 trial. Waist and shoulder straps were tightly fastened to prevent extraneous movements. The  
164 waist strap was fastened across the pelvis and two other straps across the shoulders (35).  
165 This setup was comfortable and well tolerated by the participants of the study. The shoulder  
166 was in a neutral position with the upper arm parallel to the trunk (humerus in a pendent  
167 position), and the forearm was midway between pronation and supination. The elbow joint

168 was secured in a padded brace with Velcro straps. The dynamometer load cell (KinCom  
169 Dynamometer, Chattanooga, TN) consisted of four strain gauges. The wrist strap was  
170 consistently secured to the styloid process of radius and was in series with a calibrated  
171 linear response from the dynamometer load cell that was positioned perpendicular to the  
172 radius. The center of the lever arm was aligned to the distal lateral epicondyle of the  
173 humerus. Subsequently, the lever arm length was measured as the distance between the  
174 distal lateral epicondyle of the humerus and the styloid process of radius. The analogue  
175 force signal was amplified and sampled at 2048 Hz with an external analogue to digital (A/D)  
176 converter (EMG-USB2+ OT Bio elettronica, Turin, Italy). Two personal computers recorded  
177 the data with the software OTbiolab (OT Bio elettronica, Turin, Italy) and Labview 8.0  
178 (National Instruments, Austin, USA). The force signal was displayed for visual feedback  
179 during the tests. Force signals were corrected for the effect of gravity.

180

#### 181 *High-density surface electromyography recordings (HDsEMG)*

182 Two bi-dimensional arrays (matrices) of 64 electrodes each [dimensions for one matrix: 1  
183 mm in diameter, 8 mm inter electrode distance, 13 rows (10.9 cm) x 5 columns (3.7 cm),  
184 gold-coated; OT Bioelettronica, Turin, Italy] (Fig.1 A) were used for recording HDsEMG  
185 signals. The skin was treated by shaving, light abrasion and cleansing with 70% ethanol. An  
186 experienced investigator identified the muscle belly of the biceps brachii (BB) through  
187 palpation and a surgical marker was used to delineate the perimeter of the muscle. Before  
188 placing the electrodes, the arm circumference and the skinfold thickness (Harpenden  
189 skinfold caliper, Milan, Italy) were measured. Successively, both matrices were placed over  
190 the BB using bi-adhesive foams (SpesMedica, Battipaglia, Italy). The grids were mounted  
191 closed to each other to form an array of 128 electrodes (Fig 1.A). The array was located  
192 between the proximal and distal region of the BB, along the direction of the muscle fibers,  
193 covering most of the BB area (26) (Fig 1.A). The large number of electrodes used allowed  
194 the accurate identification of the innervation zone and selection of channels with propagating  
195 action potentials. Moreover, the high-density configuration improves the reliability of MFCV



196 estimates and of the EMG recordings considerably (26, 49). The ground electrode was  
197 placed on the wrist of the non-dominant arm. Two reference electrodes were placed on the  
198 vertebra prominens and on the acromion. The EMG signals were amplified and band-pass  
199 filtered and converted to digital data by a multichannel amplifier (3dB bandwidth, 10-500 Hz;  
200 EMG-USB2+ multichannel amplifier, OT Bioelettronica, Turin, Italy). The same multichannel  
201 amplifier synchronized the HDsEMG and force signals.

202

### 203 **Procedures**

204 Before the measurements, the volunteers performed a standardized warm-up, which  
205 consisted in four contractions at 50% of their perceived maximal voluntary force, four at  
206 ~75%, and one submaximal ~90% contraction. Each contraction was separated by 15 s.  
207 Following the warm-up with a recovery time of 5 min, the subjects completed three MVC,  
208 with 1 minutes of rest in between. The volunteers were encouraged to “push as hard as  
209 possible” for at least 3 s while receiving feedback on the exerted force and on the force  
210 exerted in the previous MVC contractions. The greatest force was recorded as the maximum  
211 voluntary force (MVF). After 5 minutes of rest eight explosive force contractions were  
212 performed in two blocks of four contractions each. The blocks were separated by 5 min of  
213 rest and the individual contractions within each block were separated by 20 s of rest. For the  
214 explosive force contractions, volunteers were instructed to relax and flex the elbow “as fast  
215 and hard” as possible after hearing an auditory cue. Volunteers were instructed to exceed  
216 the 75% of MVF threshold, which was displayed with a horizontal cursor on the monitor,  
217 without performing any countermovement. Only contractions that did not show any counter  
218 movement ( $\leq 0.5$  Newtons (N) from the baseline of force in the 150 ms before the onset of  
219 force) were included within each block and used for the analysis.

220

### 221 *Force signal analysis*

222 In the offline analysis, the analogue force signal was converted in N and multiplied by the  
223 respective lever arm in order to obtain torque (N\*m). Successively, the torque signal was

224 filtered with a low-pass fourth-order, zero-lag Butterworth filter with a cut-off frequency of 400  
225 Hz. The torque onset ( $T_0$ ) was determined with a visual detection method used in previous  
226 studies (50). After the onset detection was found, the torque was filtered with zero-lag  
227 Butterworth filter with a cut-off frequency of 20 Hz. This two-step filtering procedure allowed  
228 to first detect precisely the onset of torque in the 400 Hz low pass filtered signal (51) and  
229 then the 20 Hz filter removed all the non-physiological frequencies in the signal. The 20 Hz  
230 low pass filter guaranteed an undistorted signal in all cases with respect to the 400 Hz  
231 filtered signal, that was checked in all the explosive torque contractions. The onset value  
232 was used to determine the torque values at 50 ms ( $T_{50}$ ), 100 ms ( $T_{100}$ ), 150 ms ( $T_{150}$ ), and  
233 200 ms ( $T_{200}$ ) after the onset (Fig. 1 C-D). The five contractions with the highest torque  
234 values at  $T_{150}$  were used for the analysis. The absolute torque values at different time points  
235 were normalized by the respective maximal torque ( $T$  / maximal voluntary torque (MVT)).  
236 The RTD (i.e.,  $RTD_{100-150} = T_{150} - T_{100} / 0.05$  s) was calculated in three-time intervals,  $RTD_{0-50}$ ,  
237  $RTD_{50-100}$ , and  $RTD_{100-150}$  for both the absolute and relative torque values (e.g.,  $RTD-rel_{0-50}$ )  
238 (Fig. 2 A-B). The torque analysis was completed with MATLAB 2015 (MathWorks Inc.,  
239 Natick, MA).

240

### 241 *EMG Processing*

242 Single differential HDsEMG signals (SD) were calculated from the monopolar derivations for  
243 each column of the two bi-dimensional arrays. SD signals for each column were visually  
244 inspected and the six SD channels with the highest coefficient of correlation (CC) ( $CC \geq 0.8$ )  
245 and clear MUAPs propagation without shape change from the nearest innervation zone to  
246 the distal tendon (Fig. 1 C-D) were chosen for the analysis. The columns of the matrix that  
247 were selected for the estimates of MFCV corresponded to the central part (between the first  
248 three central columns) of the two bi-dimensional arrays, as they corresponded to the  
249 channels with the highest quality (CC and propagation). MFCV was computed using an  
250 algorithm that allows highly accurate estimates of conduction velocities from multichannel  
251 EMG signals and whose reliability and validity has been previously assessed in both

252 isometric and dynamic contractions, with robust intraclass coefficient of correlations (>75%  
253 ICC) (23, 25, 26). During isometric contractions the between day coefficient of variability in  
254 MFCV is lower than 2%, with ICC >88% (36). The use of  $\geq 6$  EMG channels allows to detect  
255 changes of MFCV as small as 0.1 m/s when compared to estimates from a pair of bipolar  
256 signals (>0.4 m/s) (18). The BB muscle was chosen in this study because it has been shown  
257 to provide estimates of MFCV with good reliability during submaximal (50% MVC) steady  
258 state contractions (26). It has been shown that MFCV can be accurately assessed also  
259 during dynamic explosive tasks (44). Maximal muscle fiber conduction velocity ( $MFCV_{MAX}$ )  
260 was estimated during the MVF contraction in time windows of 50 ms, from 500 ms before to  
261 250 ms after peak torque during the MVF. The choice of this interval for the estimation of  
262  $MFCV_{MAX}$  was due to the delay between recruitment and motor unit peak twitch forces. After  
263 determining the maximal value of MFCV, MFCV was estimated during the explosive torque  
264 contractions in intervals of 50 ms. For each explosive contraction, the onset of EMG activity  
265 was assessed visually (Fig. 1. C-D) and MFCV was estimated from five intervals,  
266 corresponding to the electromechanical delay ( $EMD = T_0 (s) - EMG \text{ onset} (s)$ ), and the four  
267 50-ms intervals following  $T_0$  ( $MFCV_{EMD}$ ,  $MFCV_{0-50}$ ,  $MFCV_{50-100}$ ,  $MFCV_{100-150}$ ,  $MFCV_{150-200}$ ).  
268 MFCV absolute and normalized values ( $MFCV (m/s) / MFCV_{MAX}$ , e.g.,  $MFCV_{rel0-50}$ ) were  
269 averaged over the five explosive contractions selected for the analysis.

270

271

## 272 **Statistics**

273 The Shapiro-Wilk test confirmed the normal distribution of the extracted variables. The  
274 number of participants needed for the study was estimated with a statistical power analysis  
275 test (function *sampsizepr* in MATLAB) using previous data on MFCV and RTD, and  
276 successively progressively tested with the data collected in the present study. The  
277 significance level of the power test was set with a P value of 0.05. Two-way repeated  
278 measures analysis of variance ANOVA (group x time) was used to assess differences in  
279 explosive force, RTD and MFCV for both absolute and normalized values. The ANOVA

280 included the five-time intervals from EMG or torque onset during the explosive contractions.  
281 Bonferroni stepwise corrected paired t-tests were used to assess differences between  
282 groups at different time intervals. Moreover, Pearson product-moment coefficient of  
283 correlation was used to assess the linear relation between RTD and MFCV for each  
284 individual cohort and the coefficient of determination ( $R^2$ ) was used as an index of prediction  
285 power. The Bonferroni correction was applied to the regression significance values.  
286 Independent sample t-tests were used to assess differences between groups for all other  
287 variables (MVF,  $MFCV_{MAX}$ , skinfold and arm circumference). Statistical analysis was  
288 completed using SPSS version 14 (SPSS Inc., Chicago, IL) and MATLAB. The significance  
289 level was set at  $P < 0.05$ . Data are reported as mean and SD.

290

## 291 **RESULTS**

292

### 293 *Electromechanical Delay, Anthropometry, and Statistical Power*

294 The EMD did not differ between the two groups (ST  $62.42 \pm 10.81$  vs controls  $60.24 \pm 12.12$   
295 ms,  $p > 0.05$ ). Moreover, there was no difference in the subcutaneous fat layer thickness  
296 between groups (ST  $4.11 \pm 0.71$ , control group  $4.45 \pm 1.05$  mm,  $p > 0.05$ ) as assessed by  
297 skinfold measures, whereas the arm circumference was greater for the ST ( $36.01 \pm 1.51$  vs  
298  $29.3 \pm 2.58$  cm,  $p < 0.05$ ). The power analysis indicated that 7 subjects per cohort were  
299 needed to obtain a power of 90% for MFCV and RTD estimates.

300

### 301 *Torque*

302 Maximal torque was significantly greater for the ST compared to controls ( $99.64 \pm 21.62$  vs  
303  $60.56 \pm 8.74$  (N·m),  $p < 0.001$ ). The ST also developed higher torques at 50, 100, 150, and  
304 200 ms from contraction onset ( $p < 0.001$ ). When torque at different time points was  
305 expressed relative to the MVT, the ST achieved higher relative torques in the first two  
306 phases of contraction ( $T_{50}$  and  $T_{100}$ ,  $43.84 \pm 5.29$  vs  $17.12 \pm 4.61$   $T_{50}$ ,  $63.45 \pm 10.02$  vs  $33.25$

307  $\pm 4.42 T_{100} \%MVT$ ,  $p < 0.001$ ). The relative explosive torque at  $T_{150}$  and  $T_{200}$  was similar for  
308 both cohorts ( $p > 0.05$ ).

309

310 The absolute RTD during the initial phase ( $T_{50}$ ) of the contraction was greater for the  
311 resistance trained individuals than controls ( $861.82 \pm 104.60$  vs  $342.05 \pm 93.08 \text{ N}\cdot\text{m}\cdot\text{s}^{-1}$ ,  
312  $p < 0.001$ ; Fig 2A). The absolute RTD over the consecutive time windows did not differ (Fig  
313 2A). In addition, the normalized RTD was greater only in the first 50 ms of contraction for the  
314 ST ( $887.66 \pm 152.08$  vs.  $568.54 \pm 148.66 \%MVT\cdot\text{s}^{-1}$ ,  $p < 0.001$   $\%MVT\cdot\text{s}^{-1}$ ,  $p < 0.001$ ; Fig 2B).  
315 Conversely, the normalized  $RTD_{50-100}$  and  $RTD_{100-150}$  was greater for the controls ( $536.48 \pm$   
316  $112.08$  vs  $404.91 \pm 96.36 \text{ MVT}\cdot\text{s}^{-1}$ ,  $356.21 \pm 110.48$  vs  $271.41 \pm 69.44, \text{ MVT}\cdot\text{s}^{-1}$ ;  $p < 0.001$ ;  
317 Fig 2B).

318

### 319 *Muscle fiber conduction velocity*

320 Maximal MFCV at MVT ( $MFCV_{MAX}$ ) ranged from 5.05 to 5.82 m/s in ST and from 4.93 to 5.26  
321 m/s in the controls with the ST group having a significantly higher  $MFCV_{MAX}$  compared to  
322 controls ( $5.37 \pm 0.27$  vs  $5.04 \pm 0.11 \text{ m/s}$   $p < 0.001$ ).

323

324 MFCV during the explosive torque contractions (from the EMD to  $T_{200}$ ) ranged from 3.44 to  
325 5.45 m/s (and the lowest value of MFCV corresponded to the time interval during the  
326 electromechanical delay,  $MFCV_{EMD}$ ) when grouping all participants. The average MFCV  
327 values across subject at each time window can be observed for the two cohorts in Fig 3. The  
328 MFCV value consistently increased in the second-time interval ( $MFCV_{0-50}$ ) (Fig 3,  $p < 0.01$ ).  
329 This indicates recruitment of motor units with progressively larger diameter fibers with  
330 increase in torque (37, 54, 55), that is related to the progressive recruitment by size (33, 54).  
331 However, the ST achieved a higher  $MFCV_{EMD}$  compared to the controls ( $4.44 \pm 0.13$  vs  $3.83$   
332  $\pm 0.20 \text{ m/s}$ ,  $p < 0.001$ ; Fig 3A), even when  $MFCV_{EMD}$  was normalized to  $MFCV_{MAX}$  ( $82.57 \pm$   
333  $3.13$  vs  $75.86 \pm 3.55 \text{ MFCV-rel}_{EMD}$ ,  $p < 0.001$ ; Fig. 3B). Moreover, the early phase of absolute

334 and normalized MFCV estimates was correlated to RTD (Fig. 4; *RTD and MFCV correlations*  
335 *paragraph*).

336

337 The ST cohort maintained a greater absolute and normalized MFCV value throughout the full  
338 duration of the explosive contractions ( $p < 0.001$ ; Fig. 3A). Interestingly the time-MFCV curve  
339 had a similar pattern for the ST compared to the controls (Fig 3A-B). MFCV indeed  
340 increased linearly from EMD until reaching a plateau at  $MFCV_{50-100}$  ( $p < 0.001$ ) for both groups  
341 (Fig. 3A-B). This observation indirectly indicates that the muscle full motor unit recruitment  
342 may have been completed before the first 100 ms of explosive torque production.

343

344 *RTD and MFCV correlations*

345 The estimates of MFCV were positively correlated with RTD only in the time window  $RTD_{0-50}$   
346 (Fig. 4). For the resistance trained individuals, a negative correlation was found between  
347 normalized  $RTD_{100-150}$  and absolute MFCV (average  $R^2$  for all MFCV estimates when plotted  
348 as a function of  $RTD_{100-150}$  values =  $-0.59 \pm 0.24$ ,  $p < 0.001$ ). During the same RTD time  
349 window, the correlation for the controls was not significant ( $p > 0.05$ ).

350

## 351 **DISCUSSION**

352 MFCV was measured during explosive force contractions in a group of resistance trained  
353 individuals and a control cohort. ST exhibited greater explosive torque, early rate of torque  
354 development (RTD), and greater MFCV with respect to controls throughout the contraction.  
355 When explosive torque was normalized to maximal torque, ST had a higher RTD at the  
356 beginning of the contraction (0-50 ms). Moreover, a greater absolute and normalized  
357 conduction velocity ( $MFCV_{MAX}$ ) during the electromechanical delay (EMD) and in the first 50  
358 ms of torque generation was observed for the ST group. This result indicates a recruitment  
359 of motor units with greater conduction velocities. This is the first study showing that ST may  
360 recruit larger motor units in a shorter amount of time.

361

362 *Muscle fiber conduction velocity*

363 The average MFCV values are in agreement with previous reports of MFCV during steady  
364 state contractions. For example, Farina and colleagues reported estimates of MFCV in the  
365 biceps brachii during isometric steady state contractions at 50% MVC of ~4.6 m/s (26).  
366 Zwarts and Arendt-Nielsen estimated MFCV at high contraction forces of the biceps brachii  
367 and reported values ranging between 3.22 and 5.11 m/s (58). MFCV average values in the  
368 present study were also in agreement with estimates of single motor unit conduction  
369 velocities (MUCV) using intramuscular electromyography recordings during voluntary and  
370 electrical activation of the biceps brachii muscle. Moreover, the present estimates are also in  
371 accordance with other studies involving different muscular contractions and protocols (21,  
372 22, 28, 37, 38, 44, 45).

373 Interestingly, only two studies assessed MFCV in power athletes and only during electrical  
374 stimulation and maximal voluntary contractions (39, 48). Sadoyama and colleagues reported  
375 a significantly higher maximal MFCV in a group of trained sprinters compared to endurance  
376 runners (4.84 vs 4.31 m/s) (48). Moreover, they reported a significant relation between the  
377 relative area of fast twitch fibers and conduction velocity (48).

378

379 Recently, Methenitis and colleagues estimated MFCV during electrical stimulation of muscle  
380 fibers in endurance runners, power trained and ST individuals, and measured separately  
381 RTD (39). They reported significant relations between MFCV, muscle fiber cross-sectional  
382 area and rate of force development (39). However, estimates of MFCV were assessed  
383 during electrical stimulation and thus separately from the voluntary generation of explosive  
384 force. Therefore, it was not possible to associate the underlying neural strategies of muscle  
385 control to explosive force performance. Collectively, these previous results indicate that  
386 MFCV may be an indicator of muscle explosive performance, although no previous study  
387 assessed MFCV during explosive torque generation.

388

389 *Explosive torque and RTD*

390 The RTD was significantly greater for the ST during the early phase of explosive torque  
391 generation (Fig 3A). However, when the moment-time curve was normalized to the maximal  
392 strength, the RTD for the resistance trained subjects was significantly different only in the  
393 first 50 ms of the contraction (Fig 3B). Because the relative explosive torque at 150 and 200  
394 ms from contraction onset was similar between the two groups, the controls developed  
395 higher RTD during the second and third time window from force onset (Fig 3B).

396

397 Previous studies found an increase in the EMG amplitude and rate of force development in  
398 the initial phase of contraction after four weeks of explosive training (7). In addition, a greater  
399 normalized rate of force development in the first 50 ms of contraction was found for power  
400 athletes during knee extensor explosive torque (50). Because the first 50 ms of contraction  
401 strongly reflect neural activation (9, 11, 12, 46), strength or power training presumably  
402 increase RTD by a faster recruitment of motor units, as discussed in the following.

403

#### 404 *MFCV during the explosive phase of contraction*

405 ST individuals have the ability to develop higher levels of force in the first 50 ms of  
406 contraction. This seems to be associated to greater MFCV in the same time interval which  
407 indicates recruitment of motor units with greater conduction velocity. The role of motor unit  
408 recruitment during explosive force contraction is not well understood because it is not  
409 possible to identify representative populations of motor units in very short time intervals.

410

411 The primary determinant of motor unit twitch force is the number of muscle fibers innervated  
412 by the axon (13, 52). Motor unit peak twitch forces in humans range from ~6 to ~78 mN•m  
413 with maximal tetanic forces ranging from ~30 to ~200 mN•m (32, 34). Therefore, one of the  
414 mechanisms that determined the increase in RTD during the first 0-50 ms interval in the ST  
415 may have been the recruitment of larger motor units with greater and faster twitches. There  
416 is evidence showing correlations between electrically evoked twitch torque and early



417 voluntary rate of force development, that could be associated to the differences in muscle  
418 fiber composition and/or  $\text{Ca}^{2+}$  saturation for the trained individuals (3, 30).

419

420 Interestingly, the two groups showed similar EMD values, which is in accordance with a  
421 previous study that compared the EMD in a power trained and untrained cohort (50). This  
422 finding is however contradictory with a higher MFCV during the EMD. A higher absolute  
423 MFCV value should theoretically anticipate the release of  $\text{Ca}^{2+}$  and thus the rise in force.  
424 However, these problematics may be related to the techniques employed in assessing the  
425 delay between the neural and muscular apparatus. The EMD during explosive contractions  
426 may not be sensitive to differences in neural activation due to a compressed recruitment (11,  
427 56). We have recently shown, that when the electromechanical delay is assessed as the  
428 time difference between the neural drive and force during the sustained contractions the  
429 central nervous system modulates the delay broadly and according to the rate of force  
430 development (56). Indeed, the neuromechanical delay seems to be predominantly influenced  
431 by the type of recruited motor units and to the intrinsic properties of the motor neuron (5, 56).  
432 Future studies assessing the neuromechanical delay in strength/power trained individuals  
433 may be warranted.

434

435 MFCV increases with voluntary force production due to the relation between motor unit  
436 recruitment thresholds and fiber diameter (4, 8, 31, 54). This association implies that the  
437 ordered recruitment of motor units may be assessed by estimates of conduction velocity  
438 (55). We have recently reported that large, high-threshold motor units innervate fibers with  
439 large diameter (54), which explains the association between motor unit mechanical  
440 properties and conduction velocity, previously reported (4). Moreover, we have recently  
441 demonstrated that the increase in average MFCV during voluntary force contractions is  
442 associated to the progressive recruitment of motor units with increasing conduction velocity  
443 and predicts recruitment thresholds at the individual subject level (55).

444

445 In the present study, MFCV was the average of the conduction velocities of the active motor  
446 units during explosive force contractions, in time intervals of 50 ms following EMG onset. We  
447 showed that there may be significant differences in the recruited motor units during explosive  
448 tasks in ST compared to moderately active individuals. Absolute MFCV values were greater  
449 in ST throughout the full duration of the explosive contractions (Fig. 3.A). Moreover, the early  
450 absolute and normalized MFCV were positively associated to RTD (Fig. 4). Because  
451 absolute MFCV values are linearly related to the diameters of muscle fibers, higher absolute  
452 conduction velocity values may indicate that ST have muscle fibers with larger diameters  
453 due to the strength training induced hypertrophy (39), as compared to controls (20, 40).

454

455 However, when MFCV values were normalized to the maximal value during MVF (full motor  
456 unit recruitment), ST had a significantly greater MFCV-rel during the initial phase of the  
457 explosive contractions. Specifically, MFCV-rel<sub>EMD</sub> and MFCV-rel<sub>0-50</sub> were on average ~9%  
458 greater (Fig 4B). This suggests that during the early phase of explosive force, ST have the  
459 ability to recruit motor units with faster conduction velocities in a shorter time. It takes  
460 ~100ms more for the controls to reach similar values of normalized MFCV compared to the  
461 ST group. Interestingly, the changes in conduction velocity did not differ between groups  
462 (Fig. 4A-B) and the MFCV plateaued in the interval 50-100 ms that can be interpreted as full  
463 motor unit recruitment (55). This interpretation is in agreement with previous studies  
464 reporting that most motor units are recruited at 1/3 of maximal force during explosive  
465 contractions (11, 12). Moreover, MFCV increased in all subjects from the EMD to 0-50,  
466 indicating that the ordered recruitment according to the size of the motor unit was preserved  
467 during the explosive tasks in both groups.

468

469 The underlying mechanism that may determine an increase in explosive force for the ST  
470 individuals may be an anticipated recruitment of high threshold motor units with high  
471 conduction velocities. The difference between MFCV of high and low threshold motor units  
472 within a muscle is ~2 m/s (54). A faster motor unit recruitment (and conduction velocity)

473 would achieve greater peak mechanical torques in a shorter time. The release of calcium  
474 from the sarcoplasmic reticulum is correlated to the speed the action potential on the fiber  
475 membrane (17). Indeed, MFCV is related to motor unit time-to-peak twitch forces (4). The  
476 increase in MFCV may potentially allow a faster calcium uptake and thus anticipating the rise  
477 in force.

478

479 Van Cutsem and colleagues reported an increase in motor unit discharge rates following  
480 ballistic training (10) and concluded, in agreement with other studies, that RTD depends on  
481 motor unit discharge rate (10, 12, 14). On the other hand, the recruitment threshold of motor  
482 units significantly influences the discharge rate at a given absolute force (Duchateau &  
483 Baudry, 2014). Anticipating the recruitment of high threshold motor units would result in  
484 reaching motor unit peak discharge rate and motor unit peak RTD in a shorter time.  
485 Accordingly, in the present study, MFCV was positively associated with RTD (Fig 4A),  
486 suggesting that motor unit recruitment may play an important role in explosive force  
487 production.

488

489 Interestingly, the correlation between  $RTD_{0-50}$  and early MFCV values ( $MFCV_{EMD,0-50}$ ) was  
490 different for the ST and untrained individuals.  $MFCV_{0-50}$  was not correlated with  $RTD_{0-50}$  in the  
491 ST group (Fig. 4). This result indicates that ST completed the motor unit recruitment during  
492 the very early phase of explosive force, i.e. between the EMD and the first 50 ms from  
493 contraction onset (Fig. 4B). The increase in MFCV during the explosive force at the time  
494 points 50 and 100 (ms) for the ST is presumably due to some subjects continuing the  
495 recruitment, whilst the subjects with higher RTD achieving a faster plateau in MFCV (Fig. 4).  
496 Indeed, it took more time for the untrained individuals to reach high MFCV (and full motor  
497 unit recruitment) values (Fig 3,4).

498

499 It must be noted that the number of subjects in the present study may be too low for a  
500 correlation study. Moreover, the cross-sectional design cannot isolate the innate and

501 environmental factors that contributed to the explosive force and MFCV differences found  
502 between the cohorts. However, in the present study the trained individuals performed  
503 combined strength and explosive training for more than three years. Recent evidence  
504 showed a significant increase in explosive force production after twelve weeks of isometric  
505 explosive training when compared to isometric sustained-contraction strength training (6).  
506 The large differences in the early RTD for the trained subject in the present study may also  
507 indicate that the neural contributors to explosive strength could be related to chronic  
508 exposure to explosive/strength training and that the neural adaptations may continue over  
509 time. Future studies assessing the neural contributors to explosive force in large cohorts and  
510 longitudinal (>1yr) interventions are warranted.

511

#### 512 *Conclusion*

513 Resistance trained individuals showed higher RTD and explosive force in the very early  
514 phase of contraction that was accompanied by an increase in absolute and normalized  
515 MFCV, when compared to controls. These observations may be explained by recruitment of  
516 fast twitch motor units (i.e., large motor units with large muscle fibers diameters) in a shorter  
517 amount of time in the resistance trained cohort than controls. In addition to the functional  
518 implications in the study of human explosive force, the study also presents a methodology  
519 that may be applied in the assessment of the neural strategies of muscle control in health,  
520 training, and pathology.

521

#### 522 **Conflict of interest**

523 The authors declare no conflict of interest

524

525

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#### 708 **FIGURE CAPTIONS**

709 **Fig. 1. A:** Two high-density surface EMG arrays of 64 of electrodes each. **B:** Time-torque  
710 curve during an isometric explosive contraction (black line) and the activity of 128 monopolar  
711 channels recorded from the biceps brachii muscle. **C.** Ten single differential EMG signals  
712 during an explosive force contraction from a control subject. The innervation zone (IZ) and  
713 several motor unit action potentials (MUAPs) propagating in the distal direction can be seen.  
714 **D.** In these signals recorded from a strength trained individual, several MUAPs propagating  
715 at a significant higher velocity can be seen compared to the control subject. The dotted line  
716 indicates the time-torque curve.

717 **Fig 2.** Rate of torque development (RTD) in absolute (A) and normalized (B) values. Black  
718 bars represent the strength trained individuals and white bar for the controls. Data are  
719 reported as mean and SD. \* =  $p < 0.001$

720 **Fig. 3.** Muscle fiber conduction velocity (MFCV) in absolute (A) and normalized (B) values.  
721 Filled circles for the strength trained individuals. Correlation coefficients ( $R^2$  and regression  
722 lines are given). Data are reported as mean and SD. \* =  $p < 0.01$ .

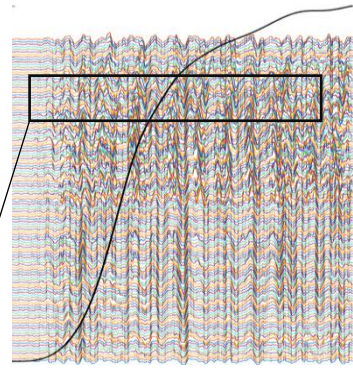
723 **Fig. 4.** Correlation between the rate of torque development during the first 50 ms of  
724 contraction ( $RTD_{0-50}$ ) and muscle fiber conduction velocity during the electromechanical

725 delay and in the first 50 ms of contraction ( $MFCV_{EMD,0-50}$ ). Filled circles for the control  
726 individuals. Correlation coefficients ( $R^2$  and regression lines are given) \* =  $p < 0.05$ .

**A. Two matrices of 64 electrodes each**



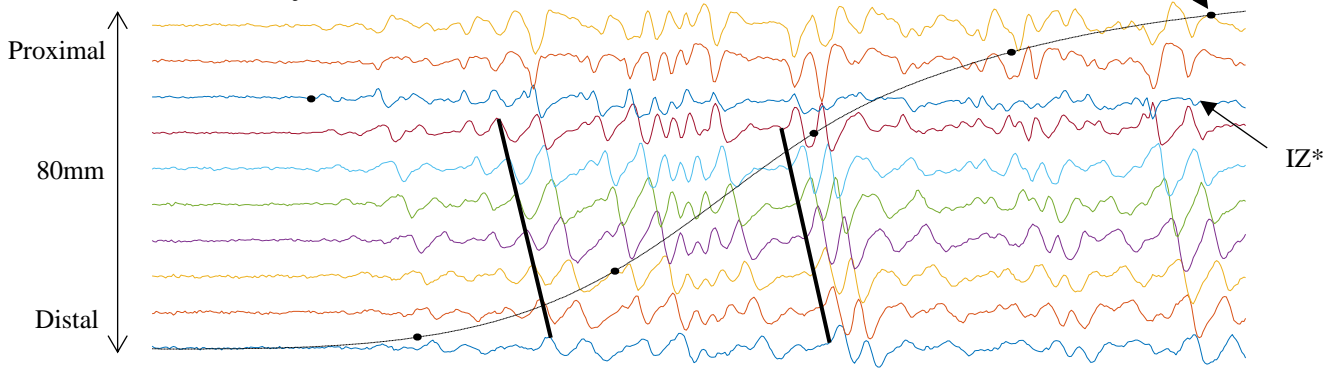
**B. 128 Monopolar EMG signals**



Single differential derivations

Force at 200 ms from force onset

**C. Control subject**



**D. Strength trained**

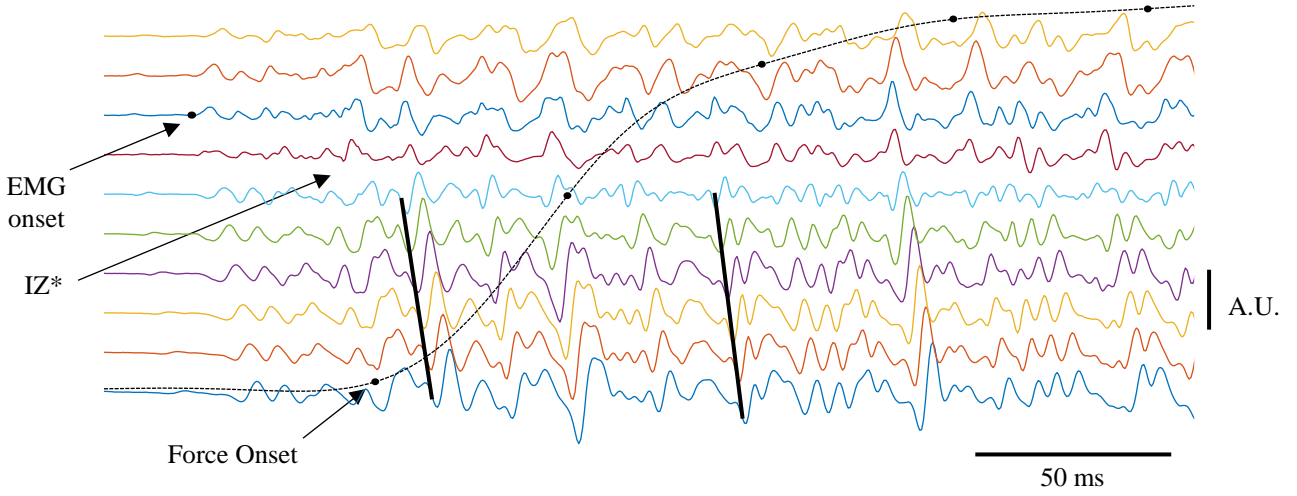
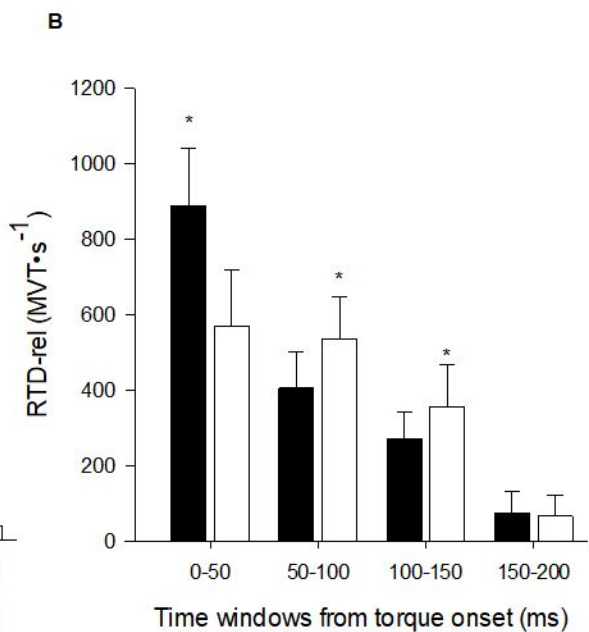
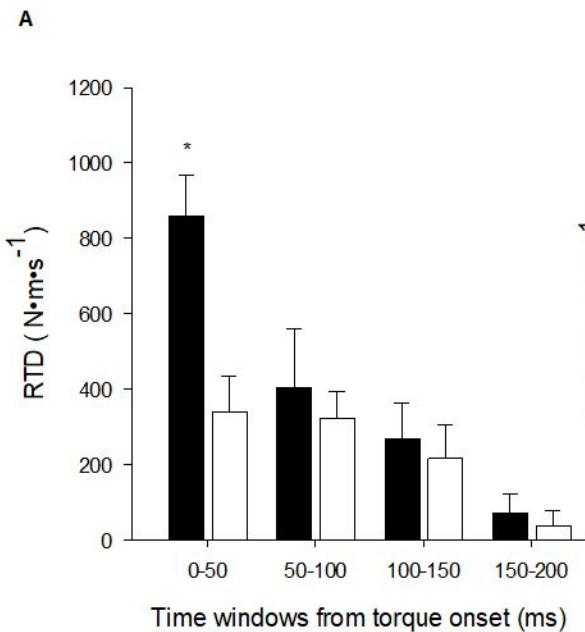


Fig 1.



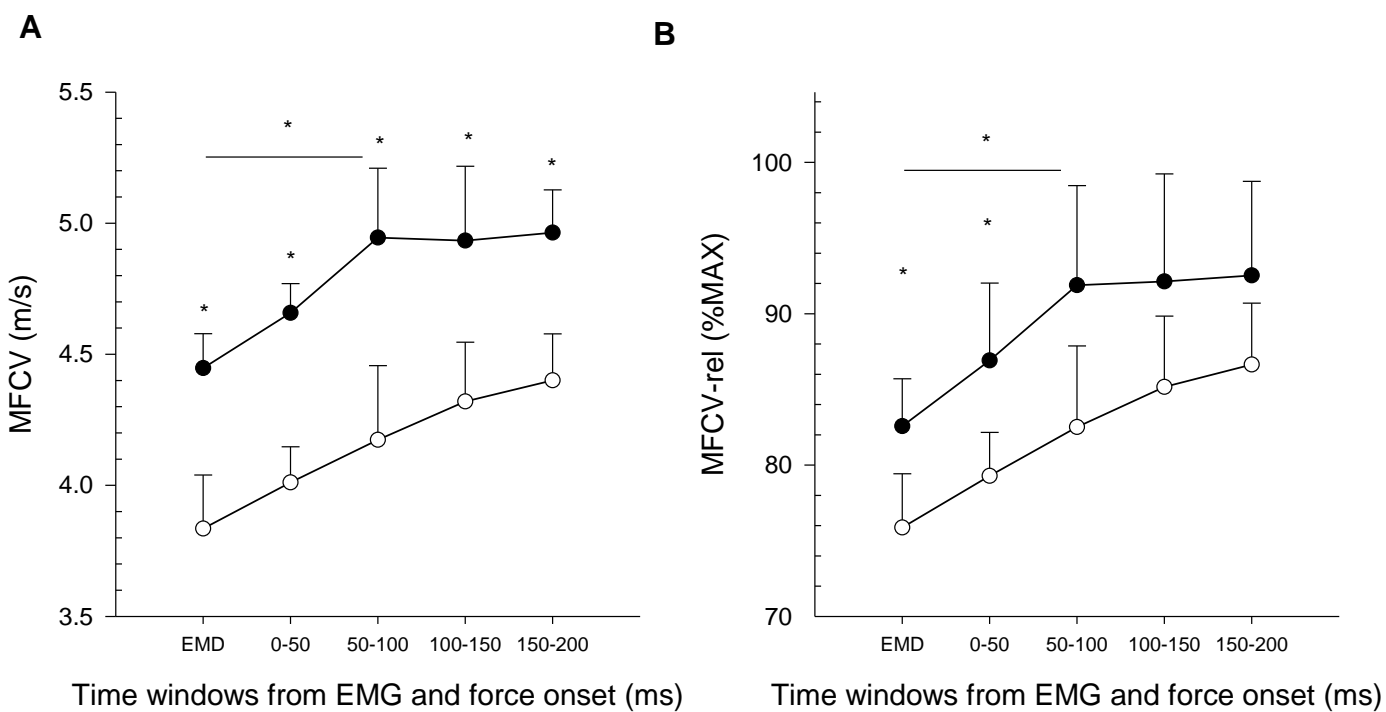


Fig 3.

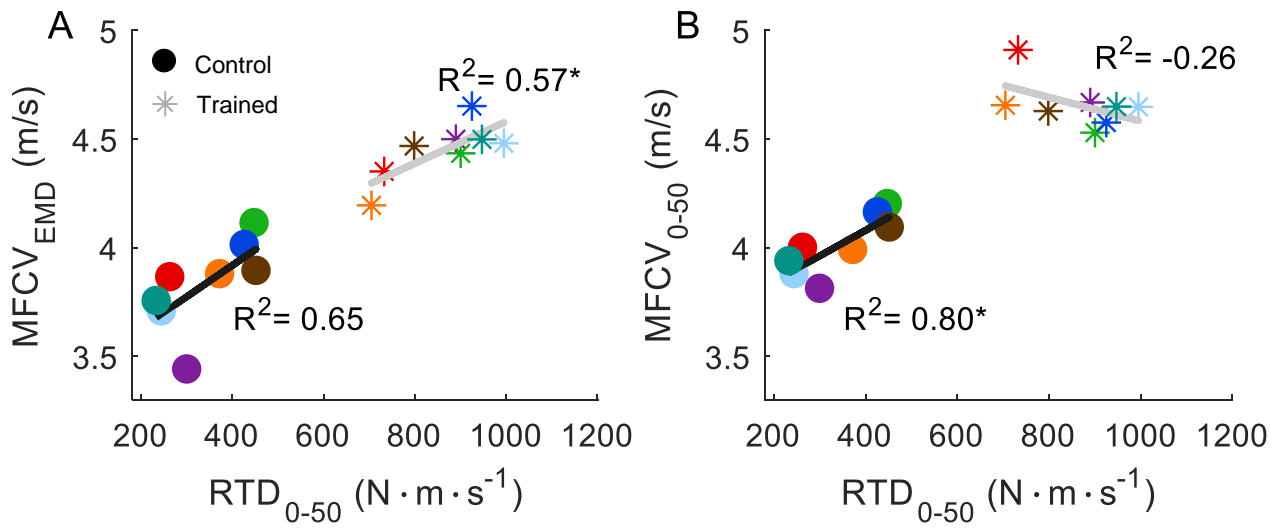


Fig 4.