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1 **ABSTRACT**

2 **Aims:** The study compares the effects of varying foam roller density (FRD) on hamstring flexibility (HF)
3 and eccentric hamstring strength (Ham_{ecc}) in active males.

4 **Methods:** Twenty-eight healthy male participants (height 176.7±5.9 cm; body mass 75.8±9.6 Kg; age
5 21.6±4.0 years) were randomly allocated to receive either a low density (TriggerPoint™, CORE roller,
6 Texas), medium density (TriggerPoint™, GRID roller, Texas), high density foam roller (FR)
7 (TriggerPoint™, GRID X roller, Texas) or allocated to a control group. Outcome measures included
8 hamstring flexibility (HF) through active knee extension (AKE) (°) and Ham_{ecc} by Nordic hamstring curl
9 exercise using the Nordbord, pre and immediately-post FR application.

10 **Findings:** Significant FR \times time interactions were found for HF ($p < 0.05$). Significant increases in AKE
11 were reported post-FR application for all FR densities ($p < 0.05$). No significant changes in strength
12 parameters (break Angle, Peak and Average Force and Torque) were found ($p > 0.05$). No significant
13 interactions between strength parameters, limb, type of roller or time were found ($p > 0.05$).

14 **Conclusions:** FR elicits immediate positive increases in HF through AKE assessment, with the lower
15 density FR displaying the largest increases in HF. No change in strength parameters were noted with the
16 increases in flexibility, however this does not denote that injury risk is reduced because of this. Findings
17 provide practitioners with insight to inform decision making for the implementation of different densities
18 of FR in practical settings.

19 **Keywords:**

20 Muscle, Sport, Strength, Recovery, Flexibility.

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22

23

24 INTRODUCTION

25 Foam Rolling (FR) is a self-myofascial release (SMR) technique prescribed by sports medicine and
26 performance practitioners thought to reduce stretch related inhibition rather than historically considered to
27 release ‘myofascial restrictions’ (Behm and Wilke, 2019). FR uses body mass to exert force over a region
28 of soft tissue via a foam roller (Cheatham et al, 2015). Manufactured in various shapes and sizes,
29 differences between surface pattern, diameter and density may influence the quality of massage on the soft
30 tissue (Cheatham et al, 2015). Several studies have explored the effects of FR, reporting changes in joint
31 range of motion (ROM) (Halperin et al, 2014; Cheatham et al, 2015; Cheatham and Stull, 2018),
32 neuromuscular recovery (Bradbury-Squires et al, 2015), pressure-pain thresholds (Cheatham and Stull,
33 2018), exercise recovery, performance preparation (Cheatham et al, 2015) and identified differences in
34 pressure between rollers (Curran et al, 2008). Recently, Wiewelhove et al, (2019) suggested the consensus
35 in the evidence base is for foam rolling to be more effective as a warm-up tool, rather than a recovery
36 strategy. Furthermore, the combinations of FR and stretching, heat or warm-up applications support current
37 interest in this area for research and applied practice for improving recovery as one example (Mohr et al,
38 2014; Oranchuk et al, 2019). Studies that consider the effects of FR on strength parameters are suggestive
39 that strength is unaffected by FR (Madoni et al, 2018; Connolly et al, 2020), which is important for injury
40 risk reduction approaches and suggestive of changes in muscle architecture in relation to joint ROM.
41 Experimental paradigms fail to fully elucidate the effect of FR on functional strength and comparison
42 between studies is difficult due to differences in methodological approaches or application of FR.
43 Furthermore, no study, to our knowledge considers the effect of varying densities as a factor on strength
44 response. Consequently, this provides limitations for a practitioner’s justification of application, posing
45 questions on performance effects, dose response, timing and optimal type of roller. Consensus for the
46 optimum protocol with regards FR for exercise preparation is lacking in the literature, with current literature
47 highlighting the need for further investigations required to define performance effect, with clarity needed
48 on the effect of varying densities of roller (Cheatham, 2018).

49 Hamstring flexibility is an essential component in sport particularly for functional movements to be
50 performed efficiently (Hoff et al, 2004). Reduced flexibility of knee and hip flexor musculature is
51 historically noted as a key factor for heightened hamstring injury risk (Henderson et al, 2010), although
52 O'Connor et al, (2019) recently suggested poor flexibility during AKE assessment of Gaelic footballers
53 was not suggestive of hamstring injury risk prediction. The historical approach is identified as a centralised
54 and simplistic aetiological explanation, with a resounding acceptance in current evidence that injury risk is
55 multifactorial (Freckleton et al, 2013), and therefore there is an ambiguity in flexibility being considered a
56 risk factor for hamstring injury alone. That said, eccentric strength and muscle pliability have been
57 indicated as key aetiological risk factors associated with sustaining hamstring injury, and improvements in
58 flexibility must be accompanied with associated functional strength gains to reduce injury risk from a multi-
59 factorial perspective (Timmins et al, 2016; Rhodes et al., 2018). Consequently, this approach may better
60 reflect typical demands of land team-based sports. Garcia-Pinillos et al, (2015) identified that limited
61 hamstring flexibility in male football players affected key performance parameters such as sprinting ability,
62 vertical jump height, agility and kicking speed, signifying the importance of hamstring flexibility and the
63 need for regular stretching to aid sports performance.

64 Despite positive physiological effects of FR and use of SMR reported in athletes and clinical practice
65 (Cheatham et al, 2015) optimal protocols with regards to roller density are yet to be established. Minimal
66 studies are available that investigate therapeutic effects of varying densities of foam rollers (Curran et al,
67 2008; Cheatham et al, 2018), and differences in methodology struggle to demonstrate consensus in
68 outcomes. Although the effects of FR are well documented research on the efficacy of parameters such as
69 cadence, technique and type of foam roller are limited, with differences in methodology across studies
70 proving difficult to decipher optimal SMR protocols. To the authors knowledge no research is available on
71 the effect of hamstring eccentric strength (Ham_{ecc}) following a bout of SMR. The aim of the current study
72 is to compare the effects of varying foam roller density (FRD) on hamstring flexibility (HF) and Ham_{ecc} in
73 active males. We hypothesized that FR would result in increases of AKE with no associated strength

74 changes in the hamstrings musculature, and that they effects would vary depending on the density of the
75 FR.

76

77 **MATERIALS AND METHODS**

78 *Participants*

79 Twenty-eight healthy male participants (height 176.7±5.9 cm; body mass 75.8±9.6 kg; age 21.6±4.0 years)
80 volunteered and were randomly allocated (randomisation.com) into a control group (CONT) or one of the
81 three FR intervention groups (low density = SD; medium density = MD; high density = HD). All
82 participants provided written and verbal informed consent to participate and completed the full study. The
83 authors confirm that the study was both reviewed and approved by the institutional review board (STEMH
84 University Research Ethics Committee) and carried out in accordance with the 2013 Helsinki Declaration.
85 To be considered as part of the appropriate sampling population, each participant met the inclusion criteria
86 of; participate in competitive team sport totalling at least 4-hours per week, of male gender and no lower
87 limb injury within 12-months. Participants were not currently applying any form of SMR at the time of
88 participation. Participants were advised not to take part in strenuous exercise of up to 48 hours before
89 participating in the study following previous protocols adopted (Lee et al, 2017b). To accommodate
90 participants normal training schedules or participation in their team sport, data collection was scheduled so
91 a minimum of 48 hours remained exercise-free before testing. This ensures standardisation throughout
92 testing to control the variability in participants activity levels prior to testing.

93

94 *Experimental Design*

95 Participants completed a familiarisation trial 7 days prior to testing to negate learning effects (Hinman.,
96 2008) and improve validity and reproducibility of results (O'Hara et al, 2012; Lim et al, 2016).
97 Familiarisation trials included repetitions of the Ham_{ecc} testing battery, hamstring flexibility testing and trial
98 repetitions of the FR. Prior to any testing all participants completed a standardised warm up consisting of
99 5-minutes cycling at submaximal intensity, and a combination of skipping, high knees and buttock kicking

100 drills, ten forward lunges per leg and two Nordic hamstring movements with low resistance (Buchheit et
101 al, 2016). All testing was completed between 13:00 and 17:00hrs to account for the effect of circadian
102 rhythm and in accordance with regular competition times (Sedliak et al, 2011).

103

104 *Assessment Procedures*

105 All measurements were collected by the same researcher throughout. Bilateral measures of hamstring
106 flexibility were quantified by performing a unilateral active knee extension (AKE) test, a highly reliable
107 test of HF (Hamid et al, 2013) quantified using a Smartphone inclinometer application. The free angle
108 measurement application (G Pro 2.3) was downloaded to the Smartphone and zeroed to the horizontal
109 position. Previous work has identified the reliability of the G Pro 2.3 with ICC reported at 0.82 – 0.92
110 (Pourahmadi et al., 2016; Keogh et al., 2019) With the patient in a supine position a starting point for
111 each trial was established by placing the Smartphone against the mid-point of the anterior tibia. The testing
112 limb was positioned in 90° of hip flexion and the knee resting in a flexed position with the contralateral
113 limb resting in hip and knee extension. The testing limb was held by the researcher on the hamstrings to
114 maintain to maintain the 90-90-degree limb position previous methods (Hansberger et al, 2019). Whilst
115 maintaining 90 degrees of hip flexion, the participant then performed knee extension to the point of
116 discomfort (Huang et al, 2010) and the angle measured. Normal ROM on the AKE test is defined as a knee
117 flexion angle of 20° or less (Cook, 2010), and angles greater than 20° have identified participants with
118 decreased hamstring extensibility (Mhatre et al, 2013).

119

120 With its reliability previously described (Opar et al, 2013), Ham_{ecc} strength metrics of peak force (PF), peak
121 torque (PT), average force (AF), average torque (AvT) were quantified using the Nordbord™ (Vald
122 Performance, Queensland). Whilst completing testing on the Nordbord™ break angle (°) was ascertained
123 by recording each trial from the sagittal plane using a Canon XA35 camera. The camera was placed on a
124 fixed stand set 3m away and 0.5m from the floor. Three reflective circular markers were attached to the
125 right greater trochanter, right lateral femoral condyle, and right lateral malleolus to calculate knee joint

126 kinematics. Minimal clothing was recommended to avoid movement of markers. Participants knelt on the
127 padded section of the NordBord with each ankle secured superior to the lateral malleolus by individual
128 braces. Participants were instructed to gradually lean forward at the slowest possible speed, maximally
129 resisting this movement with both limbs, while holding their trunk and hips in a neutral position throughout,
130 with their hands across their chest (Buchheit et al, 2016). Individual's knee position on the NordBord was
131 recorded using the integrated knee position guides with the ankle restraints at 90°, 2 cm superior to the
132 lateral malleolus to ensure the body position remained consistent between repetitions. Participants were
133 loudly exhorted to provide maximal effort throughout each repetition. A trial was deemed acceptable when
134 the force output reached a distinct peak (indicative of maximal eccentric strength), followed by a rapid
135 decline in force when the participant was no longer able to resist the effects of gravity acting on the segment
136 above the knee joint (Buchheit et al, 2016). Participants performed one set of three maximal repetitions of
137 the Nordic bilateral hamstring exercise based on previous investigations (Buchheit et al, 2016). The Nordic
138 hamstring exercise completed on the NordBord was analysed using a variation of the motion analysis
139 protocol adopted from a previous study (Lee et al, 2017a). Average and peak data was utilised for Ham_{ecc}
140 analysis. Video clips were digitized and transformed into a two-dimensional space using motion analysis
141 application software (IOS Nordics Application). Each participants' break point angle was calculated using
142 the reflective markers placed on the landmarks previously identified. The Nordic break point angle defined
143 the angle between the line joining knee and hip markers and the initial position of the participant in vertical. Break
144 angle (Θ) was determined by identifying the average of the 3 repetitions completed individually for each participant.

145
146 Pre and post FR application, Ham_{ecc} and AKE measures were taken for all participants. Each intervention
147 group received one type of FRD, either the low density (TriggerPoint™, CORE roller, Austin, Texas) (LD)
148 n=7), medium density (TriggerPoint™, GRID roller, Austin, Texas) (MD) n=7), or high density foam roller
149 (TriggerPoint™, GRID X roller, Austin, Texas) (HD) n=7). All foam rollers had the same surface pattern
150 and diameter for comparison however differed in density. The hard FRD was constructed with a hard core
151 wrapped in a firm ethylene-vinyl acetate (EVA) foam. The medium FRD had a hard-plastic core covered

152 in a comparatively softer EVA foam. Lastly, the low-density FR was manufactured with soft EVA foam
153 and without a hard core. The rolling procedure consisted of 4-bouts of 60s intervals with a recovery period
154 of 30s to allow the participants to rest their arms from supporting their body weight. The application
155 technique of FR required the participant to be seated on the floor with the roller positioned underneath their
156 dominant hamstring. The ipsilateral limb remained in a flexed position with the sole of the foot placed
157 firmly on the floor. Both arms were extended behind the body to fully support the participant's body weight.
158 The movement began with the roller at the point of the ischial tuberosity and ended at the popliteal fossa.
159 A digital timer recorded the time of each rolling session and a mobile application metronome (Soundbrenner
160 Ltd. 2018) standardised the rolling cadence at 60-beats per minute to ensure participants were able to adhere
161 to the speed (Mohr et al, 2014; Jay et al, 2014; Halperin et al, 2014; Bradbury-Squires et al, 2015).
162 Participants were instructed to remain, to the best of their ability at the speed of one second up and one
163 second down the posterior thigh and advised to place as much weight through the roller as possible (Mohr
164 et al, 2014; MacDonald et al, 2014). All participants followed the same testing order and were verbally
165 encouraged by the same researcher throughout (Marinho et al, 2015). The control group completed pre and
166 post measures with a period of 360s between measures, corresponding to the time period the intervention
167 groups completed FR for and timed with the same mobile application metronome. During the period of
168 360s the control group adopted a supine position on a plinth, whilst maintaining a knee joint angle of $\sim 60^\circ$
169 (with 0° being 'full extension') by resting their dominant limb upon the foam roller (Macgregor et al, 2018).
170 All participants were right leg dominant, determined by the limb they would naturally kick a ball with (van
171 Melick et al, 2017).

172

173 **STATISTICAL ANALYSIS**

174 A univariate repeated measures general linear model quantified main effects for FRD, time and limb.
175 Interaction effects were also quantified, and significant main effects of FRD were explored using post hoc
176 pairwise comparisons with a Bonferonni correction factor. The assumptions associated with the statistical

177 model were assessed to ensure model adequacy. To assess residual normality for each dependant variable,
178 q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardized
179 and standardised residuals were also utilised to assess the error of variance associated with the residuals.
180 Mauchly's test of sphericity was also completed for all dependent variables, with a Greenhouse Geisser
181 correction applied if the test was significant. Partial eta squared (η^2) values were calculated to estimate
182 effect sizes for all significant main effects and interactions. Partial eta squared was classified as small
183 (0.01–0.059), moderate (0.06-0.137), and large (>0.138) (Cohen, 1988). All statistical analysis was
184 completed using PASW Statistics Editor 26.0 for windows (SPSS Inc, Chicago, USA). Statistical
185 significance was set at $p \leq 0.05$, and all data are presented as mean \pm standard deviation.

186

187 RESULTS

188

189 Mean scores and standard deviations bilaterally for each strength metric quantified (PT, PF, AvT, AVF and
190 °) and AKE performance post FR intervention are seen in Table 1.

191

192 ****Insert Table 1 Here****

193

194 AKE

195 Figure 1 summarises the effects of low, medium and high-density FR on AKE pre and post application.
196 There was a significant main effect of time post FR ($F=59.79, p \leq 0.001, \eta^2=0.384$), with bilateral post-FR
197 values significantly higher post FR ($p \leq 0.001$) for all densities of roller. There were no significant
198 differences between limb identified for any group ($p > 0.05$). The control group displayed no significant
199 increase bilaterally in post AKE measures ($p > 0.05$). There was a significant FR \times time interaction
200 ($F=5.348, p=0.002, \eta^2=0.143$). No other significant interactions were displayed between limb \times time, limb
201 \times roller density ($p > 0.05$). Collapsing of the data to analyse the effect of FR density displayed significant

202 increases in range post FR intervention (Low Density: $F=23.47$, $p\leq 0.001$, $n^2=0.494$; Medium Density:
203 $F=30.57$, $p\leq 0.001$, $n^2=0.560$; Hard Density: $F=9.11$, $p= 0.006$, $n^2=0.275$).

204

205 *****Insert Figure 1 Here*****

206

207 *Eccentric Hamstring Strength*

208 Pre and post measures of PT, PF, AvT, AvF and ° are summarised in Figures 2-4. There was a significant
209 main effect for density of roller bilaterally for PT ($F=3.6$, $p<0.01$, $n^2=0.384$) PF ($F=3.137$, $p<0.05$,
210 $n^2=0.089$) AvF ($F=4.427$, $p<0.05$, $n^2=0.122$) AvT ($F=4.293$, $p<0.05$, $n^2=0.118$), and ° ($F=4.107$, $p<0.01$,
211 $n^2=0.204$), but no significant effect of time for any of these strength metrics ($p>0.05$). No significant
212 difference between pre and post measures were found for PT, PF, AvT, AvF and ° for any group ($p>0.05$).
213 There were also no significant differences between limb detected for any group ($p>0.05$). No significant
214 interactions were detected across any of the quantified strength metrics, limb or FR density ($p>0.05$).
215 Collapsing of the data to analyse the effect of FR density displayed no significant effect on eccentric
216 strength metrics post FR intervention ($p>0.05$)

217

218 *****Insert Figure 2 Here*****

219 *****Insert Figure 3 Here*****

220 *****Insert Figure 4 Here*****

221

222 **DISCUSSION**

223 The aim of the present study was to investigate the effects of varying densities of FR on HF and Ham_{ecc}
224 parameters in physically active males. The main findings from this body of work highlighted significant
225 improvements in HF quantified via AKE immediately-post a 5-minute bout of FR applied to the hamstring
226 musculature. These significant improvements were identified across all FR groups, with varying mean
227 percentage improvements bilaterally in HF displayed in relation to density of roller (low: 23% and 23%;

228 medium: 18% and 21%; high: 16% and 12%, left and right hamstrings respectively). Results identified that
229 the low-density FR displayed the largest increases in AKE measures. Although, it is important to note that
230 each participant was not exposed to all densities of roller in the present body of work. In addition, no
231 significant differences were identified between pre and post FR measures for any of the strength parameters
232 taken in line with previous literature (Madoni et al., 2018) and supporting our hypothesis. Literature has
233 identified that injury risk is heightened when increases in flexibility are not accompanied with associated
234 functional strength gains (Timmins et al, 2016). Significant differences between FR densities were
235 identified when analysing Ham_{ecc} strength metrics, however these differences are best explained by each
236 group within the present study representing a separate cohort of participants. Thus, only identifying there
237 were significant differences between groups of their strength outputs, which is represented by each groups
238 mean values. Further work should consider analysing the individual effect of FR on HF and Ham_{ecc} strength
239 metrics.

240
241 Previous research has identified that FR improves ROM across a range of joints (Bushell et al, 2015;
242 Cheatham et al, 2018; Mohr et al, 2014, MacDonald et al, 2013; Škarabot et al, 2015). Importantly the
243 current study does not assess or comment on resultant strength changes as a result of FR. This is an
244 important factor to consider, as it influences when FR may be more appropriate in terms of optimal
245 application. Hamstring injury risk is multi factorial, with flexibility and functional strength being identified
246 as two key aetiological factors (Freckleton et al, 2013). It is a common misconception in the field that
247 increases of both factors reduces injury risk (Timmins et al., 2016). Recent literature has identified that
248 increases in flexibility have been associated with reductions of functional strength through range, and thus
249 increased injury risk (Opar, 2013; Timmins et al, 2016). This body of work highlighted changes in muscle
250 architecture as a key aetiological factor, with ^o representing a metric to provide insight into this factor within
251 the present study (Greig., 2008; Rhodes et al., 2018; Rhodes et al., 2020). The present body of work
252 identified no significant changes in functional strength metrics and break angle despite increases in
253 flexibility. The consequences of these findings in a sporting context may lead practitioners to interpret that

254 no change in pre and post strength measures, with increases in flexibility mean that FR contributes to
255 reducing injury risk and may therefore be a good preparation tool for sports performance.

256

257 Solely analysing strength parameters such as AvF, PF, PT and AvT, alongside resultant improvements in
258 flexibility would suggest FR pre-training could potentially reduce injury risk. Increases in flexibility
259 without increases in break angle however may heighten injury risk (Opar, 2013; Timmins et al, 2016). This
260 risk would be relative to each individual athlete and consideration needs to be given to break angle in
261 conjunction with the athletes ROM. This approach supports recent findings by Oranchuk et al (2019) in
262 terms of individual application prescription of such therapeutic or recovery modalities. Further research is
263 required in this area and should consider a multi factorial individualised approach and longer-term effect
264 on muscle architectural changes. Consideration must be given to individual athlete analysis within practical
265 environments. This should drive decision making in relation to injury risk reduction strategies and when
266 FR should take place.

267

268 It is suggested that the increase in HF was caused by a tissue relaxation effect brought on by the direct
269 pressure of the foam roller to produce local mechanical effects. Future work should consider quantifying
270 longer-term effects of FR application and physiological mechanisms that may rationalise current findings.
271 Theorised by Krause et al, (2017), local pressure of the foam roller may affect the viscoelastic properties
272 of myofascia enabling a greater stretch to be achieved. Research has demonstrated that FR acutely
273 decreases arterial stiffness and improved vascular endothelial function, which induces a tissue relaxation
274 effect enabling a greater flexibility score to be achieved (Okamoto et al, 2014). Furthermore, ROM changes
275 may be caused as a result of a combination of other mechanisms. Such mechanisms have been postulated
276 by numerous authors (MacDonald et al, 2013; Mohr et al, 2014, Bradbury-Squires et al, 2015; Cheatham
277 et al, 2015), with little scientific evidence to support, therefore, should be met with skepticism. Theories in
278 the aforementioned work include changes in the thixotropic property of the myofascia, increases in

279 intramuscular heat and blood flow, changes in muscle spindle length, stretch perception, physical
280 breakdown of scar tissue and remobilisation of myofascia. Measuring or quantifying many of these factors
281 is impossible and conclusions drawn in the listed literature are questionable. Although the present study
282 identifies changes in muscle length, the longevity and cause of these changes in ROM are unknown and the
283 only conclusion drawn is that they are associated with FR.

284
285 Other stretching modalities have been shown to be detrimental when preparing for athletic performance,
286 such as static stretching (Fletcher et al, 2004; Wallmann et al, 2005). Results from the current study
287 demonstrate increases in hamstring flexibility, with no change reported within functional strength metrics.
288 It is important to note that the low-density FR elicited the biggest percentage change from pre to post
289 measures of flexibility. Reasons for this are unclear, however it is suggested that this may have been due
290 to the amount of pressure the participant can exert through the tissue when rolling on varying densities or
291 potentially the perception of the participants roller. The present study utilised different participants within
292 each group assigned and future work should consider a mixed method cross over design, with additional
293 measures of pressure of rolling and perception. Perceptually if participants felt they could apply more
294 pressure to a lower ('softer') FR then greater effects on tissue response, supporting the theory presented
295 earlier by Krause et al, (2017) may have occurred, resulting in a greater increase in HF in the current study.
296 Sports persons may consider the inclusion of FR as part of their routines to improve hamstring flexibility.
297 Caution must be taken however, in relation to injury risk reduction and improvements in flexibility, which
298 must be closely analysed in conjunction with break angle in association with other strength parameters.
299 Isolation of strength parameters of force and torque alongside increases in flexibility can be misleading and
300 misinterpretation of what these metrics represent can heighten injury risk.

301
302 Whilst findings in the current study provide insight for sports medicine and performance practitioners as to
303 the differences between FR densities and their effects on HF and Ham_{ecc} in active males which may be

304 advantageous to sport recovery or injury risk reduction strategies, there are limitations to the study. Results
305 may only be generalised to active males rather than elite populations, athletes or the female gender, with
306 each group representing a relatively small population. Future work should consider the completion of a
307 power calculation to identify optimal participant numbers. It is important to note that post FR strength and
308 flexibility measures were taken immediately post rolling in the current study. Thus, the lasting effects of
309 varying densities of FR are unknown with inconsistent results noted in literature suggesting that lasting
310 physiological impacts from repeated or single bouts of FR applications last between 1-3 weeks, suggesting
311 a dose-response which requires further investigation (Macgregor et al, 2018). Future studies may consider
312 observing the latent effects of these applications to determine the length of impact on HF or Ham_{ecc}. It
313 would be beneficial to report actual density values of the products utilised to determine how different they
314 are; however, density values are not reported by the manufacturer and hence the terminology of low,
315 medium or high is reported in the current study.

316

317 **Conclusion**

318 A controlled bout of FR elicits immediate positive increases in hamstring flexibility, but has no effect on
319 strength measures of PT, PF, AvT, AvF or °. Practitioners interpretation of these findings are important, as
320 it cannot be assumed that because there are no changes in strength metrics that the athlete is at a lower
321 injury risk and careful consideration must therefore be given to when FR is performed. In addition, the
322 lower density of FR displays the largest increases in flexibility which suggests varying densities of FR elicit
323 differences in functional response. Consequently, choice of FR depending on treatment or recovery aim
324 could be disseminated more accurately to athletes' requirements individually to support performance in
325 terms of readiness to train or play. Findings advocate that clear reasoning and justification for the use of
326 FR is necessary for optimal application. Future research that considers both physiological and
327 psychological effects of FR, with quantification of pressure during FR application may provide further
328 insights into optimizing modality choice for recovery approaches in sport.

329

330 **Key Points**

- 331 1. A bout of foam rolling to the hamstrings increases flexibility but no effect on muscle strength
332 parameters in a population of males.
- 333 2. Consideration as to the periodisation of foam rolling is important as it cannot be assumed that no
334 effect on strength metrics defines a lower risk of injury.
- 335 3. Lower density of foam roller demonstrates a greater increase in hamstring flexibility.
- 336 4. Choice of foam roller density is reliant on the therapeutic aims of treatment or recovery however
337 lower density foam rollers may be preferable for greater improvements in flexibility by sports
338 medicine or performance practitioners.

339

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458

459 **FIGURE CAPTIONS**

460

461 **Figure 1.** Active Knee Extension (AKE) (°) quantifying hamstring flexibility for each group (Control, Low,
462 Medium and High FR Densities) and limb, at Pre and Post-FR application timepoints. * = Significant
463 differences reported pre-post.

464 **Figure 2.** Average (AvT) and Peak Torque (PT) for Each Group (Control, Low, Medium and High FR
465 Densities) and limb, at Pre and Post-FR Timepoints. * = Significant differences reported pre-post.

466 **Figure 3.** Average (AvF) and Peak Force (PF) for Each Group (Control, Low, Medium and High FR
467 Densities) and limb, at Pre and Post-FR Timepoints. * = Significant differences reported pre-post.

468 **Figure 4.** Breaking Angle (°) for each group (Control, Low, Medium and High FR Densities), for Pre and
469 Post-FR application timepoints. * = Significant differences reported pre-post.

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