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Citation: Murray, Andrew M., Jones, Thomas, Horobeanu, Cosmin, Turner, Anthony and Sproule, John (2016) Sixty seconds of foam rolling does not affect functional flexibility or change muscle temperature in adolescent athletes. *International Journal of Sports Physical Therapy*, 11 (5). pp. 765-776. ISSN 2159-2896

Published by: International Federation of Sports Physiotherapy

URL: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5046970/pdf/ijst-11-765.pdf>

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1 Title:

2 Sixty seconds of foam rolling does not affect functional flexibility or change muscle temperature
3 in adolescent athletes

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14 **Abstract**

15 Background: Foam rolling is commonly prescribed by physiotherapists and practitioners but the
16 mechanistic effects of this intervention are not known.

17 Purpose: The aim of this investigation was to establish if a single bout of foam rolling affects
18 flexibility, skeletal muscle contractility and reflected temperature.

19 Methods: Twelve adolescent male squash players were evaluated on two separate occasions
20 (treatment and control visits) and were tested on both legs for flexibility of the hip flexors and
21 quadriceps, muscle contractility as measured by tensiomyography and temperature of the
22 quadriceps assessed via thermography at repeated time points pre & post 60 s rolling intervention
23 (pre, immediately post, 5, 10, 15 & 30 minutes post). They rolled one leg on the treatment visit
24 and did not perform rolling on the control visit.

25 Results: The main outcome measure was the flexibility of hip flexor and quadriceps at repeated
26 time points up to 30 minutes post intervention. The average foam rolling force was 68% of
27 subject's body weight. This force affected the combination of hip and quadriceps flexibility
28 ($p=0.03$; 2.4 degrees total increase with foam rolling) but not each muscle independently ($p =$
29 $0.05 - 0.98$) following a single 60s bout. Muscle contractility is not affected ($p = 0.09 - 0.93$)
30 and temperature is not increased by foam rolling across time points ($p=0.19$).

31 Conclusions: A single sixty-second bout of rolling applied to the quadriceps induces a small
32 significant change in flexibility that is of little practical relevance, while muscle contractility and
33 temperature remain unchanged. Investigation of larger doses of rolling is merited in athletic
34 populations to justify current practice.

35 Level of Evidence: 2c

36 Keywords: Adolescent; Flexibility; Tensiomyography; Thermography

INTRODUCTION

37

38 The use of self-myofascial release techniques to aid recovery^{1,2} using a foam roller is increasingly
39 popular,³ particularly as it is one of the first steps used by a pro-active athlete in self-management of
40 complaints.⁴ The practice of foam rolling appears to have outpaced the scientific literature with
41 limited publications available on its use.³ Rolling is believed to have similar effects to massage,
42 which include relief of muscle tension, increased flexibility, and improved range of motion
43 (ROM).⁵⁻⁷ There are claims that foam rolling can increase blood flow and joint ROM³ although
44 such claims are mostly inferred from research that has been performed on massage.⁴ Currently there
45 are no specific recommendations regarding the duration of foam rolling.⁸ While studies have
46 been performed, none have examined the dose response of differing bouts to investigate the
47 relationship between frequency and or volume with outcome. All studies to date have used
48 multiple bouts either within or across muscles without justification. Only one study to date has
49 examined the pressure exerted on the foam roller during the activity⁹ and a separate study has
50 examined the force that is exerted through the roller.¹⁰ The differing forces through the roller and
51 subsequently muscle based on individual's technique and body mass may influence the outcome
52 from foam rolling.

53

54 Several studies have shown that ROM is improved by foam rolling.^{1,10-13} Each of these studies
55 assess the effects of foam rolling after exercise. There have been no considerations of foam rolling
56 from a starting point of no exercise in order to elucidate the mechanism for any action it may have.
57 It has been proposed that thixotropy, in which heat or pressure is applied to a material in order to
58 make it less dense and more fluid^{4,14} may contribute to the effectiveness of foam rolling.

59 If thixotropy is an important mechanism of action, the ability to quantify a temperature change that
60 an intervention induces would appear to be essential.¹⁵ Foam rolling induced changes in ROM have
61 been suggested to be associated with changes in temperature¹⁶. The use of a non-contact diagnostic
62 tool such as thermography allows for quantification of any temperature changes¹⁵ induced by foam
63 rolling that have not previously been described.

64

65 Any temperature changes may in turn affect the muscle's contractile properties such as contraction
66 time and force production.¹⁷ Tensiomyography (TMG) can evaluate the involuntary contractility of
67 the muscle and is influenced by the viscoelastic properties of the muscle. TMG has commonly been
68 used to assess the muscle damage caused by an intervention¹⁸ but has also been used to monitor
69 muscle alterations that occur following bed rest¹⁹ and to assess any effects of recovery strategies.^{20,21}
70 TMG as a technique measures the maximal radial displacement of the muscle belly via a digital
71 transducer, when a contraction is generated by an external electrical stimulus. It offers information
72 about different parameters relating to the magnitude and speed of muscle contraction and the
73 mechanical properties of skeletal muscle.²² TMG can non-invasively quantify muscle function
74 through measurement of muscle stiffness, time and speed of contraction and any subsequent
75 changes in these variables from an intervention.²³

76

77 The goal of any foam rolling or myofascial release is to influence flexibility and/or ROM.
78 Flexibility has been widely researched using a range of different methods and devices.²⁴⁻²⁶ Some
79 utilized active participants,²⁷ others passive.²⁸ Few have utilized a standardized force during
80 application^{29,30} in order to ensure that the measurement of flexibility is not simply a measure of a

81 patient's tolerance to a stretch. This ensures reliable technique with an objective end point. Foam
82 rolling is commonly prescribed by physiotherapists and applied strength and conditioning
83 practitioners but the mechanistic effects of this intervention are not known. The aim of this
84 investigation was to establish if a single bout of foam rolling affects flexibility, skeletal muscle
85 contractility and reflected temperature. The hypothesis was that flexibility would increase due to
86 foam rolling with concurrent reduction in contractility of the muscle and increases in temperature.
87 The null hypothesis was that there would be no effect of foam rolling on the measures of flexibility,
88 muscle contraction or muscle temperature.

89

90

METHODS

Subjects

92 A prospective cohort of male adolescent squash players from an elite sports school (n=12,
93 55.0±13.4 kg, 160.7±13.5 cm, 67.7±32.6 Σ8 skinfolds mm, -0.08±1.7 yrs from Peak Height
94 Velocity, 14.2±1.4 yrs) were utilized. Testing was conducted on two separate occasions
95 separated by 7-12 days. In each case testing took place following a standardized rest day. The
96 treatment leg and order was determined by an online randomization tool (sealedenvelope.com),
97 which was then matched to the 12 subjects by drawing from a hat. The study was approved by
98 both the local research and University ethics committees and conformed to the recommendations
99 of the Declaration of Helsinki.

100

Protocol

102 On one occasion (treatment) the subject performed the rolling intervention on the anterior part of
103 the thigh of one leg while the contralateral limb acted as a control and on the other occasion
104 (control) the subject lay in a prone position for the same duration but with no foam rolling to act
105 as a full control. On both occasions the intervention occurred at the start of the athlete group's
106 morning training session (1000 – 1200h) before any exercise had been undertaken and following
107 a rest day. Athletes were free from injury, and were excluded from testing if they were not able
108 to complete in all aspects of training.

109

110 Using the low and flat section of a commercially available foam roller (Figure 1A; The Grid,
111 Trigger Point, Texas, USA) the subjects performed rolling on the thigh of the treated leg. They
112 placed their body weight on the foam roller, which was placed on a force plate (400 Series Force
113 Plate, Fitness Technology, Adelaide, Australia) sampling at 600 Hz. This measured the actual
114 force applied through the roller throughout the intervention. Other than the leg on the roller (or
115 force plate in the control condition) the subjects had two points of contact with the floor, both
116 forearms placed in front of the force plate (Figure 1B). The non-rolling leg was elevated and
117 fixed in a plank position via activation of posterior chain musculature. The rolling leg did not
118 contact the floor. The body was held in a straight line with the trunk stable and the subject facing
119 the floor. The subjects started at the proximal aspect of the thigh and rolled down toward the
120 knee in one fluid motion. Upon reaching the required depth, the direction was reversed. The
121 speed was controlled by a metronome (2s per pass) and the depth was visually indicated by tape
122 on the force plate corresponding to the length of the subject's thigh. The rolling intervention
123 covered the full anterior thigh musculature from just below the anterior-superior iliac spine to
124 just superior to the patella. The duration of the rolling intervention was 60s reflecting the

125 minimum dose prescribed by physiotherapy professionals working with the athletes, meaning
126 that 30 full rolls were completed (15 in each direction).

127 *** FIGURE 1 NEAR HERE***

128 Prior to undertaking any foam rolling the subjects were asked to stand with their feet aligned to
129 markers on the floor, to ensure a consistent position (feet shoulder width apart), in front of a
130 rubber mat, to minimize reflected heat from the environment, for a thermal image to be taken to
131 assess the baseline condition of reflected temperature. Subjects were then assessed for flexibility
132 (passive ROM) of the quadriceps and hip flexors using the '*angle at force standardized*
133 *endpoint*' technique.³⁰ Subjects then underwent Tensiomyography assessment (TMG) to examine
134 the state of the muscle. These measures were repeated at 0, 5, 10, 15 and 30 minutes post
135 intervention to examine any acute effects of the foam rolling intervention, subjects lay in a
136 supine position between measures. The measures were taken from both left and right limbs to
137 allow each subject to serve as their own internal control.

138

139 Procedures

140 *Flexibility*

141 The primary outcome measure was that of hip flexor and quadriceps flexibility. The method used
142 to assess flexibility replicated the method described by Fourchet and colleagues of the '*angle at*
143 *force standardized endpoint*',³⁰ a video based method for flexibility assessment that has been
144 established to have moderate-to-good reliability when used to monitor the passive ROM of
145 adolescent athletes.³⁰ The same investigator consistently manipulated the patient and analyzed the
146 video for the angle, to minimize test-retest variance. The camera obtaining the image was always

147 perpendicular to the end of the plinth and at a distance of 3m with the same zoom setting. A
148 hand-held dynamometer (Compact force gauge, Mecmesin, Slinfold, United Kingdom) with a
149 digital scale (0.01-N increments) was used to apply the standardized force. The flexibility
150 assessments were performed with the athlete supine. For the hip flexor measurement the pelvis
151 was aligned at the end of the plinth. Following marking of identifiable anatomic landmarks with
152 a dermatological pen for easy identification on the video, the operator maintained the non-tested
153 limb in a maximally flexed position towards the abdomen, and allowed the lower limb to be
154 tested to hang off the end of the plinth in neutral rotation. The tested limb was further extended
155 with a force of 98.1N. The hip flexor measure was the angle formed between the body and the
156 extended lower limb, as measured from a digital image.

157

158 For the quadriceps measure the patient's position was adjusted so the mid-thigh was now aligned
159 with the end of the plinth. The uninvolved limb was maintained in a maximally flexed position
160 towards the abdomen and the lower limb to be tested was in neutral position. The dynamometer
161 was used to passively flex the tested knee with a force of 78.5N. The quadriceps measure was the
162 knee flexion angle, as measured from a digital image. The measurements were then repeated on
163 the contralateral side. Regardless of the treatment side the subjects left leg was assessed first at
164 each time point.

165

166 Using the digital images obtained during the tests, digital motion analysis software (Dartfish,
167 Classroom v.5.5, 2009, GEAR Software B.V., Helmond) was employed to measure the angles of
168 interest. This occurred in a blinded fashion with the angles only matched to the trials after all

169 analysis was complete. The final angles for each muscle group were measured to the nearest 0.1°
170 according to the marked anatomic landmarks. Overall flexibility of the leg was taken as the
171 combined flexibility (sum) of the hip flexor and the quadriceps angles for each limb.

172

173 *TMG*

174 For a non-invasive measure of muscle contractility, Tensiomyography was employed. This
175 technique creates radial displacement of the muscle belly in response to an electrical stimulus
176 (~100mA) conducted through the underlying muscle tissue. These displacements are recorded at
177 the surface of the skin using a spring loaded displacement sensor (TMG-BMC Ltd, Ljubljana,
178 Slovenia). The sensor was consistently retracted to 50% of its length to ensure a consistent initial
179 pressure. The sensor was positioned perpendicular to the thickest part of the rectus femoris
180 muscle belly.²² This position was established with visual inspection of the voluntary contracted
181 rectus femoris and palpation of the area.²¹ Self-adhesive electrodes were placed ~5cm on
182 opposite sides of the sensor in the sagittal plane, over the rectus femoris. Once the exact position
183 of the sensors was determined they were marked with a dermatological pen to ensure placement
184 remained constant throughout the visit. Before proceeding an acetate layer was used to mark the
185 sensor and electrode positions over the skin on each leg. This traced the placement as well as any
186 anatomical or visual landmarks for each subject to ensure consistent placement on the second
187 visit.

188

189 All measurements were performed with subjects in a supine position on a padded plinth. A
190 triangular foam wedge was placed under the knee to create a knee joint fixed at 120° angle.²¹ A

191 series of contractions of increasing amplitude (~10mA) was used to obtain a maximal response
192 i.e. no further muscle displacement could be produced as evidenced by a plateau in the twitch
193 response curves.²² Only the maximal output data were used for analysis. Maximal radial muscle
194 belly displacement (Dm), contraction time between 10 and 90% Dm (Tc) and the time taken
195 from onset of the electrical stimulus to 10% of the maximal radial displacement (delay time; Td)
196 of the rectus femoris were measured via TMG at each time point. These collective measures
197 provide a comprehensive analysis of muscle state³¹ with each representing a different facet of
198 contractility. Dm (expressed in millimeters) depends on the muscle tone or stiffness. High scores
199 indicate a lack of muscle tone (i.e. more compliant and relaxed muscle – expected after rolling).
200 The time variables (measured in ms) represent the reaction time of the muscle (Td) and the
201 subsequent time to contract (Tc). Associating the changes in Dm, Tc and Td can give insight into
202 changes caused by foam rolling (i.e. a decrease in Dm with increase in Tc and Td would suggest
203 fatigue³¹).

204

205 *Thermal Imaging*

206 Thermography is a non-invasive technique used to measure specific thermal responses at a
207 superficial level.³² The technique has previously been used to help quantify objective measures that
208 have previously required subjective feedback such as the effects of massage.^{33,34} Following
209 palpation of the area for TMG placement a 50 x 50 mm area was marked around the area where
210 the electrode was to be placed, this was marked by four strips (3 x 50 mm) of inert aluminum
211 tape (3M, Minnesota, United States) to allow measurement of a consistent region of interest from
212 the thermal images. In post processing a consistent marker was placed in the software to allow
213 assessment of the majority of the quadriceps. From the sample this size was 110 x 46 pixels. This

214 size was chosen as it covered the majority of the subject's anterior thigh without being too large
215 (i.e. it exceeded the musculature and captured the background area within the area).

216

217 An infrared camera (FLIR T600, FLIR Systems, Oregon, USA) was positioned on a level tripod
218 directly in front of the area where the subject was to be photographed at a distance of 2m. The
219 height of the tripod was consistent across all subjects and allowed a clear image of the lower half
220 of the body to be taken. The camera was allowed to stabilize in the environment 60 minutes
221 before the first picture was taken.³⁵ A constant skin emissivity was set to 0.98 in accordance with
222 previous research.³⁶ Prior to images being taken the camera was calibrated for the reflected heat
223 and ambient conditions using the protocol recommended by the manufacturer. Images were
224 taken pre the intervention, immediately post (0 minutes) and at all subsequent time points (5, 10,
225 15 and 30 minutes) with a consistent position of the subject and camera.

226

227 Statistical Analysis

228 Data are presented as mean \pm SD. A 0.05 level of confidence was selected throughout the study.
229 Statistical analyses were conducted using Minitab 17 (Minitab, Pennsylvania, United States).
230 The normality of each measure was established. Each measure in turn was assessed as the
231 independent variable against the time, condition and the interaction. A general linear model for
232 repeated measures was used to assess normalized differences between conditions standardized to
233 the Pre-condition and the force applied for each visit with factors of Time, Condition and their
234 interaction for each variable. Post-hoc analysis was undertaken using Tukey's HSD. The
235 difference between the treated leg and the control leg were normalized for each time point to the

236 initial Pre-measurement for each variable in each condition. Then the difference between the
237 treatment condition and control condition were calculated and assessed after interactions
238 between time and group were also examined.

239
240 In addition, probabilistic magnitude-based inferences about the true value of outcomes were
241 employed for variables with a practical relevance.³⁷ Dependent variables were analyzed to
242 determine the effect of the designated intervention as the difference in change following each
243 condition. To calculate the possibility of benefit, the smallest worthwhile effect for each
244 dependent variable was the smallest standardized change in the mean – 0.2 times the between-
245 subject SD for baseline values of all participants.³⁷ This method allows practical inferences to be
246 drawn using the approach identified by Batterham and Hopkins.³⁷

247
248 Inter- and intratrial reliability analyses were conducted on all dependent variables. All data used
249 for reliability analyses were obtained from the control limb. Intertrial reliability was established
250 using data obtained over the course of each individual trial. Intrasession reliability was
251 established via analyzing data from the same time points across control and treatment trials.
252 Reliability was determined using intra-class correlation coefficients (ICC), calculated using the
253 two-way random method, Pearson's correlation coefficients (r) and coefficients of variation
254 (CV) as previously described.³⁸

255
256 RESULTS

257 Flexibility

258 While there were differences between subjects for flexibility of hip flexor ($p=0.01$) and overall
259 flexibility of the leg (combined flexibility of hip flexor and quadriceps) ($p=0.01$), there was no
260 effect on quadriceps ($p=0.37$). There was no effect on hip-flexor, quadriceps or overall flexibility
261 over time ($p=0.20, 0.74$ & 0.34 respectively). For condition there was no difference on hip-flexor
262 ($p=0.62$) or quadriceps ($p=0.05$) flexibility (individually) though there was for overall change in
263 flexibility where the control condition was 2.4 degrees lower overall than the treatment ($p=0.03$).
264 There were no significant interactions for hip-flexor, quadriceps or overall flexibility ($p=0.21,$
265 0.98 & 0.31). The individual values are plotted in Figure 2 along with the mean values. The raw
266 mean values are shown by treatment and condition in Table 1.

267

268 *Magnitude based inferences*

269 There were differences practically at 15 and 30 minutes using the inferential approach. In terms
270 of flexibility there was a small effect in overall flexibility of the hip flexor and quadriceps
271 combined that was possibly trivial mechanistically at 15 minutes post. At 30 minutes this
272 difference was no longer present. While there were small changes in the hip-flexor and
273 quadriceps data at 15 minutes the practical conclusion is that there are not enough data to be
274 certain of this effect.

275

*** TABLE 1 NEAR HERE ***

276

277 TMG

278 There was no effect on Tc, Dm or Td of time (p=0.99, 0.49 & 0.76 respectively), condition
279 (p=0.10, 0.24 & 0.64), nor were there any time*condition interactions (p=0.52, 0.98 & 0.18).
280 The individual values are plotted in Figure 2 along with the mean values. The raw mean values
281 are shown by treatment and condition in Table 1.

282

283 *Magnitude based inferences*

284 There were some differences practically at 15 and 30 minutes using the inferential approach. In
285 terms of Tc there was a moderate effect that is possibly negative at 15 minutes (i.e. the rolling
286 condition increases the contraction time (slower activation)) at 15 minutes post. At 30 minutes
287 this difference was small but positive rather than negative (i.e. the rolling condition demonstrated
288 a decrease in the contraction time in comparison to the control). At 30 minutes there was a
289 moderate increase in the delay time in the treatment condition that is likely negative (i.e. rolling
290 causes the muscle to activate more slowly).

291 *** FIGURE 2 NEAR HERE***

292 Thermography

293 *Small area (23 x 20 pixels)*

294 As presented in Figure 3 it is evident that there were no differences in temperature across each
295 time point (p=0.16). There were differences between conditions with the control condition being
296 colder by 0.17°C (p<0.01), although no time x condition interaction was present (p=0.59).

297

298 *Large area (110 x 46 pixels)*

299 When analyses were performed on the entire quadriceps region a condition interaction was
300 observed ($p=0.001$) with the limb being colder in control condition (-0.15°C), although no time x
301 condition interaction was present ($p=0.08$). The raw mean values are shown by treatment and
302 condition in Table 1.

303 *** FIGURE 3 NEAR HERE ***

304

305 Force

306 Within the study $68\pm 14.7\%$ of the subject's body weight on average (36.9kg) was placed on the
307 force plate in the control condition. Within the treatment condition $50\pm 12.6\%$ of the body weight
308 (27.2kg) was directed through the foam roller into the force plate on average. The difference
309 between the treatment and control conditions mean force exerted was significant ($p<0.01$). Force
310 exerted on the force plate (and roller) was similar between subjects across conditions ($p=0.21$).
311 The treatment condition ranged from a force of 27% body mass to 67% and an absolute force of
312 15.8 to 40.6 kg. The correlation between the relative and absolute values for the treatment
313 condition was $r=0.69$. The correlation between mass and average force in the treatment condition
314 was $r=0.61$.

315

316 Reliability

317 The reliability of the flexibility assessment employed here has previously been assessed and
318 analyses indicated the measure has good reliability.³⁰ Inter- and intratrial observations for TMG
319 and thermography were all significantly correlated (all $p<0.05$). Inter- and intratrial reliability

320 statistics for TMG and thermography are presented in Table 2 along with the smallest
321 worthwhile change that may be useful for future studies.

322

323 ***TABLE 2 NEAR HERE***

324

325 DISCUSSION

326 The aim of this investigation was to establish if a single bout of foam rolling affects flexibility,
327 muscle contractility and temperature. The primary finding of this study was that foam rolling had
328 no statistically significant effect on muscle contractility markers or temperature. While the
329 overall flexibility was statistically greater in the treatment condition in practical terms this is
330 insignificant as it is within the published coefficient of variation for the test (10.6%)³⁰ or in this
331 case 12.48°. The present study controlled for force applied to the limb as has been done
332 previously,³⁹ making the end point of range of motion measurement objective, rather than
333 subjective. This may be one reason why no change in ROM was seen.

334

335 Previous authors have suggested that the mechanism that foam rolling utilizes to have an effect is
336 similar to massage although no definitive consensus regarding the exact mechanism exists.⁴ A
337 recent review has highlighted that while the performance effects of massage are limited (Hedges
338 $g=0.19$), massage can be effective if the recovery interval is short especially in untrained
339 subjects.⁴⁰ The current study attempted to examine a possible mechanism of foam rolling by
340 monitoring temperature change and while objectifying the flexibility measure in order to attempt
341 to gain greater insight into the induced muscular changes that occurred, as measured by TMG.

342

343 The current data indicate there is a small but significant change after the intervention of 1 x 60s
344 bout of rolling. However, this may have little practical relevance for intervention. Other authors
345 have used different repeated interventions (e.g. 3 x 60s¹⁶) without justification however, this may
346 indicate that multiple bouts of foam rolling have a greater influence of the musculature due to a
347 larger overall dose. Previous authors that examined flexibility measures, did not specify any
348 pressure advice nor standardization for the participants and did not demonstrate a change in
349 flexibility.^{41,42} Others that have used greater forces have shown greater increases in flexibility in
350 what seems to be a dose response relationship. Sullivan and colleagues utilized a limited force of
351 13kg and found an increase in hamstring ROM of 4.3% and when using a higher force (25% of
352 body mass; ~20kg), Bradbury-Squires and colleagues demonstrated increases in knee-joint ROM
353 by 10-16%.^{13,43} There has been no direct comparison of different pressures, however, in the
354 present study an average of 50% of body mass (27.2kg) was directed through the roller at the
355 quadriceps. The authors of the current study did observe a range of forces being applied across
356 subjects that differed in absolute terms. This is a potential source of variance – as is the change
357 in load that is observed as the roller moves longitudinally across the muscle.³⁹

358

359 This study utilized trained athletic subjects. Only one other study has investigated the effects of
360 foam rolling utilizing athletes as the subject group.⁴⁴ Previous comparisons of the chronic effects
361 of static stretching in trained and un-trained subjects have reported greater effects in untrained
362 individuals⁴⁵ and this may therefore be a factor that could explain the lack of results reported
363 both in this study and that of Mikesky and colleagues as trained athletes may already possess a

364 greater ROM due to regular exercise and stretching and therefore if the flexibility is not
365 compromised foam rolling would not induce an increase in ROM.

366

367 A criticism of the mechanistic approach of the current study may be drawn from the massage
368 literature as this suggests that effects occur at the systemic whole-body level and as such designs
369 that massage only one limb and use the contralateral as an internal control should be avoided.⁴⁶
370 The counter argument is that with the current research design the authors utilized a full control
371 condition in order to detect the true difference of any intervention. The dependent variables in
372 this research were more local than systemic in nature.

373

374 Previous literature has looked at foam rolling as an acute recovery intervention after inducing
375 muscle damage.^{2,10,47} In the current study an intervention was examined without a preceding
376 bout of muscle damage. The reason for this was to try and separate the size of any effect of foam
377 rolling itself on flexibility rather than an as an analgesic or increasing the compliance of injured
378 muscle. While it is beyond the scope of this investigation to comment at length, the eccentric
379 muscle damage induced in previous studies is not always like that encountered in athletes in
380 training in terms of scope or mechanism. Also the acute use of foam rolling immediately post
381 session is not as commonplace as its use as part of the warm up before the next session 24 or 48
382 hours later.⁴⁸

383

384 While four studies have examined the time course of flexibility changes following myofascial
385 release most are limited to 10 minutes post treatment.^{1,7,47,49} Halperin and colleagues showed

386 increased ROM at one and 10 minutes post intervention. MacDonald and colleagues reported
387 increased ROM at two and 10 minutes post-intervention. One study looked at longer time
388 periods and found no effect at 30 and 60 minutes post intervention, there was however an effect
389 after 10 minutes, however the authors did not specify the duration of rolling on the hamstrings.⁴⁷
390 Only one study has observed no effect on flexibility at 10 minutes similar to this study. The
391 study in question tested the plantar flexors and used a rolling protocol of 3 x 30s.⁴⁹

392

393 Future directions

394 Future study in the area may utilize a larger relative dose (likely through a series of repeated
395 reps) to see if this induces an effect. This dose-response relationship remains to be elucidated in
396 order to scientifically influence practitioner's prescriptions.

397

398 While the dose response relationship of volume on flexibility is unclear, it appears that there is a
399 greater effect with a greater force and most studies have found meaningful improvements with
400 around 1-2 min of treatment.⁴ While the load applied during rolling was measured, an approach
401 could be taken to use the foam roller at a standardized load on the muscle relative to the subjects
402 body weight, though this approach would likely see the subject be in a supine, passive position as
403 the force is imposed on them rather than self-applied. As such this may not have as high a
404 practical relevance. The dose response relationship seems clearer for force but again is an area
405 for future investigation.

406

407 Additionally, measures of discomfort may need to be recorded during the rolling intervention as
408 there may be a psychological effect for adolescent athletes who may experience discomfort
409 during the intervention. Also, potentially without the discomfort being of a sufficient level they
410 may not perceive it to have a benefit.^{50,51} Any future investigation should utilize a standardized
411 end point for testing flexibility or ROM that is objective rather than subjective.

412

413 The time course of the intervention was only followed up to 30 minutes post. Investigation of up
414 to one hour post may be merited as athletes utilize foam rolling within their warm ups which can
415 occur in excess of one hour prior to competition.^{52,53}

416

417 CONCLUSION

418 Foam rolling had no practically significant effect on flexibility and no effect on muscle
419 contractility markers or reflected temperature within 30 minutes of rolling. The present study
420 controlled for force applied to the limb and observed no change in ROM.

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FIGURE TITLES

552 **Figure 1:** **A.** Foam roller used in intervention (Low & Flat section) **B.** Set up of subject on foam

553 roller on force plate with points of contact (both forearms and foam roller)

554 **Figure 2:** Individual value plot of standardized differences to Pre condition based on condition

555 (treatment or control). Mean values are marked.

556 **Figure 3:** Individual value plot of standardized differences to Pre condition based on condition

557 (treatment or control). Mean values are marked as is a 1⁰C line.