Resistance training with different repetition duration to failure: Effect on hypertrophy, strength and muscle activation

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Abstract

Background. This study investigated the effects of two 14-week resistance training protocols with different repetition duration (RD) performed to muscle failure (MF) on gains in strength and muscle hypertrophy as well as on normalized electromyographic (EMG) amplitude and force-angle relationships.

Methods. The left and right legs of ten untrained males were assigned to either one of the two protocols (2-s or 6-s RD) incorporating unilateral knee extension exercise. Both protocols were performed with 3-4 sets, 50-60% of the one-repetition maximum (1RM), and 3 min rest. Rectus femoris and vastus lateralis muscles cross-sectional areas (CSA), maximal voluntary isometric contraction (MVIC) at 30° and 90° of knee flexion and 1RM performance were assessed before

39 and after the training period. In addition, normalized EMG amplitude-angle and force-angle
40 relationships were assessed in the 6th and 39th experimental sessions.
41 **Results**. The 6-s RD protocol induced larger gains in MVIC in the 30º of knee angle
42 measurement than the 2-s RD protocol. Increases in MVIC in the 90º of knee angle and 1RM
43 were indifferent between the 2-s and 6-s RD protocols. For the rectus femoris muscle growth,
44 inconclusive changes were found across the ten subjects. In contrast, the 2-s RD protocol may
45 have resulted in superior vastus lateralis muscle hypertrophy. Moreover, different normalized
46 EMG amplitude-angle and force-angle values were detected between protocols over most of the
47 angles analyzed. **Conclusion**. Performing longer RD could be a more appropriate strategy to
48 provide greater gains in isometric maximal muscle strength at shortened knee positions.
49 However, similar maximum dynamic strength and muscle hypertrophy gains would be provided
50 by protocols with different RD.
51
52 **Introduction**
53 Repetition duration (RD) is an important feature of a resistance training program (ACSM, 2009)
54 influencing the strength gains and hypertrophy (i.e. quadriceps femoris muscles) (Chaves et al.,
55 2020; Tanimoto & Ishii, 2006). Nevertheless, the systematic effect of the RD on resistance
56 training is not yet fully understood (Davies et al., 2017; González-Badillo et al., 2014). It has
57 been reported that measurements on isokinetic devices showed poor training and sports
58 specificity (e.g. reduced ecological validity) and the lack of equalization of resistance training
59 protocols would be some of the limitations presented by studies that investigated the influence of
60 RD (González-Badillo et al., 2014). Moreover, the absence of registration and/or poor control
61 over the RD, especially during protocols to muscle failure (MF), may hamper its meaning for the
62 effectiveness isoinertial exercises (González-Badillo et al., 2014). Hence, RD control and
63 comparability between training protocols must be considered to be mandatory for a proper
64 understanding of the RD effect in a resistance training program.

65   A meta-analysis on the RD effect on muscle hypertrophy (including only studies with
66 protocols performed to MF) concluded that similar muscle hypertrophy responses may be
67 observed when performing RD between 0.5-s and 8-s (Schoenfeld et al., 2015). This result
68 suggests that a wide RD range may be employed in order to produce muscle hypertrophy.
69 However, in addition to RD, the meta-analysis also included studies with variations in the load
70 intensity (Schuenke et al., 2012), and studies with training protocols performed until MF
71 (Tanimoto & Ishii, 2006) or not. Consequently, the results of the meta-analysis cannot be
72 attributed to the manipulation of RD only. Previous studies have suggested that muscle strength
73 and hypertrophy are predominantly influenced by the load intensity [(e.g. percentage of one
74 repetition maximum - %1RM)] (Lasevicius et al., 2018) and by the RD (González-Badillo et al.,
75 2014; Tanimoto & Ishii, 2006). Therefore, given that different variables combined may
76 simultaneously influence the chronic responses induced by strength training (ACSM, 2009), the
77 effect of RD only within a resistance training to MF while controlled for the load intensity
78 remains unknown.

79   Another aspect to be considered in studies investigating the impact of RD on muscle
80   hypertrophy relates to the use of different assessment instruments (e.g. biopsy, magnetic
81   resonance imaging or ultrasound) and assessment locations on the muscle (e.g. 50% of the
82   muscle femur length). The cross-sectional area (CSA) is a valid measure of muscle hypertrophy.
83   However, single-point measurements somewhere along the muscle length may not adequately
84   represent the entire muscle hypertrophic response (Noorkoiv et al., 2014). Thus, a CSA analysis
85   including several assessment locations along the muscle length may possibly provide a more
86   accurate depiction of the muscle hypertrophic response in comparison with a specific region
87   along the muscle length (Noorkoiv et al., 2014) and, therefore, a more accurate analysis of
88   hypertrophy gains after resistance training programs as well.

89   Protocols performed with different RDs enforce different mechanical responses, with
90   higher force values for shorter RD (Sampson et al., 2014; Tanimoto & Ishii, 2006). As a
91   consequence, different gains in muscle hypertrophy may be induced through resistance training
92   with different RDs (Gonzalez et al., 2016). However, Sampson and Groeller (2016) showed that
93   a resistance training protocol performed with faster movements (shorter RD) produced similar
94   muscle hypertrophy when compared to a protocol with slower movements (longer RD). Given
95   that the faster movements were not executed with the maximum number of repetitions, the
96   results by Sampson and Groeller (2016) remain inconclusive about the RD effect during
97   resistance training to MF. In addition, the protocols with faster movements were performed with
98   a time under tension (TUT, up to three times shorter than the protocol with slower movement)
99   and also higher training volume. The similar muscle hypertrophy observed between protocols
100   reinforce the argument about the impact of mechanical tension (force applied by external
101   resistance to the musculature) to induce adaptations. In this sense, the higher training volume and
102   TUT performed during the longer RD protocol was probably a balance factor in relation to the
103   greater magnitude of mechanical tension observed during protocols with shorter RD (verified by
104   higher peak force values) (Sampson et al., 2014), inducing to similar muscle hypertrophy.

105   In addition, it has been shown that protocols with shorter RD performed to MF presented
106   higher degrees of normalized electromyographic (EMG) amplitude compared to protocols
107   performed with longer RD (Sakamoto & Sinclair, 2012). An increase in the EMG amplitude is
108   associated either with a higher motor unit recruitment or an increase in the firing frequency of
109   the motor units (Hunter et al., 2004). Both factors would contribute to chronic adaptations
110   associated with resistance training (Schoenfeld et al., 2014). Therefore, considering that the
111   magnitude of the mechanical tension and EMG amplitude would be determinant factors of
112   neuromuscular adaptations (Gehlert et al., 2015), protocols with shorter RD performed to MF
113   (consequently higher number of repetitions) should theoretically provide superior responses of
114   muscle hypertrophy when compared to protocols performed with longer RD.

115   As above-mentioned, protocols incorporating different RDs and repetition numbers
116   provide different mechanical (Sampson et al., 2014) and neurophysiological responses (Lacerda
117   et al., 2016; Sampson et al., 2014). As reported for muscle hypertrophy, it has been presented
118   that these factors can influence muscle strength throughout resistance training. In this sense, the

119 review by Davies et al. (2017) verified only a trend for larger gains in muscular strength
120 (measured by 1RM performance) for protocols with shorter RDs and moderate intensities (60-
121 79% 1RM) compared to longer RDs. Unfortunately, protocols with exercises leading to MF were
122 not considered in this review. Moreover, the 1RM test does not provide information on
123 maximum force values in different joint angles. In particular, the 1RM test fails to provide
124 information about maximal force values in specific sections of the ROM where a mechanical
125 disadvantage may possibly occur to explain the different adaptations to RT (van den Tillaar et
126 al., 2012). As a consequence, maximum voluntary isometric contractions (MVIC) should be
127 analyzed across a range of different joint angles to properly understand the effects of different
128 RDs (Alegre et al., 2014).

129   In the past, studies showed that different RDs evolved to different force-angle
130 relationships across the ROM. This was particularly true for the beginning and the end of the
131 muscle actions (Sampson et al., 2014; Tanimoto & Ishii, 2006). Protocols with shorter RDs
132 require faster movements. Therefore, they lead to larger peak forces at the beginning of the
133 concentric action (e.g., lengthened position during knee extension) compared to protocols with
134 longer RDs (Sampson et al., 2014). At the end of the ROM (e.g., shortened position during knee
135 extension), a decrease in force is observed when faster movements are performed. In contrast,
136 protocols with longer RDs come along with less variation in the force response throughout the
137 ROM, while larger force values appear at the end of the concentric actions (Sampson et al.,
138 2014; Tanimoto & Ishii, 2006). All in all, varied strategies to apply force throughout the
139 concentric action incorporating different RDs may promote different increases in maximal
140 isometric strength at specific points across the ROM. As a consequence, it was the aim of this
141 study to compare the effects of two protocols with different RDs performed to MF on measures
142 of maximal strength (1RM and MVIC) and muscle hypertrophy (CSA). A secondary aim was to
143 compare the effects of these RD strategies on features of the normalized EMG amplitude-angle
144 and force-angle relationships during both protocols execution. Based on our previous arguments,
145 we hypothesized that larger increases in the 1RM and the CSA would be induced by a protocol
146 with shorter RDs. In addition, the MVIC gains were expected to be different in specific areas
147 across the ROM. In particular, larger forces were expected for faster training protocol at 90º of
148 knee flexion (stretched position) and for slower protocol at 30º of knee flexion (shortened
149 position).

Materials & Methods

Study design
151 In the present study, a repeated measures design was adopted. Given that the unilateral exercise
152 model reduces inter-subject variability, it can serve to increase statistical power, as well as
153 reduce the time and cost of a study (MacInnis et al., 2017). Volunteers performed two resistance
154 training protocols with two RDs (2-s or 6-s RD protocol) for 14 weeks. The left and the right
155 legs were randomly assigned and balanced for limb dominance to either one of the protocols. Pre
156 and post-test measures included: CSA, MVIC and 1RM tests. To assess the lower limb

158 dominance voluntaries were asked to answer the following question: "If you would shoot a ball
159 on a target, which leg would you use to shoot the ball?"

160   In session 1, limb dominance was determined, volunteers were familiarized with all the
161 procedures, and training protocols were assigned to each limb. In the next session, ultrasound
162 images were recorded to determine rectus femoris and vastus lateralis muscles CSA. The
163 strength tests (MVIC and 1RM) were conducted in sessions 3 and 4 separated by at least 48h.
164 Next, subjects trained from sessions 5 to 39 for a total of 14 weeks and five training sessions per
165 week. The training sessions were separated by at least 24 h. For each week, subjects trained their
166 left or right either on days 1, 3, and 5, or on days 2 and 4 in an alternating way. Through this
167 training schedule, a minimum of 48 h inter session rest was provided for each leg. In sessions 6
168 and 39 (for each protocol), the rectus femoris and vastus lateralis EMG amplitude were assessed
169 through surface EMG while participants performed their respective training protocols. In session
170 40, separated between 72 and 120h from the last training session, the post-test ultrasound
171 measurements were conducted similar to session 2. Finally, in session 41, the MVIC and 1RM
172 post-tests were executed for both lower limbs.

173 Participants and Ethics
174 The sample size calculation was performed by using the software G.Power for Windows version
175 3.1.9.7 (Düsseldorf, Germany) and by following the guidelines proposed by Beck (2013), with a
176 priori statistical power (1 - ß) = 0.80, effect size (f) = 0.57 and 5% significance level. Number of
177 groups = 2 (protocols); number of measures = 2 (pre-post); correlation between measures = 0.90;
178 sphericity = 1. For the sample size calculation, we used the absolute AST values of the vastus
179 lateralis muscle from a previous study from our own laboratory, which was carried out with an
180 experimental design similar to the present study (Lacerda et al., 2019).Ten males aged between
181 18 and 30 years (mean ± SD: age = 23.1 ± 4.63 years; body height = 1.72 ± 0.07 m; body mass =
182 68.4 ± 9.46 kg; body fat percentage = 14.03 ± 6.56%) participated in this study.

183   The inclusion criteria for participation were: (1) no resistance training during the last six
184 months; (2) no functional limitations that could influence the 1RM test or the training protocols;
185 and (3) no use of pharmacological substances or ergogenics supplements, and no other modes of
186 resistance exercise during the study period. Subjects were informed about the study aims,
187 procedures, and risks prior to signing an informed consent form. The ethics committee of the
188 Federal University of Minas Gerais approved this study (approval number:
189 79108117.5.0000.5149), which complied with the Declaration of Helsinki. Additionally, each
190 subject was instructed not to engage in any physical activity immediately before the testing
191 sessions and to maintain the same diet before each session.

192 Experimental Session 1(anthropometric measurements)
193 After receiving information about the goals and the purpose of the study and giving written
194 consent, the volunteers answered the Physical Activity Readiness Questionnaire (PAR-Q). Next,
195 they were submitted to an anamnesis examining possible limitations related to the study
196 participation. In addition, body height, mass, and fat percentage (skinfold thickness)

197 measurements were conducted. As a next step, volunteers were positioned on a seated knee
198 extension machine (Master, Minas Gerais, Brazil) while maintaining a hip angle of 110º (angle
199 between the backrest and the equipment seat). For measurement purposes, the lateral epicondyle
200 of the femur was aligned with the rotational axis of the device and the pad of the device placed
201 approximately 3 cm above the medial malleolus. These positions were registered for future
202 replication in the subsequent tests and training sessions. All test sessions were held at the same
203 time of the day for each volunteer.

204 Experimental Sessions 2 and 40 (CSA - ultrasound measurements)
205 During these sessions, ultrasound images were recorded for the CSA analysis of the rectus
206 femoris and vastus lateralis muscles. The acquisition procedure for the CSA images was
207 conducted as described by Noorkoiv et al. (2010). Initially, volunteers remained in a dorsal
208 decubitus position on a stretcher for 15 minutes. During this period, the anterior regions of both
209 thighs were marked to identify the reference points for the ultrasound image acquisition. Next,
210 the major trochanters and lateral epicondyles of the femurs were identified, and femur length was
211 measured (Figure 1A). From the proximal end of thigh, 40, 50, 60, and 70% of femur length
212 were identified and marked on volunteer's skin by using a tape measure and a pachymeter
213 positioned parallel to the intercondylar line. Then, a line with a microporous adhesive tape was
214 attached 2cm from each percentage point on the thigh (Figure 1B) to delimitate the probe guide
215 area for the ultrasound image acquisition (Figure 1C). Finally, the distances between the
216 intercondylar line and each percentage point on the thighs were recorded for post-test replication.
217 The procedures used to acquire images in the pre-test were the same for the post-test session
218 (40th session). The latter was started no earlier than 72-120 h following the last training session.

219   - PLEASE INSERT FIGURE 1 HERE -

220   An ultrasound device (MindRay DC-7, Shenzhen, China) was used in an extended-field-
221 of-view mode with a 4 cm linear transducer. The equipment was configured with 10 MHz
222 frequency, an acquisition rate of 21 frames/s, a depth for the image capture ranging from 7.7 and
223 9.7 cm, and a gain between 50 and 64 dB. The settings were adjusted for each subject to produce
224 the clearest images of the analyzed muscles. The same experienced examiner (~ 120h of training
225 and 600 images acquired before of the study) conducted the acquisition of two images for each
226 of the given femur percentage lengths (40, 50, 60, and 70%). For the acquisition procedure, the
227 probe was placed transversely in parallel to the intercondylar line using a coupled guide on the
228 subject's thigh (probe guide) (Figure 1C). This procedure was performed with constant speed
229 (controlled by a metronome) and lasted between 12 and 15 s depending on the subject's thigh
230 circumference. Sixteen images per subject were obtained for the rectus femoris and vastus
231 lateralis muscle CSA analysis (8 pre-test + 8 post-test). Following the acquisition procedure,
232 CSAs of each muscle scan were manually demarcated by a blinded examiner using specific
233 software (OsiriX MD 6.0, Bernex, Switzerland) (Figure 2). For the data analysis, the rectus
234 femoris and vastus lateralis muscle CSA mean values were calculated using two images acquired
235 at each percentage of the femur length. Finally, based on the 40, 50, 60, and 70% length

236   measurements, the sum of four CSAs of each analyzed muscle was calculated, generating a
237   summary CSA value per muscle to avoid a possible misinterpretation based on one measurement
238   site only (Noorkoiv et al., 2010). This value was used in the statistical data analysis.

239   - PLEASE INSERT FIGURE 2 HERE -

240   Experimental Sessions 3, 4 and 41 (strength tests)
241   The strength tests were conducted during the third session in order to familiarize the subjects
242   with the procedures to be performed during the following session. After positioning the
243   participants in the equipment, a familiarization MVIC test was conducted encompassing two
244   attempts of 5s in duration with knee flexion angles of 30° and 90° (knee extended = 0º). MVIC
245   tests were conducted with both legs with 2-minute rest periods between each attempt (Lacerda et
246   al., 2019). The testing order was randomized between legs. The same order was maintained
247   during the post-test session. The highest force value registered for each attempt at knee flexion
248   angles of 30° and 90° was used in further data analyses. During the MVIC test, a verbal
249   command was given on which the subject exerted a maximum force against the fixed lever of the
250   knee extensor machine. Visual feedback of the force trace was provided to the subject as well as
251   verbal instruction from the examiners to achieve maximum strength. The load cell raw data
252   (Tedea, Bavaria, Germany) were converted into digital data (Biovision, Wehrheim, Germany)
253   and filtered through a 4th-order Butterworth low-pass filter with a cutoff frequency of 10 Hz.

254   The 1RM test familiarization was performed 10 minutes after the completion of the
255   MVIC test. Initially, according to procedures described by Lacerda et al. (2016, 2019), subjects
256   performed 10 repetitions without any weight on the equipment. The 1RM was determined in
257   concentric mode within a maximum of 6 attempts with 5-minutes rest periods in between
258   (Lacerda et al., 2016, 2019). In addition, a 5-minute rest period was given between the tests
259   conducted with each of the lower limbs.

260   In session 4, the MVIC and 1RM tests of the familiarization session were repeated. These
261   tests were also repeated in the 41st experimental session with a rest interval of at least 48h
262   following the previous session 40 (ultrasound measurements). The data measured in sessions 4
263   and 41 were used for statistical analysis.

264   Experimental Sessions 5 to 39 (training period)
265   After the initial testing period, the 14-week training commenced (35 training sessions). All
266   participants completed 100% of the training sessions. The experimental protocols consisted of 3-
267   4 sets at 50-60% 1RM with 3-minute rest periods in between. In the 2-s RD protocol, subjects
268   completed each repetition in 2 seconds (1 second concentric, 1 second eccentric). In the 6-s RD
269   protocol, subjects perform each repetition in 6 seconds (3 seconds concentric, 3 seconds
270   eccentric). The protocols complied with recommendations for resistance training and muscle
271   hypertrophy (ACSM, 2009). Previously, training protocols with similar concentric and eccentric
272   durations were already investigated in our laboratory or in others' (Lacerda et al., 2016, 2019;
273   Sakamoto & Sinclair, 2012). For both protocols, all sets were executed until the subjects were
274   unable to complete the concentric action within the required ROM (70°).

275   During the first two weeks, training sessions included 3 sets at 50% of 1RM. At third
276   week (6th training session), the intensity was increased to 60% of 1RM. From week 9 (20th
277   training session) until the end of the training period, one more set was added such that the
278   subjects. Given that any variation of the load characteristics in addition to the RD could possibly
279   bias the training adaptations, the present study controlled the load configuration and progression.

280   Every two weeks, beginning in the third week (6th training session), 1RM tests for both
281   legs were re-assessed on a weekly basis before the first training session. A 10-minute rest period
282   between the 1RM test and the start of the training session was provided. During these sessions,
283   the 1RM test was conducted at the same day time as in the pre-test to standardize the circadian
284   rhythm, which may possibly influence strength performance.

285   *Experimental Sessions 6 and 39 (2nd and 35th training sessions) (force and electromyography*
286   *measurements)*
287   The surface EMG procedure (Biovision, Wehrheim, Germany) followed the recommendations
288   by Hermens et al. (2000). For the rectus femoris and vastus lateralis muscles, bipolar surface
289   electrodes (Ag/AgCl - 3M-2223, Brazil) were aligned parallel to the muscle fiber orientation.
290   Prior to the electrode placement above the muscle bellies, the skin areas were shaved, cleaned
291   with alcohol using a cotton pad. The inter-electrode distance was 4cm which each electrode to be
292   placed 2cm distant from the center of the muscle belly. The ground electrode was attached above
293   the patella. After the electrode attachment, a silk paper was used to assess their positions as well
294   as the patella and other relevant points on the skin. In addition, the subject's two thighs were
295   photographed with the electrodes positioned. These procedures were conducted in the 6th session
296   to map the electrode positions on the thigh and to verify high reproducibility in the post-test
297   measurements (39th session).

298   To measure the ROM and the muscle action durations during both protocols, the angular
299   displacement was recorded using a potentiometer (aligned with volunteer's knee-joint). For all
300   training sessions, this device was coupled to the rotational axis of the knee extension device. The
301   potentiometer raw data were converted into angular displacement data and filtered through a 4th-
302   order Butterworth low-pass filter with a cutoff frequency of 10 Hz. The duration of each muscle
303   action was comprised of the time between the maximum (100º of knee flexion) and minimum
304   (30º of knee flexion) angular positions. Thus, the duration of the concentric action corresponded
305   to the period between the maximum and minimum angular positions. In turn, the duration of the
306   eccentric action corresponded to the time between the minimum and maximum angular
307   positions. Additionally, concentric/eccentric durations and the RDs were determined throughout
308   the angular displacement time. This potentiometer data provided online information on a laptop
309   screen for the subjects regarding the duration and ROM data of each muscle action throughout
310   the training sessions and tests (Lacerda et al., 2016, 2019). Moreover, a metronome was used to
311   help subjects maintain pre-established RDs.

312   All electromyographic, load cell, and potentiometer signals were synchronized and
313   converted by an A/D board (Biovision, Wehrheim, Germany) with a sampling rate of 4,000 Hz.

314   DasyLab software (Version. 11.0; Measurement Computing Corporation, Massachusetts, USA)
315   was used to record and process the data. The methodological procedures to record force
316   measurements were detailed in the strength tests section. The electromyographic data
317   acquisition was amplified (factor 500) and filtered (4th-order Butterworth band-pass filter of 20-
318   500 Hz) to calculate the EMG amplitude as the root mean square. Before commencing each
319   experimental session (6th or 39th), subjects were asked to perform a MVIC test for 5s on the knee
320   extension machine exercise at 60° knee flexion (controlled by the potentiometer). The highest
321   force and EMG amplitude values in the MVIC test were used as a reference for the normalization
322   of the subsequent measurements in the exercise protocols. The EMG amplitude during the MVIC
323   was measured over a 1s period from 500ms before the MVIC peak force to 500 ms after
324   (Piitulainen et al., 2013). The mean force and EMG amplitude of the concentric muscle actions
325   for each 10º knee flexion area (100º-90º, 90º-80º, up to 40-30º) was calculated and normalized
326   by the reference values from the normalization test. As a result, relatives force and EMG
327   amplitude x knee-joint angle curves (normalized force and EMG-angle) were assessed. This
328   procedure was performed for each protocol. For the acquisition of the force and EMG amplitude
329   values during experimental sessions 6 and 39, participants performed 3 sets with 50% of the
330   previous 1RM value in each protocol.

331   Statistical analyses
332   Statistical analysis was performed with SPSS for Windows version 20.0 (SPSS, Inc., Illinois,
333   USA). The normal distribution was verified by the Shapiro-Wilk test. All data were expressed as
334   mean ± *SD*. For the estimation of effect sizes, eta squared (η^2) values are considered to reflect the
335   magnitude of the differences (effect size) in each treatment with values ≤ 0.010 expressing a
336   trivial effect; values between 0.010 and 0.059 expressing a small effect; values between 0.060
337   and 0.139 a moderate effect, and values ≥ 0.140 a large effect.

338   Initially, paired sample t-tests were used to test for differences between the training
339   protocols in baseline values for the main variables analyzed (CSA, 1RM and MVIC), as well as
340   for EMG amplitude and force values obtained during the normalization. The differences between
341   the training protocols in the CSA scores were analyzed through a two-way repeated-measures
342   analysis of variance test (ANOVA) for each muscle separately, having protocol (2-s RD or 6-s
343   RD) and time (pre and post-test) as factors. In case of significant F-values a Bonferroni
344   adjustment was used for comparison purposes. The intra-rater reliability was verified by the
345   intraclass correlation coefficient ($ICC_{[3,1]}$). For the ICC calculations were conducted for both
346   CSA measures (rectus femoris and vastus lateralis) and for both the test sessions (pre and post-
347   test).

348   Similar to CSA measurements, a two-way repeated-measures ANOVA test (protocol x time)
349   was applied for MVIC at 30º of knee flexion scores. However, the 1RM and MVIC at 90º of knee
350   flexion values were significantly different at baseline. Therefore, the baseline values were
351   considered as a covariate, and an analysis of covariance (ANCOVA) was implemented using a
352   within-subject factors model. In addition, the ICC intersession values for 1RM and MVIC were

353 obtained from measures during the third (familiarization) and fourth (pre-test) sessions. The
354 familiarization and pre-test sessions were separated by at least 48 h.

355    Normalized EMG amplitude-angle relationships for the rectus femoris and the vastus
356 lateralis muscles were established during the 6th and 39th sessions to compare EMG amplitude
357 differences between the 2-s and the 6-s RD protocols. A three-way repeated measures ANOVA
358 test (session x protocol x knee joint angle) was conducted to analyze the training effects in the
359 normalized EMG amplitude for each muscle. Similar to EMG amplitude responses, a three-way
360 repeated measures ANOVA test (session x protocol x knee joint angle) was used to compare
361 normalized force-angle relationships in the 6th and 39th sessions. When necessary, a post hoc
362 Bonferroni honest significant difference test was used to identify the differences reported in the
363 ANOVA's. Furthermore, the EMG amplitude and force values for each protocol obtained during
364 the normalization test from experimental sessions 6 and 39 were compared by t-test. This
365 procedure aimed to identify possible differences in measurements in both lower limbs of the
366 same individual. Thus, the feasibility of comparing the EMG amplitude and force responses of
367 the two training protocols should be established.

368    In addition, paired sample t-tests were used to compare the RDs, ROM and TUT mean
369 values for all sets during training sessions between investigated protocols. Finally, given the
370 number of repetitions for each protocol does not meet the precepts for a parametric analysis,
371 Wilcoxon test was used to compare the values in this variable for both protocols. This data is
372 presented as median (number repetitions per set) and interquartile interval values. The level of
373 the error probability/statistical significance was set at $p \leq 0.05$ for all statistical tests.

374

Results

376 CSA
377 The intra-rater reliability values found in these sessions were 0.99 for both analyzed muscles. No
378 significant interaction was observed between protocol and time for the rectus femoris CSA ($F_{1,9}$
379 $= 1.889$; $p = 0.203$; $\eta^2 < 0.010$ "trivial"). Also, no significant differences between groups were
380 found (main protocol effect; $F_{1,9} = 0.001$; $p = 0.972$; $\eta^2 < 0.010$ "trivial"). Both training protocols
381 showed significant increases in rectus femoris CSA after training period (main time effect; $F_{1,9} =$
382 64.353; $p < 0.001$; $\eta^2 = 0,821$ "large") (Figure 3A).

383

384    In addition, no significant interaction was observed between protocol and time for the
385 vastus lateralis CSA ($F_{1,9} = 0.867$; $p < 0.376$; $\eta^2 < 0.010$ "trivial"). No significant difference
386 between the 2-s and the 6-s RD protocols were found (main protocol effect; $F_{1,9} = 0.009$; $p =$
387 0.928; $\eta^2 < 0.010$ "trivial"). Both training protocols showed significant increases in vastus
388 lateralis CSA after training period (main time effect; $F_{1,9} = 50.664$; $p < 0.001$; $\eta^2 = 0,814$ "large")
389 (Figure 3B).

390          - PLEASE INSERT FIGURE 3 HERE -

391 1RM
392 The ICC intersession value for 1RM tests was 0.98. There were significant difference in 1RM
393 values at baseline (Pre; $t_9 = 2.688$; $p = 0.025$). When baseline differences in 1RM values were
394 taken into account (within-subject factors ANCOVA), no significant main protocol effect was
395 found ($F_{1,9} = 0.412$; $p = 0.820$; $\eta^2 < 0.010$ "trivial") (Figure 4).

396

397   - PLEASE INSERT FIGURE 4 HERE -

398 MVIC at 30º of knee flexion
399 The ICC intersession value for MVIC test at 30º of knee flexion was 0.96. A significant
400 interaction was observed between protocol and time for MVIC test at 30º of knee flexion
401 measurements ($F_{1,9} = 6.576$; $p = 0.030$; $\eta^2 = 0,049$ "small"), with higher values for the 6-s RD
402 protocol. Furthermore, a significant main effect of time ($F_{1,9} = 7.581$; $p = 0.023$; $\eta^2 = 0,273$
403 "large") was detected. Conversely, no significant main effect of protocol was found ($F_{1,9} = 1.990$;
404 $p = 0.192$; $\eta^2 = 0,101$ "moderate") (Figure 5).

405   - PLEASE INSERT FIGURE 5 HERE –

406 MVIC at 90º of knee flexion
407 The ICC intersession value for MVIC test at 90º of knee flexion was 0.94. There were significant
408 differences at baseline (Pre; $t_9 = 2.640$; $p = 0.027$). When baseline differences in MVIC test at
409 90º of knee flexion values were taken into account (within-subject factors ANCOVA), no
410 significant main protocol effect was found ($F_{1,9} < 0.001$; $p = 0.996$; $\eta^2 < 0.010$ "trivial") (Figure
411 6).

412   - PLEASE INSERT FIGURE 6 HERE –

413 Normalized EMG amplitude-angle relationship
414 The EMG amplitude values obtained during the normalization tests showed no significant
415 difference between the 2-s RD and the 6-s RD training protocols (rectus femoris - $t_{19} = 0.701$, $p =$
416 0.503) (vastus lateralis - $t_{19} = 0.773$, $p = 0.455$).

417   No significant interaction between time x protocol x knee joint angle was observed for
418 the normalized EMG amplitude data of rectus femoris ($F_{6,54} = 2.025$; $p = 0.143$; $\eta^2 < 0.010$
419 "trivial") and vastus lateralis muscles ($F_{6,54} = 2.640$; $p = 0.106$; $\eta^2 < 0.010$ "trivial"). However,
420 significant differences in the rectus femoris EMG amplitude were observed between the 2-s RD
421 and the 6-s RD training protocols in all knee-joint angles analyzed during 6th and 39th sessions
422 (protocol x knee-joint angle interaction - $F_{6,54} = 66.554$; $p < 0.001$; $\eta^2 = 0.199$ "large") (Figure
423 7AB). The 2-s RD protocol resulted in larger normalized EMG amplitude scores in six of the
424 seven knee-joint angles analyzed (100-90º to 50-40º). Conversely, the 6-s RD protocol provided
425 significantly larger rectus femoris EMG amplitude in the last knee-joint angle (40-30o) only. The

426 same results were verified for the vastus lateralis EMG amplitude (protocol x knee joint angle
427 interaction - $F_{6,54} = 51.007$; $p < 0.001$; $\eta^2 = 0.179$ "large") (Figure 8AB).

428 In addition, no significant interactions were detected between time x knee joint angle for
429 rectus femoris ($F_{6,54} = 2.643$; $p = 0.070$; $\eta^2 < 0.010$ "trivial") and vastus lateralis muscles ($F_{6,54} =$
430 0.414; $p = 0.866$; $\eta^2 < 0.010$ "trivial"). Also, no significant interactions were detected between
431 time x protocol for rectus femoris ($F_{1,9} = 0.168$; $p = 0.692$; $\eta^2 < 0.001$ "trivial") and vastus
432 lateralis muscles ($F_{1,9} = 0.014$; $p = 0.910$; $\eta^2 < 0.001$ "trivial"). No significant main effect for the
433 time factor (rectus femoris: $F_{1,9} = 0.143$; $p = 0.714$; $\eta^2 < 0.010$ "trivial") (vastus lateralis: $F_{1,9} =$
434 2.434; $p = 0.153$; $\eta^2 = 0.043$ "small") was detected. In contrast, significant main effects were
435 found for the training protocol (rectus femoris: $F_{1,9} = 29.46$; $p < 0.001$; $\eta^2 = 0.202$ "large")
436 (vastus lateralis: $F_{1,9} = 16.131$; $p = 0.003$; $\eta^2 = 0.225$ "large") and for knee-joint angle (rectus
437 femoris: $F_{6,54} = 15.673$; $p < 0.001$; $\eta^2 = 0.111$ "large") (vastus lateralis: $F_{6,54} = 10.179$; $p > 0.001$;
438 $\eta^2 = 0.037$ "small").

439 - PLEASE INSERT FIGURES 7 AND 8 HERE -

440 Normalized force-angle relationship
441 The force values obtained during the normalization showed no significant difference between
442 both training protocols analyzed ($t_{19} = 0.732$; $p = 0.478$).

443 Significant differences in the normalized force-angle relationship were observed between
444 the 2-s RD and the 6-s RD training protocols during 6th and 39th sessions (protocol x knee-joint
445 angle x time - $F_{6,54} = 2.652$; $p = 0.025$; $\eta^2 = 0.033$ "small"). In the 6th session, the 2-s RD
446 protocol exhibited significantly larger normalized force values in the first four knee-joint angles
447 analyzed (100-90º to 70-60º). The same was true for the first three knee-joint angles (100-90º to
448 80-70º) in the 39th experimental session. In contrast, for the 6-s RD protocol larger normalized
449 force values were found in the last two knee-joint angles (50-40º 40-30º) during sessions 6 and
450 39. In addition, significant changes in the force x angle relationships between training sessions
451 were detected only for the 2-s RD protocol. These changes were related to a reduction in the
452 force values from 70-60º until 40-30º of knee flexion (Figure 9AB).

453 Moreover, significant interactions were found between the time x knee joint angle ($F_{6,54} =$
454 14.243; $p < 0.001$; $\eta^2 = 0.011$ "small") and the protocol x knee-joint angle ($F_{1,9} = 296.591$; $p <$
455 0.001; $\eta^2 = 0.370$ "large"). No significant interaction was observed for the interaction of time x
456 protocol ($F_{1,9} = 2.483$; $p = 0.150$; $\eta^2 < 0.010$ "trivial"). Finally, no significant main effect for
457 time ($F_{1,9} = 1.807$; $p = 0.212$; $\eta^2 = 0.074$ "moderate") and for protocol ($F_{1,9} = 1.555$; $p = 0.703$; η^2
458 < 0.010 "trivial"), but a significant main effect for knee-joint angle ($F_{6,54} = 7.453$; $p < 0.001$; $\eta^2 =$
459 0.026 "small") were identified.

460 - PLEASE INSERT FIGURE 9 HERE -

461 RD, TUT, Number of repetitions and ROM
462 As expected, 6-s RD protocol showed longer average RD than 2-s RD protocol (2.04 ± 0.08 s;
463 5.98 ± 0.09 s, respectively; t_{69} = 284.488, $p < 0.001$). In addition, larger TUT mean values were
464 observed in the 6-s RD protocol (mean for all sets = 43.47 ± 10.92; 1st set = 52.5 ± 15.83, 2nd set
465 = 42.58 ± 12.25, last set (3rd or 4th) = 36.98 ± 10.89) as compared to the 2-s RD protocol (mean
466 for all sets = 30.51 ± 7.52; 1st set = 38.1 ± 10.55, 2nd set = 29.57 ± 7.98, last set (3rd or 4th) =
467 25.09 ± 7.17) $(t_{69}$ = 15.951; $p < 0.001$). In regard to the number of repetitions, the Wilcoxon test
468 showed significantly larger median values for the 2-s RD protocol (median for all sets = 14 [12-
469 17]; 1st set = 18 [21.25-17], 2nd set = 14.5 [16.25-12.75], last set (3rd or 4th) = 12 [14-11]) as
470 compared to the 6-s RD protocol (median for all sets = 7[6-8]; 1st set = 9 [8-10], 2nd set = 7 [6-8],
471 last set (3rd or 4th) = 6 [5-7]) $(U_{69}$ = 7.294; $p < 0.001$). Last not least, but no significant
472 differences were detected between the 2-s RD and the 6-s RD protocols in the ROM average
473 values (2-s RD: 70.77 ± 0.79°; 6-s RD: 70.99 ± 0.65°; t_{69}= 1.903, $p = 0.06$).

474

475 **Discussion**
476 The purpose of this study was to compare the strength and muscle hypertrophy responses
477 induced by two protocols with different RDs performed to MF. In addition, we aimed to verify
478 the effects of these RD strategies on knee extension force and EMG amplitude in the rectus
479 femoris and vastus lateralis muscles. To the best of our knowledge, no other studies have
480 compared these chronic adaptations for resistance training with different RD to MF by matching
481 intensity, set, and rest and, in addition to that, using ultrasound measurements from four different
482 parts of the muscle. The main results of the present study were: 1) the 2-s RD protocol showed
483 similar effects in maximum dynamic strength and muscle hypertrophy compared to the 6-s
484 protocol; 2) the 6-s RD protocol induced larger gains in MVIC at knee flexion of 30° than the 2-s
485 RD. However, both protocols induced similar increases in MVIC at for the 90° of knee angle and
486 in 1RM performance. Thus, RD appears to influence the joint-angle specific strength gains only
487 in shorter muscle lengths.

488 Both rectus femoris and vastus lateralis muscles had a similar increase in muscle CSA for
489 the 2-s RD and the 6-s RD protocols after 35 training sessions with a trivial effect size ($\eta^2 <$
490 0.010). Different factors have shown to explain the increase in muscle hypertrophy: elevated
491 EMG amplitude (e.g. higher recruitment of motor units and/or firing rate) (Hunter et al., 2004;
492 Lacerda et al., 2016), increase in force production (Sampson & Groeller, 2016; Sampson et al.,
493 2014), and also differences in the training volume and TUT (Schoenfeld & Grgic, 2019). In
494 general, a higher training volume is connected to an increase in the TUT. For instance, studies
495 investigating resistance protocols balanced training volume, but more substantial muscle
496 hypertrophy after training was detected with longer RD and TUT (Tanimoto & Ishii, 2006).
497 Nevertheless, in the present study, the 6-s RD protocol was executed with average TUTs
498 approximately 25% larger than in the 2-s RD protocol (43 s vs. 30 s, respectively), while the 2-s
499 RD protocol encompassed double of the 6-s RD training volume (14 vs. 7 repetition per set,
500 respectively). Additionally, the present study also showed higher EMG amplitude for the 2-s

501 compared to 6-s RD protocol, in line with previous findings (Lacerda et al., 2016; Sakamoto &
502 Sinclair, 2012), which may also have contributed to muscle hypertrophy. Thus, the larger
503 training volume and higher EMG amplitude in the 2-s RD protocol, and the longer TUT in the 6-
504 s RD protocol, may have counterbalanced each other and led to similar impact on muscle
505 hypertrophy, explaining the present findings. Therefore, these results suggest that protocols with
506 shorter RD performed with a higher training volume and higher EMG amplitude could lead to
507 muscle hypertrophy, to the same extent as protocols with longer RD performed with longer TUT.

508   The increase in the number of motor units recruited during resistance training has been
509 pointed out as a central factor to trigger muscle hypertrophy (Schoenfeld, 2013). The present
510 study demonstrated a higher EMG amplitude for the 2-s RD as compared to the 6-s RD protocol
511 during most of the ROM measurements conducted (100º to 40º). In contrast, the 6-s RD protocol
512 showed higher EMG amplitude only in the last 10º range for concentric ROM (40º to 30º). This
513 result suggests an increased motor unit recruitment during most concentric ROM for the 2-s RD.
514 However, these differences may not have been sufficient to result in a marked increase in CSA to
515 the 2-s RD protocol as compared to the 6-s RD. Although increased EMG amplitude is
516 associated with higher motor unit recruitment other factors may contribute to the changes in the
517 EMG amplitude as well such as increased firing frequency and synchronization of motor units
518 (Hunter et al., 2004). Therefore, care must be taken when interpreting EMG data obtained prior
519 and after the resistance training period.

520   According to EMG amplitude, higher force values were found during the 2-s RD protocol
521 at the beginning of concentric ROM while higher force values were observed for 6-s RD
522 protocol at the end of concentric ROM. Moreover, at the 39th experimental session, the 2-s RD
523 protocol was executed with higher muscle forces (100º to 70º) during most ROM areas compared
524 to the 6-s RD protocol (50º to 30º). These results agree with previous results showing higher
525 muscle forces at the beginning of concentric ROM when performing faster movements (Sampson
526 et al., 2014). It should be noted, however, that, although the RD of 2 s was only a third of the 6-s
527 RD, the magnitude of the forces applied in the two experimental situations were similar (43% of
528 MVIC at 39th experimental session). This result does not agree with previous studies (Sampson
529 et al., 2014). Sampson et al. (2014) compared protocols with different RDs and showed
530 differences in force produced close to 25% at the onset of concentric action. However, their
531 participants were instructed to perform ballistic movements or controlled movements within 4 s.
532 With similar protocols to those in the last study, Sampson and Groeller (2016) found similar
533 gains in muscle hypertrophy in both experimental conditions after 12 weeks of training. For
534 these authors, the higher force applied during ballistic movements would be a determinant factor
535 for muscle hypertrophy. Therefore, it is possible that in the present study, despite the higher
536 force demand during 2-s RD protocol at the beginning of concentric ROM, similar in force
537 produced between both protocols was essential so that no significant differences could be
538 detected in the CSA data of rectus femoris and vastus lateralis.

539   In agreement with the CSA overall responses, the average maximal dynamic strength
540 performance (1RM test) was similar between the 2-s RD and the 6-s RD protocols (trivial effect

541   size, $\eta^2 < 0.010$). As a mixed result, higher force values were detected in the 2-s RD as compared
542   to the 6-s RD protocol during the initial phase of the ROM in the concentric action while the
543   1RM gains were similar between protocols. This outcome did not confirm the trend of superior
544   performance when training with fast movement velocities and moderate intensities (60-79%
545   1RM), as was indicated in a previous meta-analysis (Davies et al., 2017). Hence, our initial
546   hypothesis was rejected.

547   In line with previous research (Sampson & Groeller, 2016), we did not find differences
548   in 1RM performance originating from different RD protocols using the same load intensity. In
549   contrast, other investigators had found higher 1RM gains when utilizing fast movement
550   velocities (González-Badillo et al., 2014; Padulo et al., 2012). The discrepancy between these
551   results may be associated to different RD adopted in these studies. Although the movement time
552   in the 2-s RD protocol was three times shorter than in the 6-s RD protocol, participants were not
553   instructed to perform explosive movements, which was the case in other studies (González-
554   Badillo et al., 2014; Padulo et al., 2012). It has been reported a greater EMG amplitude and
555   impulse production when ballistic movements were performed (Maffiuletti et al., 2016). This
556   factor may have influenced the occurrence of adaptations favorable to the 1RM increase for
557   faster protocols in these studies (González-Badillo et al., 2014; Padulo et al., 2012), which was
558   not observed in the present research. Importantly, in the abovementioned studies at least one of
559   the analyzed protocols was performed to MF. Thus, differences within the levels of effort must
560   be assumed (González-Badillo et al., 2014; Padulo et al., 2012; Sampson & Groeller, 2016).
561   Moreover, performing repetitions to MF provide a maximum effort for all individuals during
562   both protocols (Dankel et al., 2017), which may have been a determinant factor in not having
563   difference in 1RM gains between the two protocols investigated in the present study. Therefore,
564   training to MF could hamper the effect of RD on maximum dynamic strength performance
565   observed in previous studies.

566   In addition, it has been reported that exposure to successive 1RM tests on a three-week
567   basis may bias in the 1RM individual's performance when comparing different resistance
568   protocols (Morton et al., 2016). Consecutive measurements may evolve to a similar motor
569   pattern within the 1RM tests. Hence, it appears possible that existing differences between
570   training protocols may not be detected (Bernardi et al., 1996). Data from an untrained control
571   limb would enable a better understanding of the effect of repeated exposure of both trained limb
572   to 1RM tests. Thus, the lack of a control limb was a limitation of the present study and must be
573   considered when interpreting the results. Accordingly, studies on RD effects showing
574   inconclusive results for the 1RM tests may have other outcomes further to the 1RM measurement
575   procedures (Pereira & Gomes, 2007). Therefore, MVIC tests performed at different joint angles
576   may be a valid alternative to investigate the effect of different training protocols on muscle
577   strength responses. Given that protocols with different RD provide changes in force production
578   that varies over the ROM (Sampson et al., 2014), it was hypothesized that greater isometric
579   maximal strength gains would be found in knee-joint angles with higher instantaneous force
580   values applied.

581   Similar to the 1RM scores, the increases in the MVIC values at 90º of knee flexion did
582   show comparable improvements by both RD training protocols. A trivial effect size ($\eta^2 < 0.010$)
583   reinforces the result found by t-tests. Based on the TE values, the individual analyses showed
584   that 40% of the sample did not respond substantially differently for either of the two training
585   protocols. In turn, 3 participants each showed substantial improvements in either the 2-s RD or
586   the 6-s RD protocol. Conversely, larger gains were observed in the MVIC at 30º of knee flexion
587   for 6-s RD protocol. However, a small effect size was observed for the analysis of the interaction
588   effect between protocol and time ($\eta^2 = 0.048$) and must be considered when interpreting the
589   results. Based on results from previous studies (Alegre et al., 2014), we hypothesized that the
590   distinct force-angle relationship obtained during the two training protocols would influence the
591   MVIC gains at different knee-joint angles. These previous studies, in general, presented larger
592   maximum strength gains in the joint angles near the training angle/ROM used in the
593   corresponding training. In contrast, in the present study, our subjects performed both training
594   protocols with the same ROM (70º) varying the force generated along with the angular exercise
595   range (100º to 30º). Data from the 39th training session (Figure 8B) show that in the initial (100-
596   90º) and final (40-30º) ranges of the concentric testing action largest differences in force
597   production were detected between the protocols (7 vs. 13%). Additionally, the 2-s RD protocol
598   showed higher values at the beginning and the 6-s RD protocol at the end of the testing
599   movement. Given that type of mechanical stimulus (i.e. type of contraction) may contribute to
600   the specific training adaptations (Buckthorpe et al., 2015) it appears possible that the higher force
601   production in the 6-s RD protocol compared to the 2-s RD protocol at the end of concentric
602   action might be sufficient to produce differences in isometric force gains at 30º but not at 90º of
603   knee flexion. Furthermore, increases in isometric force after training have been associated with
604   increases in EMG amplitude (Noorkoiv et al., 2014). The EMG-angle relationship for the 6-s RD
605   protocol showed higher normalized EMG amplitude at 40-30º of knee-joint angle (end of
606   concentric action) and so help to explain the force gains at 30º of knee flexion. Moreover,
607   previous studies verified joint-angle specific strength gains close to trained angle/ROM (Alegre
608   et al., 2014) while others only showed joint-angle specific strength gains for resistance training
609   performed in shorter muscle lengths (Noorkoiv et al., 2014), reinforcing the results obtained in
610   the present study up to 30º of knee flexion. However, it should be emphasized that the
611   mechanisms suggested explaining distinct strength gains at specific joint angles are still poorly
612   understood (Alegre et al., 2014; Noorkoiv et al., 2014).

613   A limitation of the intra-individual experimental design is a possible cross-training or
614   cross-education effect (Beyer et al., 2016). There is evidence in the literature indicating that the
615   cross-training effect, if it occurs, would be restricted to neural parameters and muscle strength
616   gains while morphological changes (e.g., CSA) would not be influenced by this effect (Beyer et
617   al., 2016). In this respect, muscle strength gains in the contralateral limb should evolve from an
618   increase in the motor neuron activation and are not related to morphological adaptations.
619   However, previous studies investigating the crossing-effect for EMG amplitude showed
620   inconclusive results (Hortobágyi et al., 1997; Lee & Carroll, 2007). For example, Hortobágyi et

621   al. (1997) found that changes in the EMG amplitude of the untrained limb depending on the
622   training mode performed (e.g., type of muscle action). The neuromuscular changes were similar
623   to the changes in muscle strength. In addition, researchers found that the cross-training effect
624   contributes to approximately 7.8% of the muscle strength gain of the contralateral limb (Munn et
625   al., 2004). Such adaptation was explained by neural mechanisms involving acute facilitation
626   within the motor cortex of the untrained contralateral limb following excitation of the trained
627   limb (Fisher et al., 2016). The training protocols were performed with a minimum interval of 24h
628   in order to minimize the acute effect of unilateral training reducing the maximal strength
629   performance in the contralateral limb. Finally, and most important to our study, it has been
630   argued that, when both limbs of an individual are trained with different protocols, the cross-
631   training effect is minimal or non-existent (Munn et al., 2004; Bell et al., 2020). Hence, we
632   expected that any difference in the strength responses between limbs would be due to training
633   protocols and not owing to a crossing effect (Fisher et al., 2016).

Conclusions

635   This study showed that protocols with different RD performed to MF produced similar muscle
636   hypertrophy gains despite differences in the EMG amplitude and force-angle relationships.
637   Therefore, different training volumes and TUTs based on the different RDs appear to produce a
638   similar stimulus to skeletal muscle growth. Thus, we argue that an increased training volume
639   provided by performing faster movements to MF would promote similar muscle hypertrophy
640   when compared to higher TUTs during slower movements. It is noteworthy that the highly
641   trained individuals possibly require larger training volumes in order to achieve chronic
642   adaptations (i.e. muscle hypertrophy) associated with resistance training as compared to
643   untrained or moderately trained individuals (Figueiredo et al., 2018). Yet, although no
644   differences in 1RM gains between protocols were found, our MVIC data provides important
645   insight for the understanding of joint-angle specific strength responses induced by RDs. We
646   demonstrate that high force production in the end of concentric action during the 6-s RD protocol
647   induced higher maximal isometric strength at 30º of knee flexion when compared to the 2-s RD
648   protocol.

649   Repetition duration is considered an essential variable of resistance training (Dankel et
650   al., 2017; Davies et al., 2017; Pereira & Gomes, 2007; Tanimoto & Ishii, 2006), but recent
651   studies are not supporting this view on strength and muscle hypertrophy (Davies et al., 2017;
652   Schoenfeld et al., 2015). Nevertheless, this investigation has shown that resistance training
653   performed to MF with longer RD could be a more appropriate strategy to provide greater gains in
654   maximal muscle strength at shortened knee positions, although different RD would induce
655   similar muscle hypertrophy. Thus, the current results have practical applications for individuals
656   seeking health-related improvements in muscular strength and hypertrophy. Overall, it should
657   note that the results presented here are limited to the exercise and subject characteristics similar
658   to those of our current study. However, future studies with females and trained individuals are
659   needed to clarify the impact of protocols with different RDs on the chronic adaptations
660   associated with resistance training performed to MF.

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Figure 1

Thigh marking procedures (A and B) and ultrasound images acquisition (C). Probe guide (indicated by white arrow)(D).
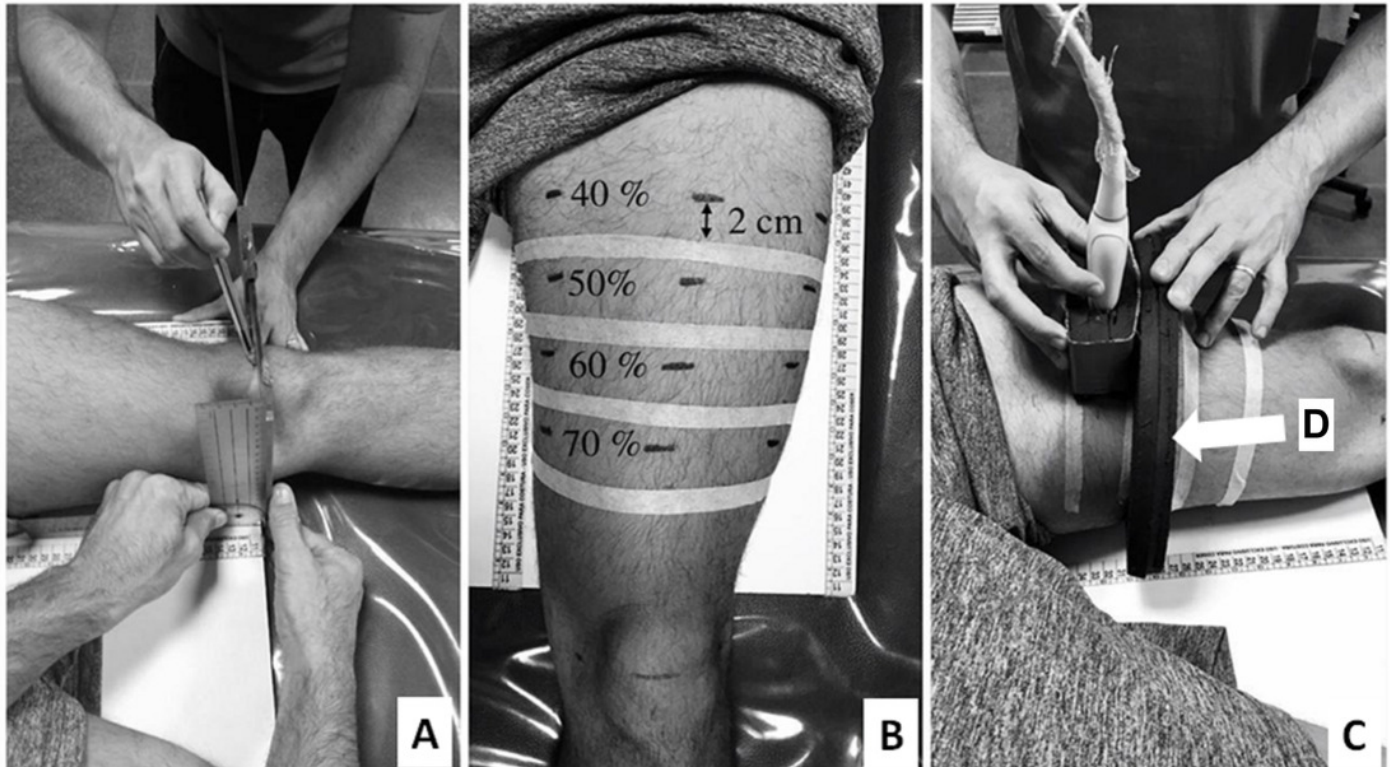
Figure 2

Ultrasound images and cross-sectional areas (CSA) at 40% (A); 50% (B), 60% (C), and 70% (D) of femur length. Rectus femoris (RF) and vastus lateralis (VL).
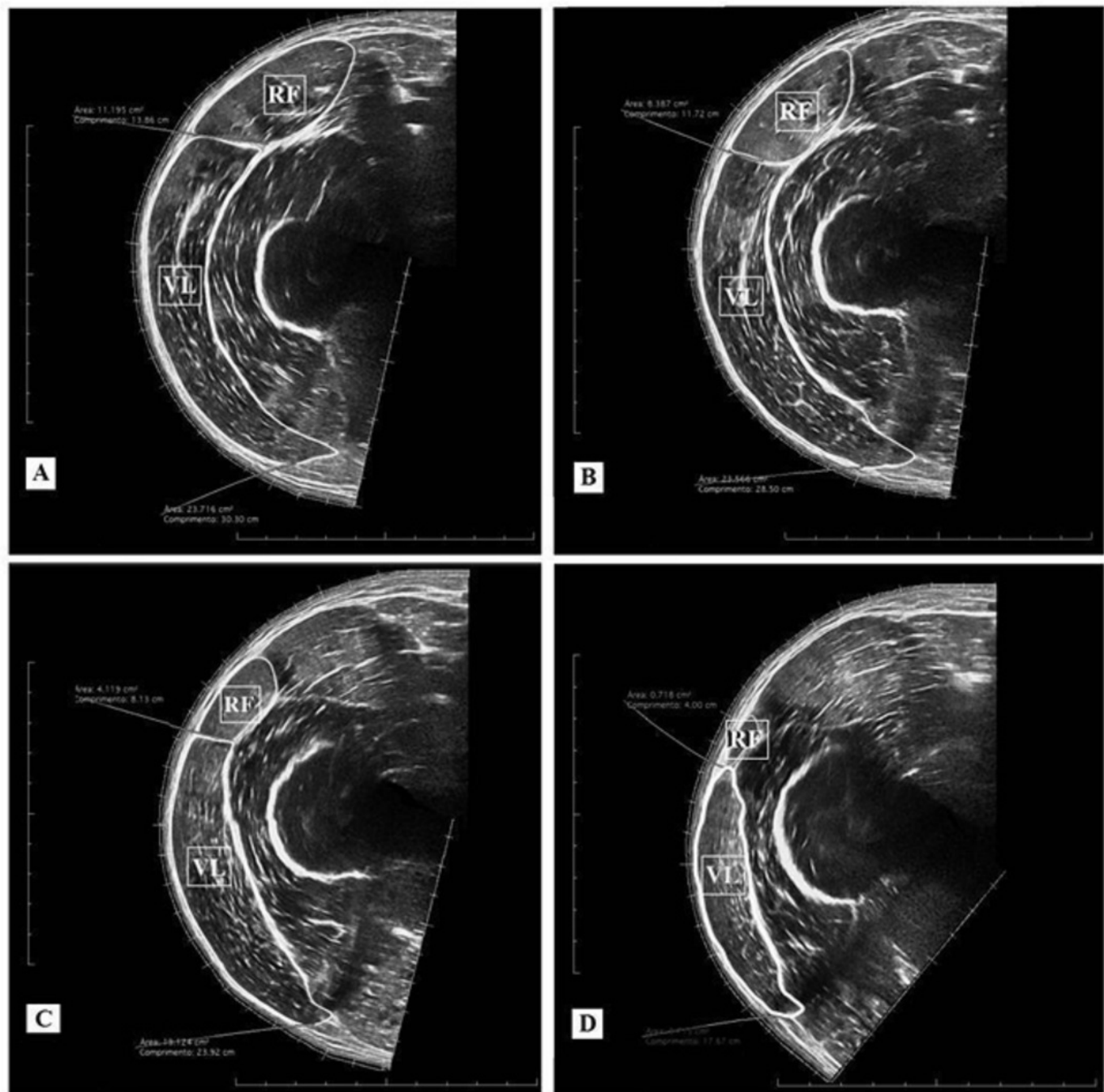
Figure 3

Rectus femoris (A) and vastus lateralis (B) muscle cross-sectional areas (CSA) at pre-test to post-test for each training protocol.

Mean (vertical bars); standard deviation (vertical lines); individual values for each training

protocol (black circles). [#] Post-test higher than pre-test for both protocols (time main effect).
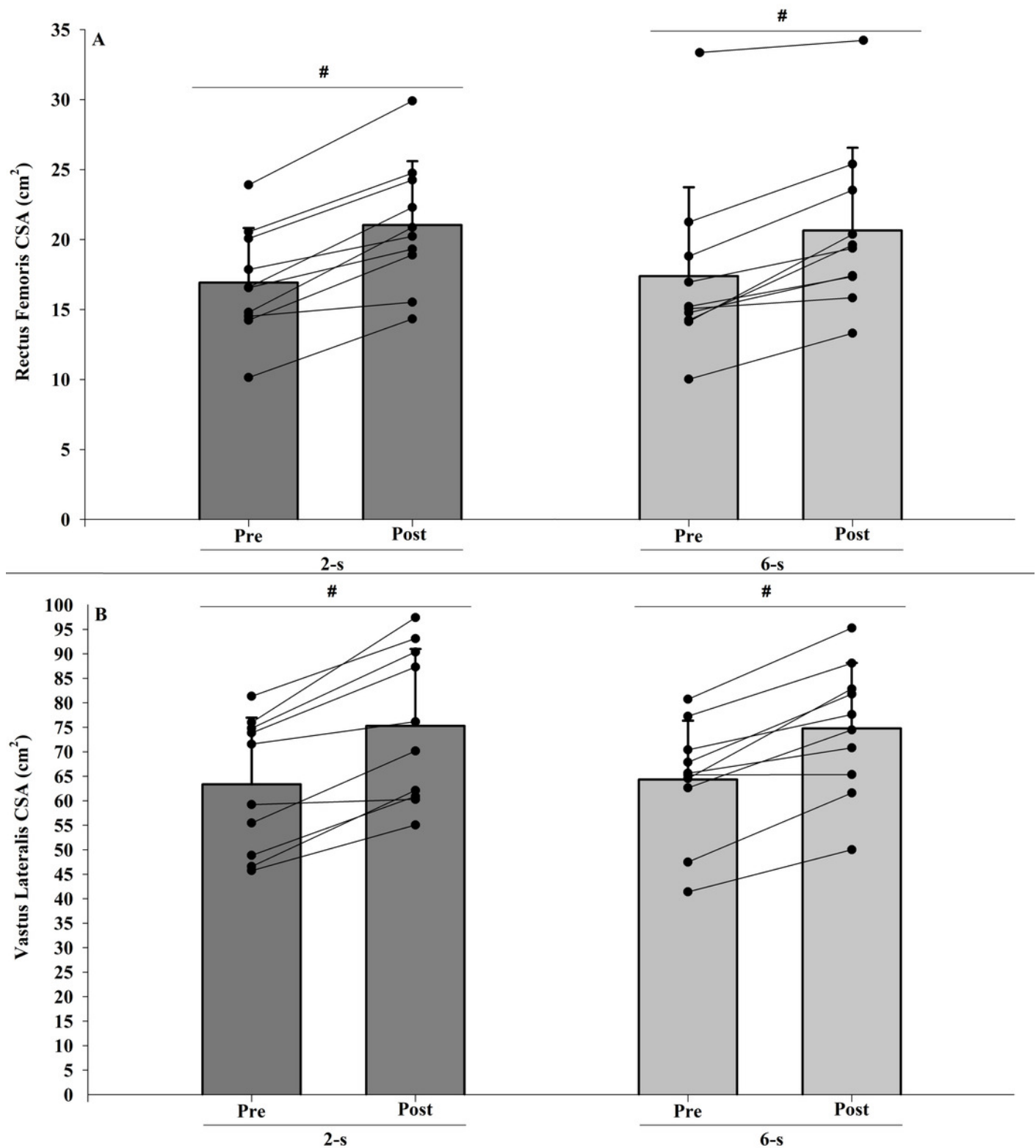
Figure 4

Maximal dynamic strength (1RM) test at post-test for each training protocol.

Mean (vertical bars); standard deviation (vertical lines); individual values for each training protocol (black circles).
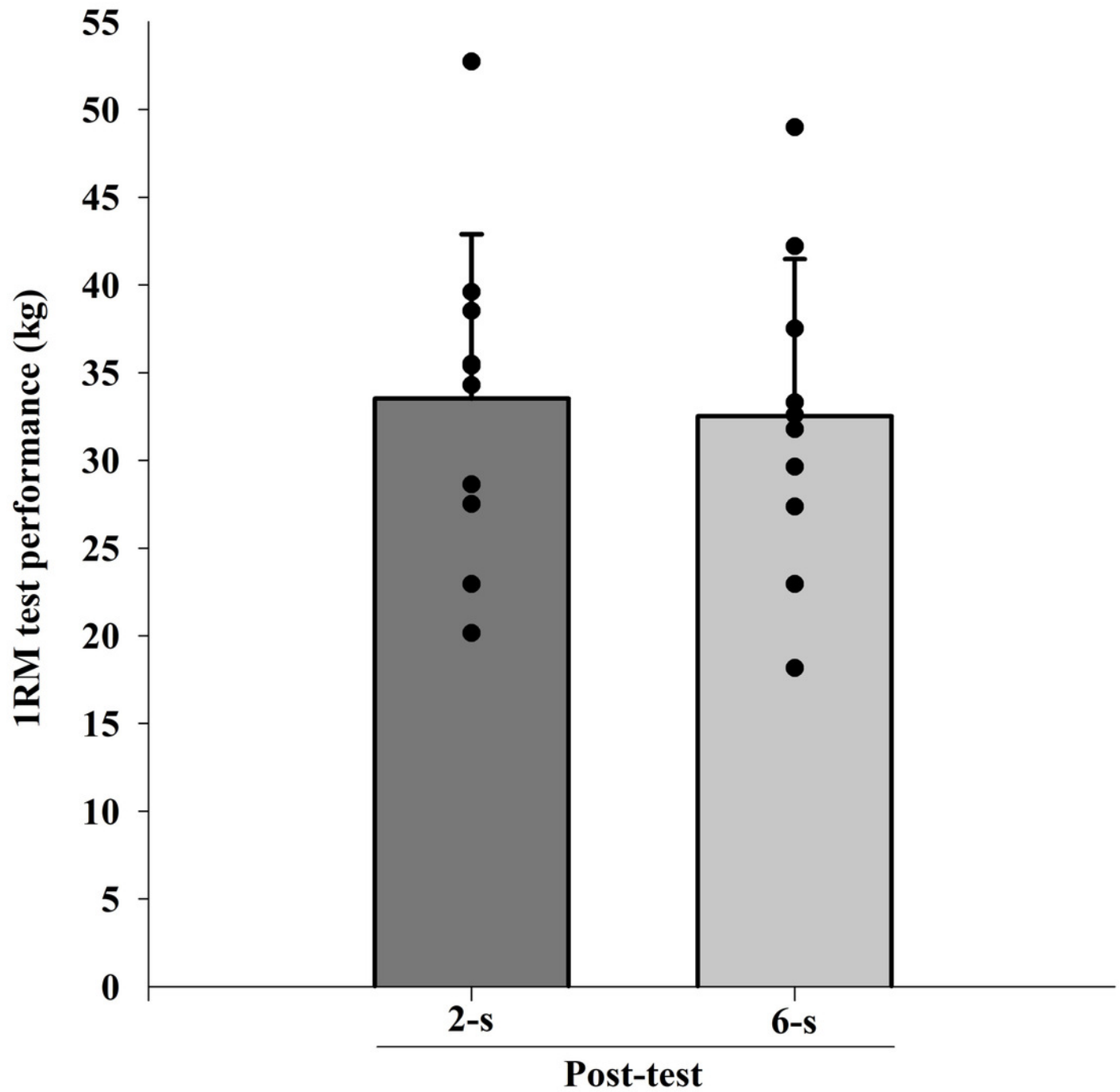
Figure 5

Maximal isometric strength (MVIC) at 30° of knee-joint angle at pre-test to post-test for each training protocol.

Mean (vertical bars); standard deviation (vertical lines); individual values for each training protocol (black circles). * 6-s RD protocol higher than 2-s RD protocol. # Post-test higher than pre-test for both protocols (protocol and time interaction effect).
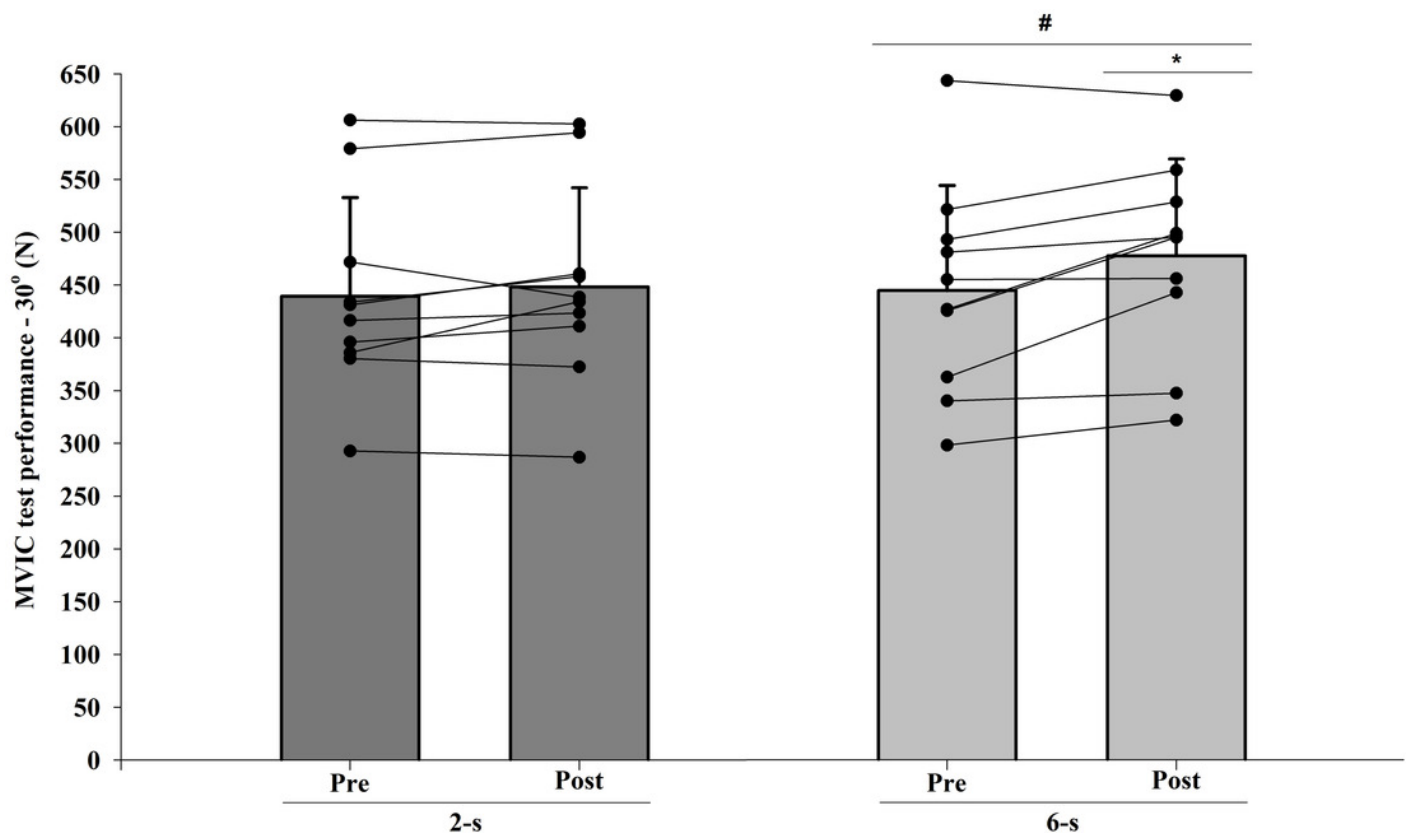
Figure 6

Maximal isometric strength (MVIC) at 90° (B) of knee-joint angle at post-test for each training protocol.

Mean (vertical bars); standard errors (vertical lines); individual values for each training protocol (black circles).
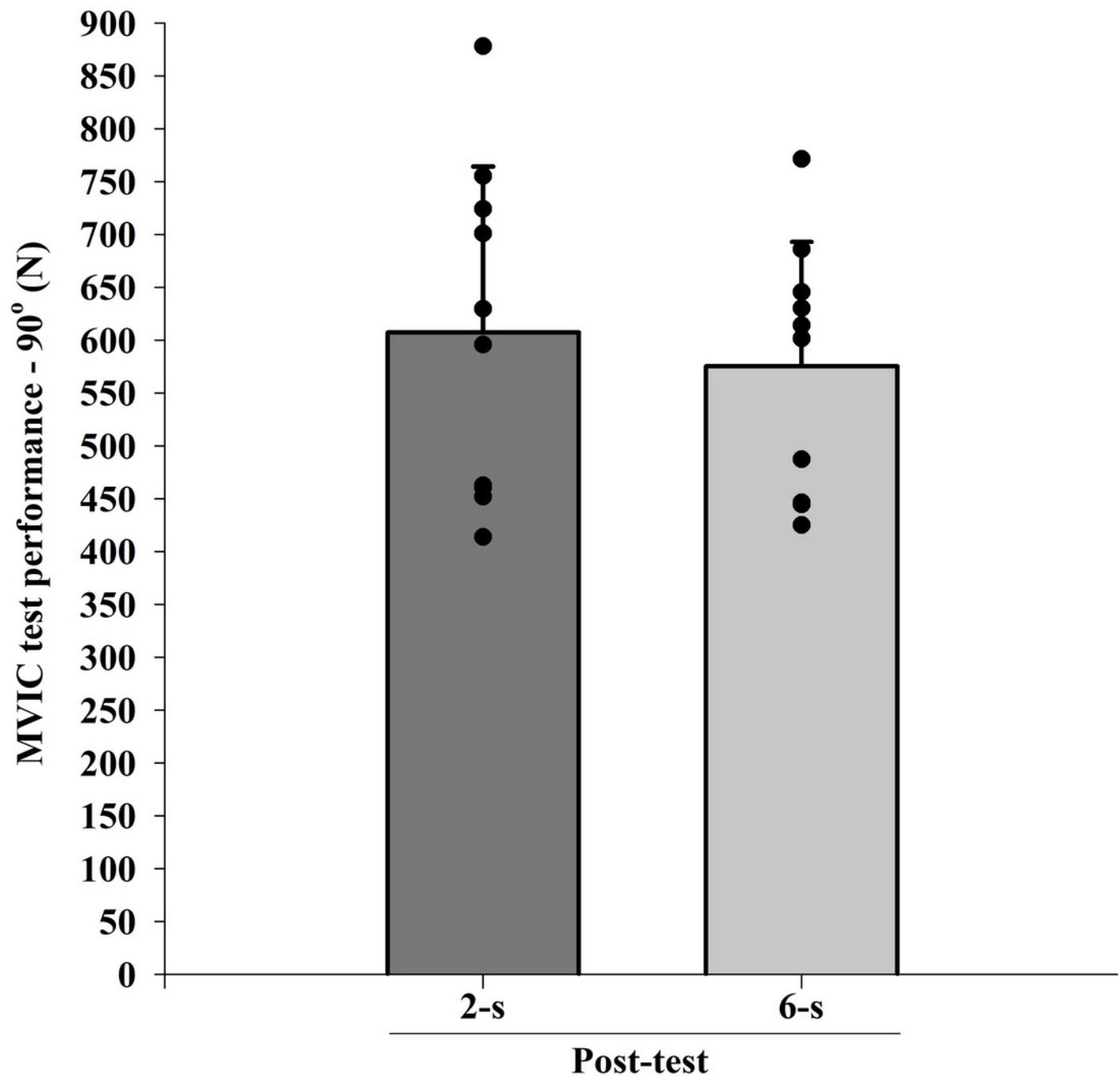
Figure 7

Rectus femoris concentric normalized EMG amplitude x knee-joint angle curves during 6th (A) and 39th (B) experimental sessions at 2-s and 6-s RD protocols.

Mean values for 2-s RD (white triangles); Mean values for 6-s RD (black circles); standard errors (vertical lines). * Significant difference between protocols. # Higher than previous jointangle (6-s RD protocol). & Lower than all previous joint angles, except for 100-90° (2-s RD protocol).
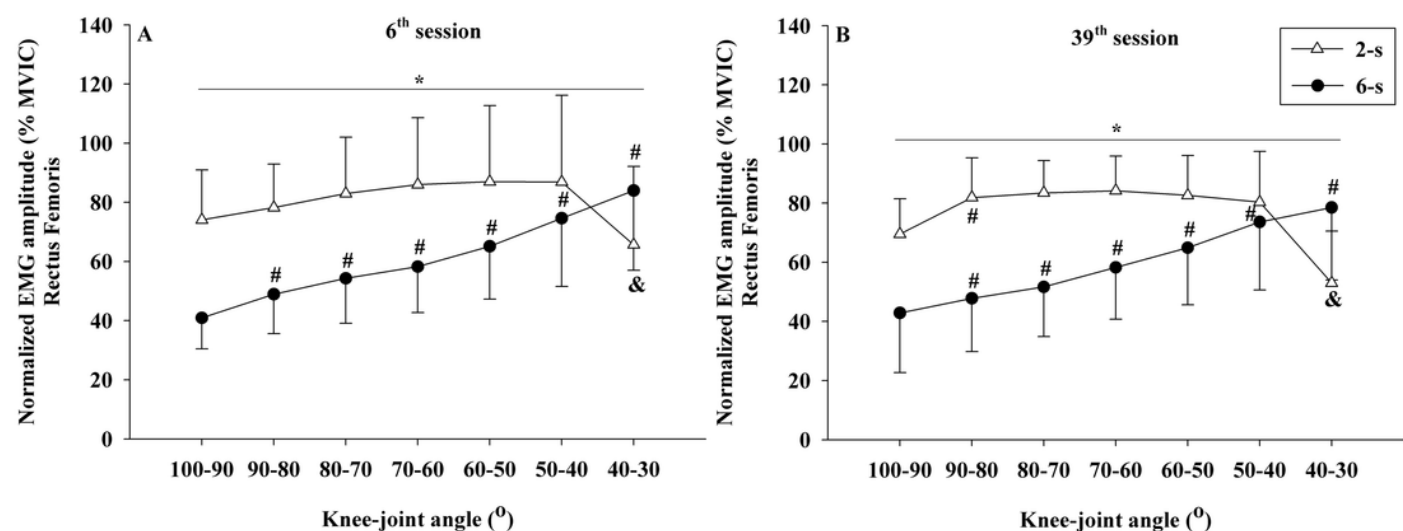
Figure 8

Vastus lateralis concentric normalized EMG amplitude x knee-joint angle curves during 6th (A) and 39th (B) experimental sessions at 2-s and 6-s RD protocols.

Mean values for 2-s RD (white triangles); Mean values for 6-s RD (black circles); standard errors (vertical lines). * Significant difference between protocols. [#] Higher than previous joint angle (6-s RD protocol). [&] Lower than all previous joint angles (2-s RD protocol).
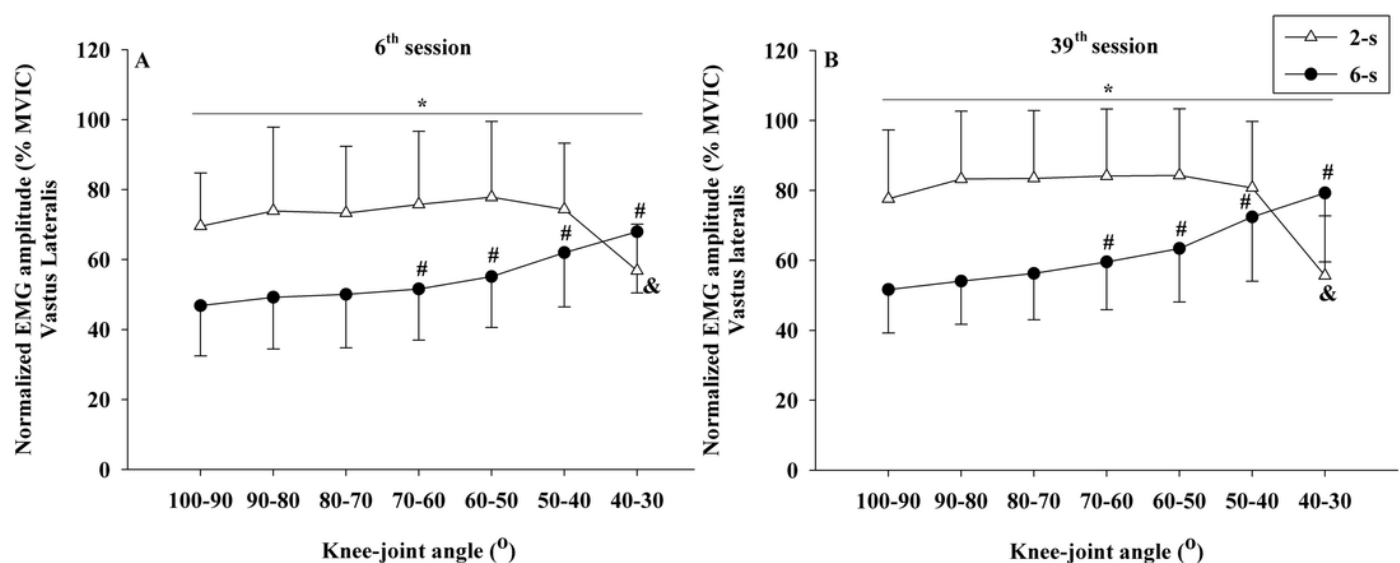
Figure 9

Concentric normalized force x knee-joint angle curves during 6th (A) and 39th (B) experimental sessions at 2-s and 6-s RD protocols.

Mean values for 2-s RD (white triangles); Mean values for 6-s RD (black circles); standard errors (vertical lines). * Significant difference between protocols. $^{\#}$ Higher than previous joint angle (6-s RD protocol). $^{\&}$ Lower than previous joint angle (2-s RD protocol).