Unilateral hamstring foam rolling does not impair strength but the rate of force development of the contralateral muscle

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Background. Self-administered foam rolling (SAFR) is an effective massage technique often used in sport and rehabilitation settings to improve range of motion (ROM) without impairing the strength performance. However, the effects of unilateral SAFR on contralateral non-intervened muscle's rate of force development (RFD) are unknown. Therefore, the purpose of this investigation was to examine the acute effects of unilateral hamstrings SAFR on the contralateral limb flexibility, the isometric strength, and the RFD parameters. **Methods.** Thirty-four subjects (21 women) completed two separate randomly sequenced experimental visits, during which the control (rested for 10 minutes) or ten, 30-second SAFR were performed with the dominant hamstring muscle group. Before (Pre) and after (Post) the interventions, the contralateral hip flexion passive ROM, the maximal explosive isometric strength of the contralateral knee flexors with the corresponding prime mover muscles' surface electromyographic (EMG) amplitude were measured. Separate two-way (time × intervention) repeated measures analyses of variance (ANOVAs) were used to examine the potential changes of the dependent variables. **Results.** The SAFR significantly improved the contralateral limb ROM (Pre vs. Post: 68.3 ± 21.0 vs. 73.2 ± 23.2 degrees, $p < 0.001$; $d = 0.22$). No change was found for the contralateral isometric strength or the maximal EMG amplitude. For the RFD parameters, the percent changes of the RFDs for the first 50, 100, and 200 ms of the maximal explosive isometric contraction were -31.2%, -16.8%, and -10.1%, respectively, following the unilateral SAFR, relative to the control condition. In addition, the decrement of the first 50-ms RFD reached statistical significance ($p = 0.007$; Cohen's $d = 0.44$). **Conclusion:** Ten sets of 30-second unilateral hamstring SAFR improved the ROM of the non-intervened contralateral limb, but decreased its ability to generate force, especially during the early phase (e.g., 50 ms) of the maximal explosive contraction.

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Abstract

Background. Self-administered foam rolling (SAFR) is an effective massage technique often used in sport and rehabilitation settings to improve range of motion (ROM) without impairing the strength performance. However, the effects of unilateral SAFR on contralateral non-intervened muscle's rate of force development (RFD) are unknown. Therefore, the purpose of this investigation was to examine the acute effects of unilateral hamstrings SAFR on the contralateral limb flexibility, the isometric strength, and the RFD parameters.

Methods. Thirty-four subjects (21 women) completed two separate randomly sequenced experimental visits, during which the control (rested for 10 minutes) or ten, 30-second SAFR were performed with the dominant hamstring muscle group. Before (Pre) and after (Post) the interventions, the contralateral hip flexion passive ROM, the maximal explosive isometric strength of the contralateral knee flexors with the corresponding prime mover muscles' surface electromyographic (EMG) amplitude were measured. Separate two-way (time × intervention) repeated measures analyses of variance (ANOVAs) were used to examine the potential changes of the dependent variables.

Results. The SAFR significantly improved the contralateral limb ROM (Pre vs. Post: 68.3 ± 21.0 vs. 73.2 ± 23.2 degrees, $p < 0.001$; $d = 0.22$). No change was found for the contralateral isometric strength or the maximal EMG amplitude. For the RFD parameters, the percent changes of the RFDs for the first 50, 100, and 200 ms of the maximal explosive isometric contraction were -31.2%, -16.8%, and -10.1%, respectively, following the unilateral SAFR, relative to the control condition. In addition, the decrement of the first 50-ms RFD reached statistical significance ($p = 0.007$; Cohen's $d = 0.44$).

Conclusion: Ten sets of 30-second unilateral hamstring SAFR improved the ROM of the non-intervened contralateral limb, but decreased its ability to generate force, especially during the early phase (e.g., 50 ms) of the maximal explosive contraction.

Introduction

Foam rolling is a type of massage technique that has been extensively used both in athletic and rehabilitation settings, mainly due to its portability and ease of use. Over the last decade, the increasing number of research studies have focused on the examinations of performing self-administered foam rolling (SAFR) as a pre-exercise warmup and/or a post-exercise recovery strategy. These research studies have examined the short-term effects (Beardsley & Skarabot 2015; Cheatham et al. 2015; Freiwald et al. 2016; MacDonald et al. 2013) and the potential long-term musculoskeletal adaptations (Macgregor et al. 2018) following the SAFR interventions. Briefly, SAFR consists of using one's body weight to position a specific muscle group onto a dense foam roller while moving back-and-forth to simulate soft tissue mobilization. With the undulating massage-like mechanical pressure placed upon the target muscle(s), the SAFR is an effective tool to promote soft tissue extensibility (Barnes 1997; MacDonald et al. 2013), as well as to enhance recovery from high-intensity exercise (D'Amico & Gillis 2017; Macdonald et al. 2014; Pearcey et al. 2015). More specifically, the SAFR can improve joint range of motion (ROM) (Beardsley & Skarabot 2015; Cheatham et al. 2015; Freiwald et al. 2016; Healey et al. 2014; Junker & Stoggl 2015; MacDonald et al. 2013; Madoni et al. 2018; Monteiro et al. 2017; Su et al. 2017) and increase pain pressure threshold (PPT) (Cheatham & Baker 2017; Cheatham et al. 2017; Pearcey et al. 2015) without necessarily impairing subsequent athletic performance (Behara & Jacobson 2017; Healey et al. 2014; MacDonald et al. 2013).

In addition to the aforementioned effects that SAFR directly imposes on the local intervened muscle group, potential changes in musculoskeletal functions on the contralateral homologous or non-related heterologous (nonlocal) muscle group were also observed more recently. For example, Killen et al. showed an acute improvement on the contralateral hip flexion passive ROM after a unilateral hamstring SAFR intervention (Killen et al. 2018). Similar crossover and nonlocal effects were also reported by others for the ankle dorsiflexion ROM (Garcia-Gutierrez et al. 2018; Kelly & Beardsley 2016). However, in a study where a small area (the sole of the foot) was rolled, no statistically significant crossover effects were demonstrated which, according to the authors, may be the result of insufficient afferent (e.g., mechanoreceptors, nociceptors, and proprioceptors) feedback from the rolling induced-mechanical pressure on tissue (Grabow et al. 2017).

Recent work suggests that foam rolling can also have nonlocal effects potentially influencing muscle mechanical sensitivity. For example, high-intensity foam rolling or rolling massage may decrease the contralateral or nonlocal muscle mechanical sensitivity (Aboodarda et al. 2015; Cavanaugh et al. 2017b; Cheatham & Baker 2017; Cheatham et al. 2017), thereby leading to an enhancement of the stretch tolerance of these muscles. Recent work from Behm's group (Aboodarda et al. 2018; Cavanaugh et al. 2017a; Young et al. 2018) showed that the intervention of foam rolling or rolling massage could even cause the reduction of excitability at the muscular, spinal, and supraspinal levels. Thus, with the decreased corticospinal (Aboodarda et al. 2018) and spinal (Young et al. 2018) excitabilities, it is interesting and important to

116   examine if there are any central-mediated changes on the contralateral or nonlocal muscles, due
117   to the intervention of unilateral SAFR.
118   Cavanaugh et al. (2017) found that three, 30-s unilateral heavy rolling massage on the
119   calf muscle impaired the force generation during the first 200 ms (F200) but not the peak torque
120   for the ipsilateral muscle maximal voluntary isometric contraction (MVIC). In addition, they also
121   found that the F200 of the contralateral non-intervened muscle did not change after massaging
122   the contralateral muscle (Cavanaugh et al. 2017b). It is important to mention that, during the
123   early phase (e.g., 25-75 ms) of an explosive contraction, the RFD can be influenced by neural
124   factors such as the maximal motor unit firing rate, the motor unit high frequency discharges
125   (doublet) at the onset of muscular action, and the reduction in motor unit recruitment thresholds
126   linked to central mechanisms (e.g., increased spinal motoneuron excitability) (Maffiuletti et al.
127   2016; Rodriguez-Rosell et al. 2018). For contraction of longer duration (>75ms), the RFD is
128   more influenced by speed-related properties of the muscle and MVC force per se (Maffiuletti et
129   al. 2016). Thus, examining the RFD during the first 50 ms, or the first 100 ms from the onset of
130   an explosive contraction may serve as a better and more sensitive parameter than the RFD
131   parameters during the later phase or peak force, for monitoring potential altered excitation-
132   induced changes in the force generating ability of the nonlocal muscles (Maffiuletti et al. 2016).
133   In addition, these RFD parameters often serve as better predictors of motor/athletic performance
134   than the peak force in real life scenarios such as an athletic event (Maffiuletti et al. 2016).
135   Therefore, the main purpose of this study was to investigate whether 10 sets of 30-s
136   unilateral SAFR intervention could induce potential changes in the RFD parameters (the RFD of
137   the first 50 ms: RFD_{0-50}; RFD_{0-100}; and RFD_{0-200}) of the contralateral hamstring muscle groups.
138   This study is based on a project where other parts of the data was published previously (Killen et
139   al. 2018). With the larger sample size from the current data pool, the effects of unilateral SAFR
140   on the contralateral non-intervened muscle flexibility, isometric strength, as well as the prime
141   movers' surface electromyographic (EMG) amplitude were also examined. If the contralateral
142   RFD_{0-50} and RFD_{0-100} changed after foam rolling, then it is possible that neural mechanism(s)
143   might have played a role influencing the contralateral non-intervened limb muscles. As shown in
144   Cavanaugh et al. (Cavanaugh et al. 2017b), the RFD_{0-200} and the peak force of the contralateral
145   muscle group would not likely to be statistically different following the unilateral SAFR. This
146   work will build upon previous work by explicating the effects of high volume, long duration
147   SAFR on musculoskeletal functions. The potential practical applications of this research may not
148   be suitable for athletic performance, but may be of great importance for clinical practice
149   (Cheatham et al. 2015). For instance, as physical therapists may have their patients utilize
150   relatively high-volume, long duration SAFR to improve unilateral limb ROM, it is also important
151   to understand the potential rolling-induced effects on the non-intervened contralateral limb
152   muscles.
153
154   **Materials & Methods**
155   **Subjects**

156   Thirty-four adults (male: n = 13, mean ± SD age = 24 ± 4 years; height = 174.3 ± 9.2 cm;
157   body weight = 84.3 ± 15.2 kg; female: n = 21, age = 21 ± 1 years; height = 162.8 ± 3.5 cm; body
158   weight = 65.5 ± 13.4 kg) participated in this investigation. All subjects were healthy and
159   physically active (performed resistance exercises at least once per week, and aerobic exercises at
160   least twice per week 6 months leading up to this study). In addition, all subjects were familiar
161   with foam rolling, and they all had the experience of performing foam rolling exercises
162   previously. Prior to any experimental testing, each subject completed an informed consent and a
163   pre-exercise health and exercise status questionnaire, which indicated no current or recent
164   neuromuscular or musculoskeletal disorders in the lower body. During the consenting process,
165   the subjects were instructed to maintain their normal habits in terms of dietary intake, hydration
166   status, and sleep during the investigation. In addition, they were refrained from performing any
167   upper or lower body resistance exercise at least 72 hours prior to each testing session. All
168   experimental procedures for this investigation were approved by the University Institutional
169   Review Board (Approval Code: 17-062).
170
171   **Design**
172   This investigation used a within-subjects randomized crossover design to examine the
173   potential crossover effects of unilateral hamstring SAFR. Specifically, dependent variables
174   included contralateral hip flexion passive ROM, knee flexion RFD parameters (RFD_{0-50}, RFD_{0-100}, and RFD_{0-200}) and isometric strength, as well as the hamstring muscles biceps femoris (BF)
175    $_{100}$, and RFD_{0-200}) and isometric strength, as well as the hamstring muscles biceps femoris (BF)
176   and semitendinosus (SEMI) EMG amplitude before (Pre) and immediately after (Post) the
177   unilateral SAFR. After the first visit served as the familiarization to practice generating explosive
178   isometric force and the SAFR protocol, the following experimental visits were conducted with a
179   randomized order, during which the SAFR and control conditions were delivered. Between
180   visits, a minimum of 24 hours of rest was provided. All measurements were taken from the
181   subject's non-dominant (NONDOM) leg, and the interventions were performed on the subject's
182   dominant (DOM) leg. Five subjects (three males) were left-footed, based on the leg dominance
183   test (which foot the subject would kick a soccer ball).
184
185   **Procedures**
186   Upon arrival during each experimental visit, the subjects were instructed to lie down on a
187   medical bed in the supine position for a two-minute rest. The pre-tests were then conducted as
188   the following order: NONDOM hip flexion passive ROM (Pre-ROM), and NONDOM knee
189   flexor isometric strength testing (Pre-MVIC). Following the baseline tests, either the control or
190   SAFR intervention was performed. During the control visit, the subjects lay down on the same
191   medical bed for ten minutes. During the SAFR visit, the subjects performed the same protocol as
192   described in Killen et al. (Killen et al. 2018). Briefly, with a foam roller (FitPlus Premium High-
193   Density Foam Roller, Fit Plus LLC, Chattanooga, TN, USA) placed between the dominant
194   hamstring muscle group and a yoga mat, the subject was asked to foam roll the hamstring
195   muscles with a 1-s up (roll to the ischial tuberosity)/1-s down (roll to the popliteal fossa) tempo.

196 During the SAFR, the DOM leg was maintained with an extended position, and the subject
197 crossed the NONDOM ankle on top of the DOM leg. Ten sets of 30-s SAFR with 30-s rest (lie
198 down on the yoga mat with both legs extended and relaxed) between sets were performed by the
199 subjects. Immediately following the intervention, tests (Post-ROM and Post-MVIC) were
200 conducted using the exact same order and manner as during the Pre-measurements.
201
202 **Measurements**
203 *Hip Flexion passive ROM*
204   The straight leg raise test was used to measure the NONDOM hip flexion passive ROM
205 in the supine position. With a Baseline® Bubble® inclinometer (Fabrication Enterprises Inc.,
206 White Plains, NY) placed on the NONDOM knee cap, a member of the research staff grasped the
207 ankle of the DOM leg and raised it slowly to the point where the subjects first felt tension from
208 the hamstring muscle group. The value from the inclinometer was then recorded as the
209 NONDOM hip flexion passive ROM. To ensure measurement consistency, the researcher used a
210 Sharpie pen to mark the location where the inclinometer was placed, and for subsequent
211 measurements, the researcher placed the inclinometer in the exact same spot to perform this
212 measurement. In addition, extra care was taken to ensure the NONDOM knee was kept straight
213 during this procedure. At least three trials with 15-s rest between trials were performed to
214 establish the NONDOM hip flexion passive ROM. If the values from any two trials differed
215 more than 2 degrees, then extra trials would be conducted. The average of the three closest trials
216 was then calculated and recorded as the NONDOM hip flexion passive ROM.
217
218 *Isometric Testing (RFD and Isometric Strength)*
219   Following the measurement of NONDOM hip flexion passive ROM, the subjects were
220 instructed to lie down on the same medical bed with the prone position. With both ankles
221 hanging off the edge of the medical bed, the subjects kept the knee joints straight and relaxed.
222 The research staff then put a cuff around the NONDOM ankle and connected the cuff to one end
223 of a force transducer (Model SSM-AJ-500; Interface, Scottsdale, AZ, USA), with the other end
224 of the transducer attached to a wooden platform mounted on the floor. Before testing the
225 NONDOM knee flexor MVC strength, the subjects were instructed to perform three isometric
226 contractions at about 50% of the perceived maximal effort to warmup. Specifically, they were
227 told to "squeeze as fast as possible", as they practiced during the familiarization session. The
228 subjects then performed three, 3-s MVICs of the NONDOM knee flexors with 2 minutes of
229 recovery between the contractions. During each MVIC, the research staffs provided a verbal
230 countdown "three, two, one, pull" to the subject, with specific emphasis on "pull as fast as
231 possible and hard", based on the instruction recommendation by Maffiuletti et al. (Maffiuletti et
232 al. 2016). During all maximal contractions, the research staffs provided strong verbal
233 encouragement.
234   The surface EMG signals were detected through two bipolar surface EMG electrodes
235 (input impedance > $10^{15}\Omega$, DE 2.1 Single Differential Surface EMG Sensor, Delsys, Inc., Natick,

236 MA; 10 mm interelectrode distance) placed on the NONDOM BF as well as the SEMI muscles,
237 based on the electrode placement recommendations from the SENIAM project.(Hermens et al.
238 1999) The electrodes' locations were recorded and marked with a pen to ensure the electrodes
239 were placed on the exact same spots during both experimental visits. A reference electrode (5.08
240 cm diameter Dermatrode HE-R, American Imex, Irvine, CA) was placed over the 7th cervical
241 vertebrae during data collection. Prior to detecting any EMG signals, all skin sites were shaved
242 with a razor and cleansed with rubbing alcohol. In addition, all the surface EMG sensors were
243 firmly secured to the skin with stripes of adhesive tapes.
244
245 *Force and Surface EMG Signal Processing*
246    During each MVIC trial, both the force and EMG signals were sampled at 20 KHz with a
247 16-channel Bagnoli™ desktop EMG system (Delsys, Inc., Natick, MA), and stored in a
248 laboratory computer (Dell XPS 8900, Round Rock, TX) for further analyses. The EMG signals
249 were preamplified (gain = 1000) and went through a 4th-order Butterworth filter with the
250 bandpass set at 20 - 450 Hz. A custom-built LabVIEW (LabVIEW, National Instruments,
251 Austin, Texas) program was used to analyze the RFD parameters, and the peak force along with
252 its EMG amplitude. For each MVIC, the peak force output was determined from the highest
253 mean 500-ms portion of the force plateau during the contraction of the 3-s MVIC. The isometric
254 strength was determined by the highest peak force output among all three MVICs. The EMG
255 amplitude was then calculated as the root-mean-square (rms) of the same 500-ms window
256 corresponding to the peak force of the contraction. To determine the RFD during the MVICs, we
257 first determined the force onset point at which the force signal exceeded the baseline by 2% of
258 the baseline-to-peak value (Andersen et al. 2010). The RFD was then calculated as the slope of
259 the force-time curve (Δforce/Δtime) derived at time intervals of 0-50 (RFD_{0-50}), 0-100 (RFD_{0-100}), and 0-200 (RFD_{0-200}) ms relative to the onset of the contraction (Aagaard et al. 2002). The
261 RFD values from the contraction that produced the highest peak force were selected for
262 subsequent statistical analyses.
263
264 **Statistical Analyses**
265    Test-retest reliability was calculated across the pre-values from two experimental visits
266 by determining the intraclass correlation coefficient (ICC; relative reliability) using Model "3,1"
267 (Weir 2005). In addition, the standard error of the measurement (SEM) was calculated for
268 measures of absolute reliability using the equation from Hopkins (Hopkins 2000a) and Weir
269 (Weir 2005): SEM = squat root (1-ICC). Lastly, the coefficient of variation (CV) was calculated
270 as a normalized measure of the SEM using the equation: CV = (SEM/Grand mean) × 100
271 (Hopkins 2000a).
272    Assumptions for normality of distribution for all model (fit) residuals were checked and
273 confirmed using the Shapiro-Wilk test. Separate two-way (time [Pre vs. Post] × intervention
274 [Control vs. SAFR]) repeated measures ANOVAs were performed to examine potential changes
275 of all the dependent variables before and after the different interventions. When appropriate, the

276   follow-up tests included paired t-tests with Bonferroni corrections (if there was an interaction).

277   All statistical tests were conducted using statistical software (IBM SPSS Statistics 25.0, IBM,

278   Armonk, NY) with alpha set at 0.05. In addition, effect sizes Cohen's *d* (Cohen 1992) were

279   calculated to assess the treatment effect (Control vs. SAFR) and time effect (Pre vs. Post) for

280   each dependent variable. The Cohen's *d* was calculated as $(Mean_1 - Mean_2)$ / pooled Standard

281   Deviation (SD_{pooled}), where SD_{pooled} = square root $[(SD_1^2 + SD_2^2) / 2]$, with 0.2, 0.6, and 1.2 as

282   the thresholds for small, medium, and large effect sizes, respectively, based on Hopkins'

283   interpretations for the magnitude of effect size (Hopkins 2000b). Lastly, separate Tufte

284   slopegraphs with the Cumming estimation plots (Figure 1) were generated to display the

285   complete statistical information regarding all RFD parameters before and after interventions

286   (Control vs. SAFR) (Ho et al. 2018).

287

Results

289   *Test-retest Reliability*

290   Table 1 shows the ICC, SEM, and CV of measurement variables (contralateral hip

291   flexion passive ROM, contralateral knee flexion isometric strength, RFD_{0-50}, RFD_{0-100}, RFD_{0-200},

292   and contralateral BF and SEMI muscle maximal EMG amplitude).

293

294   *NONDOM Hip Flexion Passive ROM*

295   The results from the two-way repeated measures ANOVA indicated that there was a

296   statistically significant time × intervention interaction ($F(1, 33) = 27.371$, $p < 0.001$). The

297   follow-up paired samples *t*-tests indicated that the NONDOM hip flexion passive ROM

298   significantly increased following the SAFR (mean ± SD: Pre vs. Post = 68.3 ± 21.0 vs. 73.2 ±

299   23.2, $t = 6.625$, $p < 0.001$; $d = 0.22$), but not following the control (Pre vs. Post = 68.4 ± 20.7 vs.

300   68.2 ± 21.2, $t = 0.301$, $p = 0.383$; $d = 0.01$). In addition, the Post-ROM value were significantly

301   higher following the SAFR than that following the control (SAFR vs. Control = 73.2 ± 23.2 vs.

302   68.2 ± 21.2, $t = 2.943$, $p = 0.003$; $d = 0.23$).

303

304   *NONDOM Knee flexors Isometric Strength and EMG Amplitude*

305   The two-way ANOVA showed neither an interaction ($F(1, 32) = 3.784$, $p = 0.061$) nor

306   main effects (time and intervention) for the isometric strength of the NONDOM knee flexors. In

307   addition, no interactions (BF: $F(1, 30) = 0.038$, $p = 0.847$; SEMI: $F(1, 30) = 0.162$, $p = 0.690$) as

308   well as main effects (time and intervention) were found for the EMG amplitude of both BF and

309   SEMI muscles.

310

311   *RFD Parameters*

312   For the RFD_{0-50}, the two-way ANOVA indicated that there was a time × intervention

313   interaction ($F(1, 31) = 5.834$, $p = 0.022$). The follow-up paired samples *t*-tests indicated that the

314   RFD_{0-50} value significantly decreased following the SAFR (Pre vs. Post = 1626 ± 1325 vs. 1125

315   ± 937, $t = 2.630$, $p = 0.007$; $d = 0.44$), but not following the control (Pre vs. Post = 1756 ± 1611

316   vs. 1778 ± 1578, $t = 0.115$, $p = 0.455$; $d = 0.01$). In addition, the RFD_{0-50} was significantly lower

317   following the SAFR than that following the control (SAFR vs. Control = 1125 ± 937 vs. 1778 ±
318   1578, $t = 3.100$, $p = 0.002$; $d = 0.50$).
319   For both RFD_{0-100} and RFD_{0-200}, the results from the two-way ANOVAs did not show any
320   time × intervention interactions (RFD_{0-100}: $F(1, 31) = 3.152$, $p = 0.086$; RFD_{0-200}: $F(1, 31) =$
321   0.872, $p = 0.358$). Figure 1 displays the individual absolute change scores (delta) of the Control
322   vs. SAFR interventions and the paired mean changes in all RFD parameters.
323
324   Insert Table 1 and Figure 1 here
325
326   **Discussion**
327   The main purpose of this investigation was to examine whether unilateral SAFR exercise could
328   influence the contralateral muscle RFD parameters. Additionally, the contralateral limb passive
329   ROM, and the isometric strength along with the maximal EMG amplitude were also examined.
330   Ten, 30-s unilateral hamstring SAFR increased the contralateral passive hip flexion ROM by
331   almost 5 degrees. In addition, the contralateral isometric strength along with the prime movers'
332   maximal EMG amplitudes were not statistically significantly altered after the SAFR intervention.
333   These results were consistent with the ones from our previous report (Killen et al. 2018).
334   Regarding the RFD parameters, to our knowledge, this is the first study to investigate potential
335   crossover effect of unilateral SAFR on the contralateral muscle RFD. Specifically, the
336   contralateral RFD_{0-50} significantly decreased following the unilateral SAFR. Relative to the
337   control condition, the SAFR imposed a small treatment effect ($d = 0.42$) on the decrement of the
338   RFD_{0-50}. In addition, the estimation plots with each paired mean difference (between
339   deltaControl and deltaSAFR) suggest that the mean differences for deltaControl and deltaSAFR
340   were below zero (mean deltaControl was less than mean deltaSAFR) for both RFD_{0-100} and
341   RFD_{0-200} (Figure 1).
342   With the RFD_{0-50} demonstrating the statistically significant reduction, and the relatively
343   larger mean differences for both the RFD_{0-100} and RFD_{0-200} before and after the unilateral SAFR,
344   as compared to the control, it is also important to notice the magnitudes of the changes in these
345   RFD parameters. Relative to the control condition, the average percent changes of the
346   contralateral muscle RFD_{0-50}, RFD_{0-100}, and RFD_{0-200} following the SAFR were -31.2%, -16.8%,
347   and -10.1%, respectively, showing a diminishing decline as the time interval for RFD lengthens.
348   Folland and colleagues (Folland et al. 2014) used surface EMG to examine the relative
349   contribution from the neural and contractile components in the early and late phases of the knee
350   extension force-time curve. Based on their multiple linear regression analysis, the agonist muscle
351   EMG amplitude was particularly important explaining the variance in explosive force during the
352   initial phase (e.g., 25-75 ms). Furthermore, neural factors such as the motor unit recruitment and
353   discharge rate, the presence of motor unit doublet discharges, the spinal motoneuron excitability,
354   and the corticospinal excitability are also important contributing to the RFD during the initial
355   phase of a rapid contraction (Maffiuletti et al. 2016; Rodriguez-Rosell et al. 2018). While for
356   longer duration (e.g., > 75 ms), the speed-related properties of the muscle and MVC force per se

357 become more important for the RFD (Maffiuletti et al. 2016). Thus, the statistically significant
358 reduction for the contralateral muscle RFD_{0-50} might have been originated from the change(s) of
359 one or some of the above-mentioned neural factors, induced by the unilateral SAFR.
360   The next obvious question is how ten, 30-s unilateral SAFR could influence the central
361 nervous system, causing a change on the contralateral muscle RFD. In addition, another
362 important question is where in the entire corticospinal pathway that this crossover could occur.
363 As mentioned, repetitive high-intensity foam rolling or rolling massage exert mechanical
364 pressure on skin, muscle, and fascia, primarily influencing mechanoreceptors and nociceptors
365 (Behm et al. 2013), such as the type Ib Golgi tendon organs, the cutaneous receptors, and the
366 type III/IV interstitial free nerve endings. A potential mechanism could be originated from the
367 activation of the most abundant intrafascial mechanoreceptors, type III and IV receptors, due to
368 the high-volume long duration of foam rolling. Specifically, nociceptive stimuli (e.g., rolling-
369 induced mechanical pressure on soft tissue) could induce neurophysiological responses,
370 including the influence on the descending pain modulation circuit (Vigotsky & Bruhns 2015). In
371 addition, diffuse noxious inhibitory control (a painful stimulus can be inhibited by another
372 nonlocal noxious stimulus) may also serve as a central pain-modulatory mechanism influencing a
373 nonlocal site. In the current investigation, unfortunately, it is not possible to identify the specific
374 location that the potential crossover occurred at the corticospinal pathway, due to the lack of
375 spinal and corticospinal excitability measurements.
376   Previously, Cavanaugh et al. (Cavanaugh et al. 2017b) performed three, 30-s unilateral
377 heavy (7 out of 10 based on the visual analog pain scale: uncomfortable or induced some pain
378 with most subjects) rolling massage on the subjects' calf muscle, but only found statistically
379 significant decrease in the RFD_{0-200} for the ipsilateral, but not for the contralateral homologous
380 muscle. An obvious difference between the current study and Cavanaugh et al. is the different
381 interventions (foam rolling vs. rolling massage). However, review articles (Cheatham et al. 2015;
382 DeBruyne et al. 2017) comparing foam rolling vs. rolling massage did not identify any
383 intervention-related differences per se. Instead, the duration difference between these
384 interventions might have played a more important role. Specifically, our subjects performed a
385 total of 300 seconds foam rolls within a 10-minute period. This volume was significantly higher
386 than the one (a total of 90 seconds 2-s up/2-s down rolling massage) from Cavanaugh et al.
387 (Cavanaugh et al. 2017b). Previously, Monteiro et al. (2017) compared the effects of 60 vs. 120
388 seconds of SAFR on joint ROM, and found longer duration/higher volume produce larger
389 treatment effect (Monteiro et al. 2017). In addition, when implementing different SAFR
390 durations into fatiguing resistance exercise sets (e.g. three sets of 10-repetition maximum load to
391 failure), volumes with greater than 90 seconds were detrimental to fatigue resistance (Monteiro
392 & Neto 2016). Thus, comparing to Cavanaugh et al. (2017b), it is possible that greater amount of
393 the nociceptive stimulus from the current high-volume, high-intensity SAFR intervention might
394 have induced greater inhibition, thereby showing more prominent crossover effects on the RFD
395 parameters. In addition, the current SAFR intervention also seemed to decrease the contralateral
396 knee flexors muscle pain perception through central pain-modulatory system, thereby leading to

397 an enhancement of the stretch tolerance of these muscles (evidenced by the increased
398 contralateral limb ROM).
399   With the novel finding of the contralateral muscle RFD parameters, we do want to point
400 out several limitations of this investigation and emphasize a caution when interpreting the
401 results. First, we did not specifically examine the RFD parameters of the unilateral intervened
402 muscle group, mainly due to the primary focus of this investigation was the contralateral
403 crossover effect. Since the crossover effects were present in the non-exercised contralateral
404 muscle RFD parameters, the unilateral rolled muscle is more likely affected. Obviously, future
405 studies should identify the time window of the crossover effect as well as the magnitudes of
406 changes in RFD parameters in the unilateral intervened muscle. Besides the above-mentioned
407 limitation, our methodology also included some limitations need to be pointed out. For example,
408 the subjects were recruited based on convenience sampling. The investigators in this study were
409 not blinded to the measurements of the dependent variables, which could have affected the
410 outcome measures. In addition, the SAFR intervention should have been randomly assigned
411 between both sides of the knee flexors, for the purpose of examining potential effect of limb
412 dominance. Lastly, caution should be taken when interpreting the results due to the high-volume
413 of the intervention. Specifically, it may not be appropriate to apply the findings of the study to
414 athletic field, because most SAFR sessions prior to an exercise session or a sport event do not
415 last more than 90 seconds (e.g., 3 sets of 30-s SAFR). Thus, contralateral athletic performance
416 such as the explosive power does not necessarily decrease following a typical SAFR with a
417 shorter duration. Instead, our results may specifically be important for areas of physical therapy
418 and rehabilitation, as patients may undergo longer duration of interventions.
419

Conclusions

421   A bout of ten, 30-s unilateral hamstring SAFR intervention improved the contralateral hip
422 flexion passive ROM without altering the contralateral isometric strength performance and the
423 prime mover muscles' maximal EMG amplitudes. However, the contralateral muscle group's
424 ability to generate explosive force was impaired. In addition, the magnitudes of the impairments
425 seemed to be phase-dependent (with greater impairment observed in the early phase such as the
426 first 50 ms than those in the later ones such as the 100 and 200 ms). These results show the
427 evidence of contralateral crossover effects of unilateral SAFR.
428

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436 **References**
437 Aagaard P, Simonsen EB, Andersen JL, Magnusson P, and Dyhre-Poulsen P. 2002. Increased rate of
438   force development and neural drive of human skeletal muscle following resistance training. *J*
439   *Appl Physiol (1985)* 93:1318-1326. 10.1152/japplphysiol.00283.2002
440 Aboodarda SJ, Greene RM, Philpott DT, Jaswal RS, Millet GY, and Behm DG. 2018. The effect of
441   rolling massage on the excitability of the corticospinal pathway. *Appl Physiol Nutr Metab* 43:317-
442   323. 10.1139/apnm-2017-0408
443 Aboodarda SJ, Spence AJ, and Button DC. 2015. Pain pressure threshold of a muscle tender spot
444   increases following local and non-local rolling massage. *BMC Musculoskelet Disord* 16:265.
445   10.1186/s12891-015-0729-5
446 Andersen LL, Andersen JL, Zebis MK, and Aagaard P. 2010. Early and late rate of force development:
447   differential adaptive responses to resistance training? *Scand J Med Sci Sports* 20:e162-169.
448   10.1111/j.1600-0838.2009.00933.x
449 Barnes MF. 1997. The basic science of myofascial release: morphologic change in connective tissue. *J*
450   *Bodyw Mov Ther* 1:231-238.
451 Beardsley C, and Skarabot J. 2015. Effects of self-myofascial release: A systematic review. *J Bodyw Mov*
452   *Ther* 19:747-758. 10.1016/j.jbmt.2015.08.007
453 Behara B, and Jacobson BH. 2017. Acute Effects of Deep Tissue Foam Rolling and Dynamic Stretching
454   on Muscular Strength, Power, and Flexibility in Division I Linemen. *J Strength Cond Res* 31:888-
455   892. 10.1519/JSC.0000000000001051
456 Behm DG, Peach A, Maddigan M, Aboodarda SJ, DiSanto MC, Button DC, and Maffiuletti NA. 2013.
457   Massage and stretching reduce spinal reflex excitability without affecting twitch contractile
458   properties. *J Electromyogr Kinesiol* 23:1215-1221. 10.1016/j.jelekin.2013.05.002
459 Cavanaugh MT, Aboodarda SJ, Hodgson DD, and Behm DG. 2017a. Foam Rolling of Quadriceps
460   Decreases Biceps Femoris Activation. *J Strength Cond Res* 31:2238-2245.
461   10.1519/JSC.0000000000001625
462 Cavanaugh MT, Doweling A, Young JD, Quigley PJ, Hodgson DD, Whitten JH, Reid JC, Aboodarda SJ,
463   and Behm DG. 2017b. An acute session of roller massage prolongs voluntary torque development
464   and diminishes evoked pain. *Eur J Appl Physiol* 117:109-117. 10.1007/s00421-016-3503-y
465 Cheatham SW, and Baker R. 2017. Differences in pressure pain threshold among men and women after
466   foam rolling. *J Bodyw Mov Ther* 21:978-982. 10.1016/j.jbmt.2017.06.006
467 Cheatham SW, Kolber MJ, Cain M, and Lee M. 2015. The Effects of Self-Myofascial Release Using a
468   Foam Roll or Roller Massager on Joint Range of Motion, Muscle Recovery, and Performance: A
469   Systematic Review. *Int J Sports Phys Ther* 10:827-838.
470 Cheatham SW, Stull KR, and Kolber MJ. 2017. Comparison of a vibrating foam roller and a non-
471   vibrating foam roller intervention on knee range of motion and pressure pain threshold: A
472   randomized controlled trial. *Journal of Sport Rehabilitation*:1-23.
473 Cohen J. 1992. A power primer. *Psychol Bull* 112:155-159.
474 D'Amico AP, and Gillis J. 2017. The influence of foam rolling on recovery from exercise-induced muscle
475   damage. *J Strength Cond Res*. 10.1519/JSC.0000000000002240
476 DeBruyne DM, Dewhurst MM, Fischer KM, Wojtanowski MS, and Durall C. 2017. Self-Mobilization
477   Using a Foam Roller Versus a Roller Massager: Which Is More Effective for Increasing
478   Hamstrings Flexibility? *Journal of Sport Rehabilitation* 26:94-100.
479 Folland JP, Buckthorpe MW, and Hannah R. 2014. Human capacity for explosive force production:
480   neural and contractile determinants. *Scand J Med Sci Sports* 24:894-906. 10.1111/sms.12131
481 Freiwald J, Baumgart C, Kühnemann M, and Hoppe MW. 2016. Foam-Rolling in sport and therapy –
482   Potential benefits and risks. *Sports Orthopaedics and Traumatology* 32:267-275.
483   10.1016/j.orthtr.2016.07.002

484 Garcia-Gutierrez MT, Guillen-Rogel P, Cochrane DJ, and Marin PJ. 2018. Cross transfer acute effects of
485   foam rolling with vibration on ankle dorsiflexion range of motion. *J Musculoskelet Neuronal*
486   *Interact* 18:262-267.
487 Grabow L, Young JD, Byrne JM, Granacher U, and Behm DG. 2017. Unilateral Rolling of the Foot did
488   not Affect Non-Local Range of Motion or Balance. *J Sports Sci Med* 16:209-218.
489 Healey KC, Hatfield DL, Blanpied P, Dorfman LR, and Riebe D. 2014. The effects of myofascial release
490   with foam rolling on performance. *J Strength Cond Res* 28:61-68.
491   10.1519/JSC.0b013e3182956569
492 Hermens H, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, Disselhorst-Klug C, and Hägg G. 1999.
493   SENIAM European recommendations for surface ElectroMyoGraphy: Result of the SENIAM
494   Project. *Enschede, The Netherlands: Roessingh Research and Development.*
495 Ho J, Tumkaya T, Aryal S, Choi H, and Claridge-Chang A. 2018. Moving beyond P values: Everyday
496   data analysis with estimation plots. *bioRxiv*:377978. 10.1101/377978
497 Hopkins WG. 2000a. Measures of reliability in sports medicine and science. *Sports Med* 30:1-15.
498   10.2165/00007256-200030010-00001
499 Hopkins WG. 2000b. A new view of statistics. *Available at*
500   *https://www.sportsci.org/resource/stats/effectmag.html*.
501 Junker DH, and Stoggl TL. 2015. The Foam Roll as a Tool to Improve Hamstring Flexibility. *J Strength*
502   *Cond Res* 29:3480-3485. 10.1519/JSC.0000000000001007
503 Kelly S, and Beardsley C. 2016. Specific and Cross-over Effects of Foam Rolling on Ankle Dorsiflexion
504   Range of Motion. *Int J Sports Phys Ther* 11:544-551.
505 Killen BS, Zelizney KL, and Ye X. 2018. Crossover Effects of Unilateral Static Stretching and Foam
506   Rolling on Contralateral Hamstring Flexibility and Strength. *Journal of Sport Rehabilitation*:1-
507   27. 10.1123/jsr.2017-0356
508 Macdonald GZ, Button DC, Drinkwater EJ, and Behm DG. 2014. Foam rolling as a recovery tool after an
509   intense bout of physical activity. *Med Sci Sports Exerc* 46:131-142.
510   10.1249/MSS.0b013e3182a123db
511 MacDonald GZ, Penney MD, Mullaley ME, Cuconato AL, Drake CD, Behm DG, and Button DC. 2013.
512   An acute bout of self-myofascial release increases range of motion without a subsequent decrease
513   in muscle activation or force. *J Strength Cond Res* 27:812-821. 10.1519/JSC.0b013e31825c2bc1
514 Macgregor LJ, Fairweather MM, Bennett RM, and Hunter AM. 2018. The Effect of Foam Rolling for
515   Three Consecutive Days on Muscular Efficiency and Range of Motion. *Sports Med Open* 4:26.
516   10.1186/s40798-018-0141-4
517 Madoni SN, Costa PB, Coburn JW, and Galpin AJ. 2018. Effects of Foam Rolling on Range of Motion,
518   Peak Torque, Muscle Activation, and the Hamstrings-to-Quadriceps Strength Ratios. *J Strength*
519   *Cond Res* 32:1821-1830. 10.1519/JSC.0000000000002468
520 Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, and Duchateau J. 2016. Rate of force
521   development: physiological and methodological considerations. *Eur J Appl Physiol* 116:1091-
522   1116. 10.1007/s00421-016-3346-6
523 Monteiro ER, Cavanaugh MT, Frost DM, and Novaes JD. 2017. Is self-massage an effective joint range-
524   of-motion strategy? A pilot study. *J Bodyw Mov Ther* 21:223-226. 10.1016/j.jbmt.2016.10.003
525 Monteiro ER, and Neto VG. 2016. Effect of Different Foam Rolling Volumes on Knee Extension Fatigue.
526   *Int J Sports Phys Ther* 11:1076-1081.
527 Pearcey GE, Bradbury-Squires DJ, Kawamoto JE, Drinkwater EJ, Behm DG, and Button DC. 2015.
528   Foam rolling for delayed-onset muscle soreness and recovery of dynamic performance measures.
529   *J Athl Train* 50:5-13. 10.4085/1062-6050-50.1.01
530 Rodriguez-Rosell D, Pareja-Blanco F, Aagaard P, and Gonzalez-Badillo JJ. 2018. Physiological and
531   methodological aspects of rate of force development assessment in human skeletal muscle. *Clin*
532   *Physiol Funct Imaging* 38:743-762. 10.1111/cpf.12495

533   Su H, Chang NJ, Wu WL, Guo LY, and Chu IH. 2017. Acute Effects of Foam Rolling, Static Stretching,
534   and Dynamic Stretching During Warm-ups on Muscular Flexibility and Strength in Young
535   Adults. *Journal of Sport Rehabilitation* 26:469-477. 10.1123/jsr.2016-0102
536   Vigotsky AD, and Bruhns RP. 2015. The Role of Descending Modulation in Manual Therapy and Its
537   Analgesic Implications: A Narrative Review. *Pain research and treatment* 2015:292805-292805.
538   10.1155/2015/292805
539   Weir JP. 2005. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM.
540   *J Strength Cond Res* 19:231-240. 10.1519/15184.1
541   Young JD, Spence AJ, and Behm DG. 2018. Roller massage decreases spinal excitability to the soleus. *J
542   Appl Physiol (1985)* 124:950-959. 10.1152/japplphysiol.00732.2017
543

Figure 1

Individual responses and the paired mean differences for comparisons (the absolute change scores of the Control vs. SAFR) of all three RFD parameters (RFD_{0-50} , RFD_{0-100}, RFD_{0-200})

The paired mean differences for comparisons (the absolute change scores of the Control vs. SAFR) of all three RFD parameters (RFD_{0-50} , RFD_{0-100}, RFD_{0-200}) are shown in the above Cumming estimation plot. The raw data (the change score) is plotted on the upper axes; each paired set of observations is connected by a line. On the lower axes, each paired mean difference is plotted as a bootstrap sampling distribution. Mean differences are depicted as dots; 95% confidence intervals (CIs) are indicated by the ends of the vertical error bars. For each paired comparison, the paired mean difference (Δ) with 95% CI are provided as the following format: Δ [95 CI: lower bound; 95CI upper bound]

DeltaControl (RFD_{0-50}) vs. DeltaSAFR (RFD_{0-50}): -503.0 [95 CI: -936.0; -149.0]; SEE = 293.89

DeltaControl (RFD_{0-100}) vs. DeltaSAFR (RFD_{0-100}): -182.0 [95 CI: -367.0; -14.5]; SEE = 125.94

DeltaControl (RFD_{0-200}) vs. DeltaSAFR (RFD_{0-200}): -64.8 [95 CI: -225.0; 29.6]; SEE = 67.99

Note: RFD = rate of force development; SAFR = self-administered foam rolling; SEE = standard error of the estimate
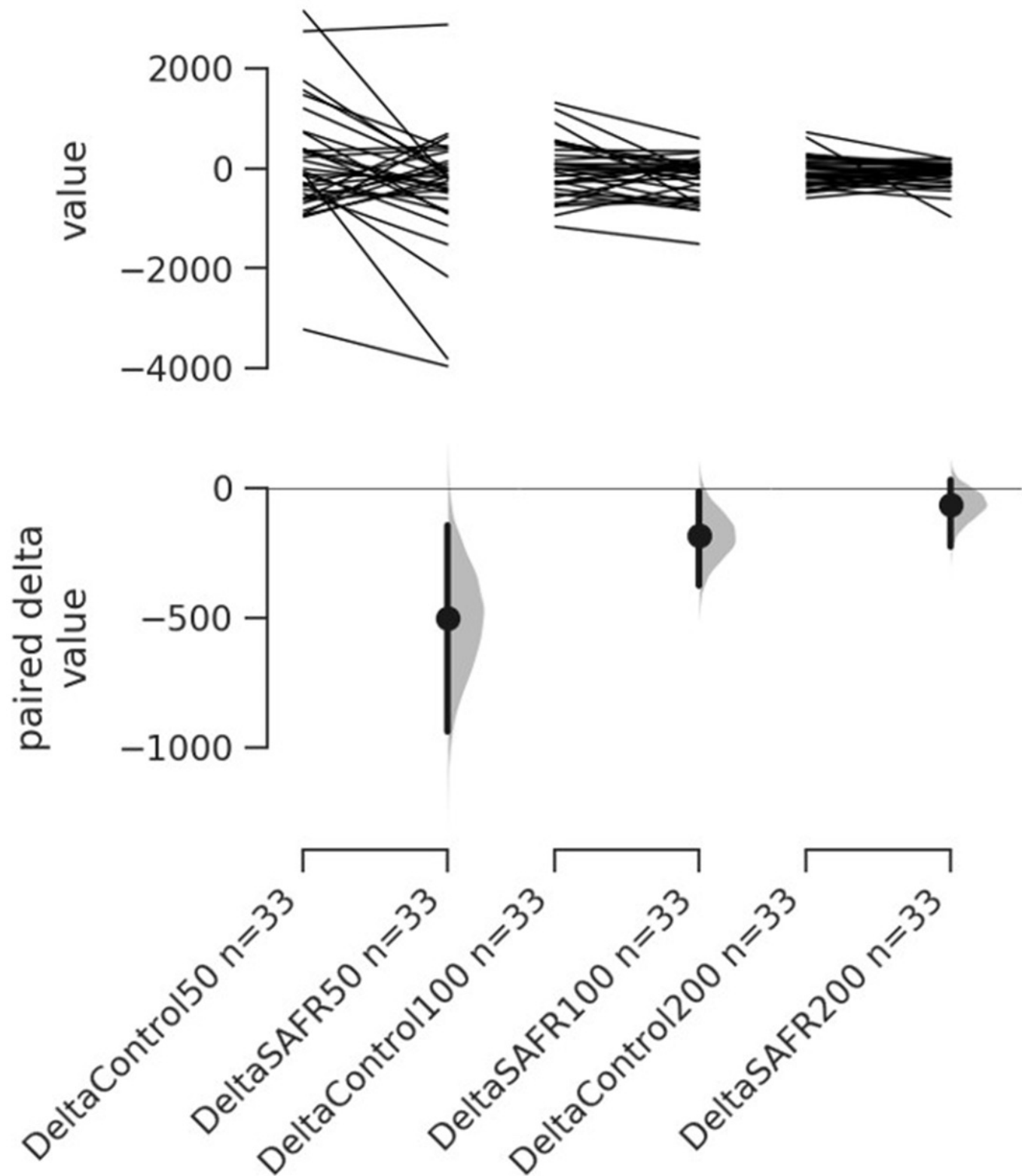
Table 1 **(on next page)**

Test-retest reliability for dependent variables

The intraclass correlation coefficient (model "3,1") (ICC (3, 1)), standard error of measurement (SEM), and coefficient of variation (CV) of variable measurements (the contralateral hip flexion passive range of motion [ROM], the contralateral biceps femoris [BF] and semitendinosus [SEMI] EMG amplitude, the contralateral knee flexion isometric strength, and the rate of force development (RFD) for the first 50 [RFD_{0-50}], 100 [RFD_{0-100}], and 200 [RFD_{0-200}] ms of the maximal isometric contraction).

1 **TABLE 1.** The intraclass correlation coefficient (model "3,1") (ICC (3, 1)), standard error of

2 measurement (SEM), and coefficient of variation (CV) of variable measurements (the

3 contralateral hip flexion passive range of motion [ROM], the contralateral biceps femoris [BF]

4 and semitendinosus [SEMI] EMG amplitude, the contralateral knee flexion isometric strength,

5 and the rate of force development (RFD) for the first 50 [RFD_{0-50}], 100 [RFD_{0-100}], and 200

6 [RFD_{0-200}] ms of the maximal isometric contraction).

Variable Measures	ICC (3,1)	SEM	CV (SEM %)
Passive ROM (°)	0.91	4.26	6.2%
Isometric Strength (N)	0.88	34.27	10.6%
EMG Amplitude of BF (µV)	0.84	31.76	23.8%
EMG Amplitude of SEMI (µV)	0.80	38.55	30.2%
RFD_{0-50} (N/s)	0.81	633.00	37.9%
RFD_{0-100} (N/s)	0.84	312.39	23.5%
RFD_{0-200} (N/s)	0.87	184.06	17.2%