

1 **Manuscript Title** Lower-limb muscle excitation, peak torque and external load responses to a 120-
2 minute treadmill-based soccer-specific simulation

3
4
5

6 **Authors** Adam Field¹ · Richard Michael Page² · Liam Corr¹ · Robert Naughton¹ · Matthew Haines¹ ·
7 Liam David Harper¹ · Sean Hudson¹

8

9 ¹ School of Human and Health Sciences, University of Huddersfield, Huddersfield, HD1 3DH, United
10 Kingdom.

11 ² Department of Sport & Physical Activity, Edge Hill University, St. Helens Road, Ormskirk,
12 Lancashire, L39 4QP, United Kingdom.

13

14 **Funding**

15 This research did not receive any specific grant from funding agencies in the public, commercial, or
16 not-for-profit sectors.

17

18 **Ethical approval**

19 Institutional review board approval was granted for this study.

20

21 **Acknowledgements**

22 The authors gratefully appreciate the efforts of the participants.

23

24

25 **Author responsible for correspondence:**

26 Mr Adam Field

27 Address as above

28 +44 (0) 1484 471157

29 Twitter: @acfield1992

30 Email: Adam.Field@hud.ac.uk

31 ORCID: 0000-0002-2600-6182

32 **Abstract**

33 **Purpose** The aim of this study was to investigate thigh musculature excitation and torque generation in
34 response to soccer-specific exercise incorporating an extra-time (ET) period. **Methods** Twelve semi-
35 professional soccer players performed 120-min treadmill-based soccer-specific exercise. Surface
36 electromyography (EMG) signals for the rectus femoris (EMG_{RF}) and biceps femoris (EMG_{BF}) were
37 measured as the mean response across a pre-determined 10-second sprint bout during each 15-min block
38 of exercise. Peak eccentric torque of the knee flexors (eccKF) and concentric torque of the knee
39 extensors (conKE) were recorded across angular velocities of 60, 180 and 270 deg·s⁻¹ immediately pre-
40 and post-exercise. Tri-axial PlayerLoad™ (PL-T) was monitored throughout exercise and defined
41 across vertical (PL-V), anterior-posterior (PL-AP) and medial-lateral (PL-ML) planes of motion.
42 **Results** A reduction in normalised EMG_{RF} amplitude was evident at 105–120 min, versus 0–15 min
43 (–12.5%; *p*=0.037), 15–30 min (–12.5%; *p*=0.047) and 45–60 min (–14%; *p*=0.030). Peak torque of
44 the eccKF was significantly reduced from pre- to post-exercise at 60 (–7.7%; *p*=0.018), 180 (–10.5%;
45 *p*=0.042) and 270 deg·s⁻¹ (–7.5%; *p*=0.034). A main effect for time was identified for PL-T (*p*<0.010),
46 PL-V (*p*=0.033) and PL-AP (*p*<0.010). **Conclusions** These findings suggest that muscle excitation of
47 the rectus femoris is reduced during ET, accompanied with a deficit in the torque generation of the knee
48 flexors following 120 min of soccer-specific activity. Practitioners should adequately condition players
49 for the additional ET period by incorporating exercises into training schedules that develop fatigue-
50 resistant eccentric hamstring strength to minimise injury risk.

51

52

53

54

55

56

57 **Keywords** EMG · Strength · Efficiency of movement

58 **Introduction**

59 Soccer is characterised by an intermittent activity profile, involving rapid changes of direction,
60 accelerations, decelerations and sprints. While soccer is traditionally competed over 90 min, several
61 tournaments (e.g., FIFA World Cup, UEFA Champions League and English FA Cup) proceed to an
62 additional 30 min period known as extra-time (ET) when scores are tied. Notably, during the previous
63 four FIFA World Cup competitions 33% of knockout phase matches have proceeded to ET, with 50%
64 requiring 120 min of match-play at the 2014 FIFA World Cup competition (Harper, Fothergill, West,
65 Stevenson, & Russell, 2016). Match-play observations suggest that external workload (i.e., total and
66 high-speed distance covered, as well as number of sprints, accelerations and decelerations) is reduced
67 relatively ($\text{m}\cdot\text{min}^{-1}$) during ET compared to the initial 90 min (Peñas, Dellal, Owen, & Gómez-Ruano,
68 2015; Russell, Sparkes, Northeast, & Kilduff, 2015). It is likely that these performance decrements are
69 exercise induced as a result of peripheral and central fatigue-related processes (Brownstein et al., 2017;
70 Thomas et al., 2017).

71

72 Peripheral fatigue corresponds to a reduced muscle contractility occurring at the neuromuscular
73 junction/within muscle, whereas central fatigue originates at the central nervous system; reducing
74 activation of motor neurons, which can manifest as diminished muscular activation (Brownstein et al.,
75 2017; Thomas et al., 2017). Previous research suggests that simulated and actual match-play elicits a
76 deficit in knee extensor force production (peripheral fatigue), alongside a reduction in neural drive from
77 the central nervous system (central fatigue) (Brownstein et al., 2017; Thomas et al., 2017). It has also
78 been observed that 120 min of simulated soccer causes peripheral and central patterns of fatigue, with
79 additional reductions in voluntary muscle activation identified during ET, indicating fatigue during this
80 additional period may be primarily of central origin (Goodall et al., 2017). However, the exact within-
81 match fatigue source has yet to be investigated across 120 min of soccer-specific exercise. This may be
82 because measuring the precise origin of fatigue is difficult due to the complex interaction of the
83 biological and psychological processes, and as such several indirect methods of assessment are often
84 used such as subjective scales (Harper et al., 2017; Field et al., 2020), physical performance indices

85 (Goodall et al., 2017; Thomas et al., 2017) and muscle activation measurements (Rahnama et al., 2006;
86 Page et al., 2019).

87

88 The reduction in lower-limb force production following prolonged intermittent activity has previously
89 been linked with modified twitch contractility properties that can impair torque production and changes
90 in muscle excitation measured through an electromyography (EMG) signal (Gibson, Lambert &
91 Noakes, 2001; Rahanama et al., 2003; Rahanama, Lees & Reilly, 2006). It has been demonstrated that
92 90-min treadmill-based soccer activity elicits muscle contractile deficits in knee extensors and flexors
93 (Rahanama et al., 2003), and changes in muscle excitation of the lower limbs, measured via surface
94 EMG (Rahanama, Lees & Reilly, 2006). A reduction in excitation of the lower-limb muscles appears
95 to be further exacerbated by repeated bouts of a soccer simulation with minimal recovery, mimicking
96 fixture congestion (Page et al., 2019). Thereby, while there appears to be a detrimental effect of 90 min
97 of soccer-specific exercise and simulated fixture congestion on muscle excitation, no previous studies
98 have assessed the potentially deleterious impact of an ET period on muscle excitation measured using
99 surface EMG.

100

101 PlayerLoad™ (PL), a software-derived metric (Catapult Innovations, Australia), is an applied and
102 sensitive measure that accounts for the demanding speed changes (i.e., accelerations and decelerations)
103 accrued across three-planes of motion (Barret et al., 2016; Nicolella, Torres-Ronda, Saylor, &
104 Schelling, 2018). Previous studies incorporated standardised bouts of activity throughout simulated
105 match-play and identified an increased PL during the latter stages of 90 min (Page et al., 2015), which
106 has shown to persist into the ET period (Field et al., 2020). An increase in PL values across standardised
107 bouts of motorised treadmill-based exercise is indicative of impaired movement efficiency (Field et al.,
108 2020). This has previously been linked with an increased energy cost to perform a fixed bout of activity,
109 causing players to become biomechanically less efficient whilst running (Wilk, Nau & Valero, 2009).
110 Although, such adjustments in running gait are performed subconsciously to conserve energy, this can
111 result in a reduction in lower extremity stiffness and an increased injury susceptibility of soft tissues
112 (Hughes & Watkins, 2008). However, microsensor technology placed at the upper trunk has yet to be

113 validated in relation to quantifying injury-risk and sport-specific movements (Chambers, Gabbett, Cole,
114 & Beard, 2015). Similarly, it is contentious as to whether the within-match changes in PL and discrete
115 planar contributions are reflective of running patterns in relation to specific lower-limb musculature
116 (Cormack, Mooney, Morgan, & McGuigan, 2013; Verheul et al., 2019). Additionally, the devices that
117 are used to measure PL in an applied soccer setting, typically involves placement in a vest worn by
118 players. Therefore, PL has more application in a sporting context due to the ease of measurement
119 compared with less feasible alternatives such as EMG and isokinetic peak torque measures. Therefore,
120 assessing PL metrics in conjunction with excitation and torque responses of major lower-limb muscles
121 appears warranted to provide practically compatible alternatives. This will in turn facilitate our
122 understanding of whether PL changes correspond with local fatigue patterns of thigh musculature
123 during prolonged intermittent activity.

124

125 Due to various contextual factors and the changing demands of soccer match-play, it is often difficult
126 to identify mechanisms associated with reductions in physical performance and injury-risk profiles.
127 Consequently, soccer simulations are used to control the external influences associated with soccer
128 matches (Castellano, Blanco-Villaseñor & Alvarez, 2011). To overcome the self-pacing elements
129 associated with soccer match-play, treadmill-based simulations have been used to standardise the
130 activity profile throughout exercise, such that the responses are a result of a reduced physical capacity
131 as opposed to alterations in the activity profile (Grieg et al., 2008; Page et al., 2016). Accordingly,
132 treadmill-based soccer simulations using fixed bouts of activity might provide a better tool than free-
133 running simulations to investigate the change in physical capacity (Page, Marrin, Brogden, & Greig,
134 2015). In support of treadmill-based running, when comparing a free running simulation that
135 incorporates changes of direction with treadmill running; they appear to be largely comparable in
136 relation to kinematic, kinetic, spatiotemporal, musculotendinous and muscle activation outcomes
137 (Azidin, Sankey, Robinson, & Vanrenterghem, 2013; Van Hooren et al., 2019).

138

139 In light of the above, the aim of the present study was to assess thigh musculature excitation and peak
140 torque production, as well as changes in PL metrics in response to 120-min of treadmill-based soccer-

141 specific exercise. It was hypothesised that ET would reduce the degree of excitation and torque
142 production of the thigh musculature, and that this additional 30 min period would elicit increases in PL
143 values.

144

145 **Material and Methods**

146 Participants

147 Institutional ethical approval was granted, and the study adhered with the most recent version of the
148 Declaration of Helsinki. Twelve semi-professional soccer players (mass: 74 ± 8 kg; height: 179 ± 3 cm;
149 age: 22 ± 3 years; maximal oxygen uptake [$\dot{V}O_{2\max}$]: 59 ± 7 ml·kg·min⁻¹) provided written informed
150 consent. An *a priori* power calculation was undertaken (GPower v3.1; Germany) which deemed a
151 sample size of 11 sufficient based on 95% power ($1 - \beta$), an alpha (α) of 0.05, and a large effect size
152 (Cohen's $d = 1.1$) to detect significant differences for EMG based on previous data (Page et al., 2019).
153 Participants were recruited on the basis they were male with > 5 years of soccer experience and had no
154 medical contraindications to exercise (e.g., musculoskeletal injury). Participants visited the laboratory
155 on three separate occasions and were to avoid strenuous exercise external to the study throughout this
156 testing period. Participants refrained from caffeine for 12 h and alcohol 24 h prior to testing. Mean
157 participant energy and macronutrient intake was recorded across the 24 h period prior to testing through
158 use of weighed food diaries (energy: 1998 ± 490 Kcal, carbohydrates: 218 ± 66 g, protein: 111 ± 45 g,
159 fat: 75 ± 19 g).

160

161 Preliminary visits and study design

162 The preliminary visit involved taking anthropometric measures of height (SECA 213 portable
163 stadiometer, SECA, Germany) and mass (SECA 875 electronic flat scale, SECA, Germany), and the
164 completion of a $\dot{V}O_{2\max}$ test. This involved a graded ramp test until volitional exhaustion in order to
165 assess participant's eligibility. A secondary visit was used for familiarisation, which included a full
166 habituation of experimental procedures including the completion of a 120 min simulation. This was
167 preceded by a standardised treadmill-based warm-up that consisted of 10 min of aerobic activity with
168 multiple sporadic speed changes and a dynamic stretching sequence. One week thereafter, the third and

169 final visit involved the main trial. This included the 120 min soccer simulation following the completion
170 of the same warm-up as described above. During the main trial, *ad libitum* intake of a carbohydrate–
171 electrolyte solution was permitted (Lucozade Sport, GlaxoSmithKline, Gloucestershire, UK).
172 Participants ingested a mean of 729 ± 28 ml.

173

174 Soccer simulation

175 The soccer simulation was performed on a treadmill (h/p/ cosmos pulsar® 3p: h/p/cosmos sports &
176 medical GmbH, Germany) consisting of eight 15 min periods, with a HT period interspersing the 3rd
177 and 4th and a 5 min passive rest interspersing the 6th and 7th periods. The protocol was validated
178 alongside 90-min of match-play (Page et al., 2015). Two additional bouts were incorporated for the ET
179 period, with the PL responses demonstrating very strong reliability over 120 min (Pearson’s correlation
180 coefficient = 0.75–0.92; Field et al., 2020). Participants completed 16.26 km during the 120-min
181 protocol (Field et al., 2020), with the activity profile designed to replicate the velocities, durations, and
182 frequencies of speed changes associated with match-play (Page et al., 2015). The simulation repeated
183 the same fixed activity profile every 15 min (Table 1) and data were analysed accordingly. The activity
184 profile was standardised to minimise the potential inertial delay associated with instantaneously
185 reaching the desired velocities on a treadmill (Yao et al., 2019). The 120 min simulation was divided
186 into eight epochs including: E1 (00:00–14:59 min), E2 (15:00–29:59 min), E3 (30:00–44:59 min), E4
187 (45:00–59:59 min), E5 (60:00–74:59 min), E6 (75:00–89:59 min), E7 (90:00–104:59 min), E8
188 (105:00–119:59 min).

189

190 ***INSERT TABLE 1***

191

192 Surface electromyography

193 The EMG signal of the rectus femoris (EMG_{RF}) and biceps femoris (EMG_{BF}) of the dominant leg
194 (defined as the preferred kicking leg) were recorded using wireless surface EMG sensors (Inter-
195 electrode distance 10mm; Trigno™, Delsys, USA). In accordance with recommendations for surface

196 EMG sensor placement procedures (Stegeman, Blok, Hermens & Roeleveld, 2000), the skin was shaved
197 and cleaned prior to electrode attachment to reduce impedance. To ensure that movement artefacts were
198 minimal, the electrodes were carefully taped to the skin using surgical tape. The EMG activity was
199 recorded at 2000Hz and processed using Delsys software. In accordance with the methods of Page et
200 al., (2019), the EMG signal was recorded over a single 10-second action within each 15-min bout of
201 the soccer simulation to capture the myoelectric activity for the entire acceleration and deceleration
202 phase (running velocity of 25 km·h⁻¹). An example of the EMG_{RF} and EMG_{BF} data obtained from a
203 single participant across the initial (E1) and final (E8) 10-second sprint bout is provided in Figure 1.
204 This specific action was chosen in accordance with the injury etiology of the knee flexors being mainly
205 associated with the deceleration stage during the late swing phase of sprinting (Chumanov et al., 2012;
206 Setuain, Lecumberri & Izquierdo, 2017).

207

208 ***INSERT FIGURE 1***

209

210 To process the EMG data, the raw EMG signals were low pass filtered at 500Hz and high pass filtered
211 at 10Hz to preclude movement artefacts, using a Butterworth fourth order filter. The signal was then
212 rectified and smoothed using a root mean square (RMS) smoothing factor with a 50-ms time constant
213 (Hader et al., 2014). The mean RMS value was obtained for each 10-second recording to quantify the
214 mean EMG (the degree of muscle excitation) for each bout of the soccer simulation (Rahnama et al.,
215 2006; Page et al., 2019). The amplitude mean was analysed as opposed to the single peak data point
216 because it is a more stable reference value, and less sensitive to duration differences across intervals
217 (Konrad, 2005). The EMG signal recording for the pre-determined sprint during E1 was used as the
218 reference value for normalisation of E2–E8. Similar to previous methods (Pincivero, Aldworth,
219 Dickerson, Petry & Shultz, 2000), a decision was taken to normalise against the first sprint because
220 participants were likely in a less fatigued state during the initial bout of activity and sprint measures are
221 more functionally relevant than an isolated maximal voluntary contraction. The normalised EMG data
222 were expressed as a percentage of the mean value obtained during E1. This method was undertaken in
223 accordance with recommendations for the normalisation of EMG amplitudes (Besomi et al., 2020).

224 Isokinetic testing

225 Peak eccentric torque of the knee flexors (eccKF) and peak concentric torque of the knee extensors
226 (conKE) were measured immediately post warm-up/pre-exercise and post-exercise using the Cybex
227 HUMAC Norm isokinetic dynamometer with HUMAC2009 software version 0.8.4 (CSMI, USA). The
228 agonist-antagonist relationship of the eccKF/conKE are often used to detect imbalances with a low ratio
229 being associated with an aetiological risk factor for hamstring injury (Rahnama, Lees & Bambaecichi,
230 2005). Knee flexor strength deficits as a result of fatigue are commonly observed during the latter stages
231 of simulated and actual match-play (Greig, 2008; Small, McNaughton, Greig & Lovell, 2010). During
232 the eccentric phase of contraction, injury risk is heightened as fatigued muscles are more likely to suffer
233 stretch injuries due to an impaired capacity to resist over lengthening (Croisier et al., 2008; Opar,
234 Williams & Shield, 2012). The preferred kicking leg was tested at three respective angular velocities of
235 180, 270 and 60 deg·s⁻¹. This specific order was used to reduce potential fatigue induced by slower
236 velocities (Greig, 2008). One set was performed for each speed (i.e., three sets) which included five
237 repetitions completed through a range of 0–90° (0° equal to full extension) and were interspersed by a
238 30-second passive rest period. Once seated, participants were secured, and the contralateral limb was
239 isolated as per manufacturer guidelines. To account for the influence of the participants limb weight to
240 subsequent torque generation, the HUMAC2009 software automatically performs a gravity correction
241 procedure. This involves the participant's passive limb being weighed at anatomical zero (defined as
242 full knee extension). Due to several factors, the participants are not always able to achieve a limb
243 position which is exactly horizontal to the ground. As such, the software corrects for angular error from
244 the horizontal using the following equations:

245 **Limb weight = Torque measured/ Sine(angle)**

246 During the test, the limb weight contribution is then calculated as:

247 **Torque correction value = Limb weight calculated above * Sine(angle)**

248 *Note. The (angle) refers to the angle from horizontal at which the limb weight measure was initially*
249 *performed.*

250 The limb is working against gravity (i.e., eccentric knee flexor and concentric knee extensor work
251 involves an upward motion) and, as such, the limb weight contribution value for each participant is
252 subsequently added as a constant value to their torque curves.

253

254 PlayerLoad™

255 A portable accelerometer (Kionix KXPA4, Kionix Inc., Ithaca, NY, USA), integrated within a GPS-
256 unit (OptimEye S5, Catapult Innovations, Scoresby, Australia), continuously recorded PL data at
257 100Hz. PlayerLoad™ is a vector magnitude calculated as the square root of the instantaneous rate of
258 change in acceleration across individual planes of motion and divided by a scaling factor (Graham,
259 Zois, Aughey & Duthie, 2019). The same device was used between simulations as intra-device test re-
260 test has demonstrated good reliability as evidenced by low coefficient of variations (CV: 0.01–3.0%)
261 and intra-class-correlations (ICC: 0.77–1.0; Nicoletta, Torres-Ronda, Saylor & Schelling (2018)). This
262 device was placed directly inferior to the 7th cervical vertebrae inside the pouch of a tightly fitted
263 garment to reduce excessive movement. Tri-axial data were recorded across the vertical (PL-V),
264 anterior-posterior (PL-AP) and medial-lateral (PL-ML) vectors. The subsequent summation of the
265 planar contributions provided a combined value for PL total (PL-T). These metrics were defined as the
266 accumulated mean value across each 15 min block of exercise and expressed as arbitrary units.

267

268 Statistical Analysis

269 Eight EMG data points were absent across six participants due to technical difficulties with the wireless
270 recording, though all other data were presented for analyses. Linear mixed modelling (LMM) is
271 appropriate for repeated measures designs that involve random and fixed level factors with missing
272 data; assuming data are missing at random (Di Salvo, Gregson, Atkinson, Tordoff & Drust, 2009). As
273 such, LMM analysis was employed for the current study. Initially, the normality of residuals was
274 checked through visually examining q-q plots, boxplots and histograms, and residuals > 3.0 SD from
275 the mean were removed. Within-subject LMM with both fixed (i.e., *time* [E1–E8]) and random (i.e.,
276 *participant*) factors were assessed. The model fit was determined using Akaike’s information criterion
277 (AIC) with the most suitable for all variables deemed the first order auto-regressive (AR-1) repeated

278 covariance structure for the repeated measures. Main effects for time were identified *post hoc* using
279 Fisher's LSD with 95% confidence intervals (CI) for the difference reported where significance was
280 detected. Unless otherwise specified, data are expressed as mean \pm SE and were analysed using SPSS
281 version 26.0 (SPSS Inc., Chicago, IL, USA). Alpha was accepted as $p \leq 0.05$ prior to analyses.

282

283 **Results**

284 Significant reductions were identified for normalised EMG_{RF} between E8 ($87.5 \pm 4.3\%$; 95% CI = 78.9
285 to 96.2) versus E1 (-13% ; $100 \pm 4\%$; 95% CI = 92 to 102%; 95% CI for diff = -24 to -1 ; $p = 0.037$),
286 E2 (-12% ; $99 \pm 4\%$; 95% CI = 91 to 108%; 95% CI for diff = -23 to -2 ; $p = 0.047$) and E4 (-13% ;
287 $100 \pm 4\%$; 95% CI = 92 to 108%; 95% CI for diff = -23 to -1 ; $p = 0.030$). No significant time effects
288 were observed for EMG_{BF} ($p = 0.73$).

289

290 As illustrated in Figure 2A, a significant reduction in peak torque of 10.5% was observed for eccKF₁₈₀
291 from pre- (162.3 ± 9.0 Nm; 95% CI = 143.2 to 181.3 Nm) to post-exercise (145.2 ± 9.0 Nm; 95% CI =
292 126.1 to 164.3 Nm; 95% CI for diff = -33.9 to -0.8 ; Nm; $p = 0.042$). Peak torque was significantly
293 reduced by 7.5% for eccKF₂₇₀ from pre- (159.0 ± 9.0 Nm; 95% CI = 139.4 to 178.6 Nm) to post-exercise
294 (147.2 ± 9.0 Nm; 95% CI = 127.6 to 166.7 Nm; 95% CI for diff = -22.4 to -1.3 Nm; $p = 0.034$), and by
295 7.7% for eccKF₆₀ from pre- (159.5 ± 7.9 Nm; 95% CI = 142.4 to 176.6 Nm) to post-exercise ($147.2 \pm$
296 7.9 Nm; 95% CI = 142.4 to 176.6 Nm; 95% CI for diff = -21.7 to -3.0 Nm; $p = 0.018$; Figure 2B and
297 3C). No differences were observed for the conKE data recorded pre- ($180 \text{ deg}\cdot\text{s}^{-1} = 150.8 \pm 7.7$ Nm;
298 $270 \text{ deg}\cdot\text{s}^{-1} = 116.8 \pm 5.6$ Nm; $60 \text{ deg}\cdot\text{s}^{-1} = 193.7 \pm 11.0$ Nm) when compared to post-exercise (180
299 $\text{deg}\cdot\text{s}^{-1} = 153.0 \pm 7.8$ Nm; $p = 0.441$; $270 \text{ deg}\cdot\text{s}^{-1} = 114.8 \pm 5.6$ Nm; $p = 0.493$; $60 \text{ deg}\cdot\text{s}^{-1} = 183.3 \pm 11.0$
300 Nm; $p = 0.062$).

301

302 ***INSERT FIGURE 2***

303

304 As outlined in Table 2, significant main effects for time were identified for PL-T ($p < 0.010$), PL-V (p
305 $= 0.038$) and PL-AP ($p < 0.010$), though no timepoint differences were detected for PL-ML ($p = 0.094$).

306 Mean (\pm SD) percentage contributions of PL-T were 53 ± 3 % (PL-V), 24 ± 3 % (PL-AP) and 23 ± 2
307 % (PL-ML) throughout the 120 min simulation.

308

309 ***INSERT TABLE 2***

310

311 **Discussion**

312 The main purpose of this study was to assess thigh musculature excitation and peak torque production
313 in response to 120 min of soccer-specific exercise. In line with the study hypotheses, an additional ET
314 period elicited a reduction in rectus femoris muscle excitation and decreased eccentric knee flexor peak
315 torque from pre-to-post 120 min of soccer-specific exercise. Increments in PL values were identified as
316 a function of exercise duration which was further increased during ET. However, no changes in indices
317 of isokinetic knee extensor peak torque were observed, nor did the degree of muscle excitation change
318 throughout the exercise simulation in the biceps femoris.

319

320 Normalised EMG_{RF} amplitudes were reduced during ET, though excitation deficits were not associated
321 with significant impairments in ConKE following the 120-min simulation. These results are consistent
322 with previous findings demonstrating that patterns of potentiated knee-extensor twitch force/voluntary
323 activation do not reflect deficits in maximal knee extensor force capacity following ET (Goodall et al.,
324 2017). Therefore, it is considered likely that the knee extensor fatigue experienced during ET occurs
325 centrally along the pathway and could be linked to a reduced neural drive and/or excitation contraction
326 coupling as opposed to within-muscle contractile failure and/or substrate depletion. Duration dependent
327 central fatigue development has also been observed in response to varying exercise modalities (Place,
328 Maffiuletti, Martin & Lepers, 2007; Thomas et al., 2015). However, the reduction in muscle excitation
329 during high velocity sprinting in response to an additional ET period is a novel finding and implies that
330 central fatigue (indicated through reduced surface EMG signals) may progressively become a more
331 prominent limiting factor in response to an increased exercise duration.

332

333 The reduction in EMG_{RF} amplitude during a fixed work rate soccer-specific treadmill simulation is in
334 line with the findings of Rahnama et al., (2006). However, the lack of change in EMG_{BF} amplitude
335 across 120 min in the present study was an unexpected finding and contradicts the work of Rahnama et
336 al. (2006) who reported a reduction in EMG_{BF} following a soccer-specific treadmill simulation. The
337 conflicting results might be partly attributed to differences in the soccer simulation protocol and EMG
338 measurements. Rahnama et al., (2006) used a soccer simulation which involves a different activity
339 profile (i.e., a disproportionate amount of high-speed running) to the present study. They also measured
340 the mean RMS value of EMG amplitudes in a separate protocol at three time points (pre, half-time and
341 post simulation) as opposed to during the protocol itself, potentially allowing aspects of central fatigue
342 development to dissipate. The lack of EMG amplitude inhibition for EMG_{BF} , despite the reduction in
343 EMG_{RF} in the current investigation, implies that neural fatigue may occur sooner in the quadriceps than
344 in the hamstrings during soccer-specific exercise. This is perhaps due to the repetitive braking forces
345 incurred during rapid decelerations, for which the quadriceps are a primary muscle group (Hewitt,
346 Cronin, Button & Hume, 2011). As a result, it is possible that if the hamstrings were incapable of
347 performing these functions, injury risk may have been increased during rapid deceleration movements.

348

349 The lack of change for EMG_{BF} , despite eccKF strength reductions following ET implies the strength
350 capacity of the hamstrings were impaired, but still maintained a similar level of muscular activation
351 from E1 ($100 \pm 3\%$) to E8 ($103 \pm 4\%$). Conversely, it has previously been purported that impairments
352 in contractile properties of the muscle require an elevated neural drive to maintain a constant running
353 velocity, which are reflected with larger EMG amplitudes within working muscles (Pincivero et al.,
354 2000). However, the torque reductions observed are possibly explained by a protective mechanism
355 which acts to regulate extracellular damage by enforcing a temporary energy restriction to limit the
356 recruitment of muscle fibres. This may be imposed because muscle fibres are unable to disregard
357 cerebral and neural commands which control the recruitment of motor units and subsequent muscle
358 contraction (Baird, Graham, Baker & Bickerstaff, 2012). Another plausible explanation may be that
359 musculature that play a role in flexing the knee were measured as a unit, and as such, the maintenance
360 of activation in the bicep femoris may suggest that the observed changes in peak torque may be due to

361 impairments in other such muscles — semitendinosus, semimembranosus, sartorius, gracilis,
362 popliteus and gastrocnemius — that contribute to knee flexion. It is also possible that as the biceps
363 femoris causes external rotation of the knee joint (Opar, Williams & Shield, 2012), the lack of change
364 of direction movements involved with treadmill running, may have resulted in a conservative response
365 when compared to match-play in the sense that the biceps femoris may be stressed to a greater extent
366 from changes of direction tasks.

367

368 A reduction in eccKF torque production was observed in the present study, irrespective of the isokinetic
369 testing speed. However, conKE appear to maintain their torque capacity from pre- to post-120 min,
370 despite a reduction in neural drive. Considering the standardised nature of the protocol, other
371 musculature must compensate for the reduced neural drive of the quadriceps in order to maintain the
372 propulsion needed to perform the exercise protocol. Therefore, it is possible that the reductions in knee
373 flexor peak torque are due to an inhibited quadriceps activation and subsequent changes to how other
374 musculature operate. It is also likely that differences in muscle composition can explain the disparity in
375 peak torque maintenance between muscles. For instance, while the precise anatomical properties that
376 predispose hamstrings to peripherally derived measures of reduced strength are unclear, it has been
377 purported that fibre type distribution and muscle architecture are factors that may contribute (Opar,
378 Williams & Shield, 2012). It should also be considered that symptoms of muscle damage and soreness
379 are exacerbated in response to eccentric versus concentric modes of exercise (Mirzayev, 2017).
380 Additionally, hamstring strains typically occur when the lengthening demands of the muscle exceeds
381 the tissue strength limits, with fatigued muscles able to absorb less energy before failure versus
382 unfatigued muscles (Opar, Williams & Shield, 2012; Coratella et al., 2012). Eccentric strength exercises
383 reportedly shift the optimum length-tension curve (i.e., towards greater lengths/joint angles), thus
384 reducing hamstring strain injuries at extended joint positions (Brughelli & Cronin, 2008). A 12-week
385 Nordic hamstring protocol delivered bi-weekly before training, resulted in a greater degree of
386 improvement at extended muscle lengths versus post-training (Lovell et al., 2018). As such,
387 implementing such preventative exercises within training programmes appears warranted. Practitioners
388 should develop the eccentric component of the hamstrings to increase player resistance to fatigue-

389 induced torque deficits and increase the muscle length at which eccentric hamstring torque development
390 is attained in order to reduce hamstring injury susceptibility during the ET period.

391

392 The magnitude of the reduction in eccKF torque generation from pre- to post-exercise at 270 and 60
393 deg·s⁻¹ were similar with that of previous work with corresponding measures at 300 and 60 deg·s⁻¹
394 following 90 min of a treadmill simulation (Page et al., 2019). The deficit in eccKF torque between pre-
395 and post-exercise suggests that soccer players are unable to attain eccentric peak torque of the knee
396 flexor musculature following 120 min of soccer-specific activity. However, as evident in Figure 2, large
397 inter-individual variability was present for eccKF with changes ranging from -34% to +21%
398 (depending on the isokinetic speed) between pre- and post-exercise. This suggests that muscle
399 contractile fatigue mechanisms are highly dependent on the individual and thus, torque deficits should
400 be interpreted on an individual level. Likewise, considered within a practical setting, these data may
401 have implications for squad rotation and ET substitutions, especially since a contemporary rule change
402 has been implemented permitting a fourth substitution be made during the ET period of match-play in
403 major tournaments (Hills et al., 2020). For players unable to be replaced during ET, carbohydrate
404 provision is recommended where practical to attenuate reductions in physical performance.

405

406 Reductions in muscle torque generation and subsequent compensatory adjustments in gait can manifest
407 as changes in movement patterns (Jonkers et al., 2003). Therefore, the compromised capacity of the
408 players in this study to maintain knee flexor peak torque may partially elucidate the increase in PL-AP
409 postural sway. Specifically, the mechanism likely involved an impaired ability for the hamstrings to
410 maintain hip extension (i.e., an upright trunk posture), coupled with a potential antagonistic dominance
411 of the quadriceps musculature in flexing the hip. Additionally, hamstrings are most susceptible to injury
412 during the late swing phase of sprinting due to lengthening across both hip and knee joints (Chumanov,
413 Schache, Heiderscheit, & Thelen, 2012), and are possibly in a comprised state following 120 min of
414 soccer-specific exercise. Therefore, it may be pertinent for players to employ pacing strategies to reduce
415 the impact of fatigue-induced reductions in knee flexor strength during matches that proceed to ET.
416 However, players were unable to 'self-pace' during the current study (i.e., the treadmill dictated the

417 activity profile), thus, a reduced physical capacity may have instead manifested through increases in PL
418 metrics. Furthermore, the ~7.5–10.5% deficit in knee flexor torque production identified pre- to post-
419 exercise supports an increased hamstring injury propensity and a compromised joint stability (Page et
420 al., 2019), elicited by 120 min of exercise. Therefore, players not conditioned to manage the additional
421 demands of ET, may be at an increased susceptibility to suffer an acute musculotendinous rupture
422 during this additional 30 min period.

423

424 Similar to the reduced physical performance capacity observed in the latter stages of 120-min matches
425 (Peñas et al., 2015; Russell et al., 2015), PL-T has demonstrated increases during ET when compared
426 to a number of the preceding fixed bouts of treadmill-based simulated soccer exercise (Field et al.,
427 2020). Though inferential statistics were not carried out to assess correlations, the increases in PL
428 appears to partially correspond with reductions in excitation (i.e., EMG_{RF}) and peak torque data (i.e.,
429 eccKF). Therefore, these data provide an initial step towards providing evidence that suggests PL
430 metrics are reflective of EMG and peak torque lower-limb thigh musculature changes. However,
431 prospective validation of PL metrics is required that focus intently and establish the extent to which
432 changing planar contributions reflect EMG lower-limb patterns during both treadmill and free-running
433 soccer simulations.

434

435 While this study offers novel insight into muscle excitation and torque production throughout 120 min
436 of soccer exercise, there are some methodological limitations present within the current research.
437 Firstly, the absence of additional isokinetic peak torque measures for the thigh musculature (i.e.,
438 eccentric knee extensors and concentric knee flexors) may be considered a limitation, especially given
439 the role of the knee extensors during eccentric knee flexion upon ground contact (Paquette, Peel,
440 Schilling, Melcher, & Bloomer, 2017). Reductions in strength of the eccentric knee extensors could
441 lead to kicking related injuries and therefore is an important future avenue of research. While EMG was
442 measured at 15-min time intervals throughout the simulation, peak torque was only measured pre and
443 post the 120-min protocol. This could be deemed a limitation, however, additional measures on the
444 isokinetic dynamometer at 15-min intervals would have invalidated the soccer-specific fatigue response

445 and, as such, was considered inappropriate for this study. Though participants covered distances (16.26
446 km) and performed the number of sprints ($n = 56$) comparable with an actual 120 min match (Russell
447 et al., 2015; Winder, Russell, Naughton, & Harper, 2018), the pre-arranged nature and lack of kicking,
448 jumping and tackling actions involved with simulations will inevitably impact peripheral and central
449 patterns of fatigue. Notwithstanding the considerable experimental control of our research, its lack of
450 ecological validity yields difficulty when extrapolating the data to match-play scenarios considering the
451 number of contextual variables that influence soccer match performance (Castellano, Blanco-Villaseñor
452 & Alvarez, 2011).

453

454 **Conclusion**

455 To summarise, thigh musculature excitation and peak torque production, and PL responses were
456 investigated in response to 120 min of soccer-specific activity. These novel data suggest that muscle
457 excitation of the rectus femoris was reduced during ET, though no notable change was evident in the
458 biceps femoris throughout 120 min of soccer activity. The torque generating capability of the knee
459 flexors was reduced post 120 min compared with baseline assessments. Increases in PL were evident
460 as a function of exercise, which was further increased during the additional period of ET. It is
461 recommended that exercises are implemented within the weekly training schedule to develop resistance
462 to fatigue-induced knee flexor torque deficits in order to limit injury risk during matches that progress
463 to the ET period. Likewise, carefully considered interventions should be orchestrated following ET
464 matches to promote recovery and enhance physical performance in subsequent matches.

465

466

467 **Figure Captions**

468 **Figure 1.** An example of the EMG signal recorded for an individual participant for the 10-second sprint
469 performed during E1 and E8 within the soccer-specific simulation.

470 **Figure 2.** Individual eccKF peak torque values across angular velocities of 180 (A), 270 (B) and 60
471 $\text{deg}\cdot\text{s}^{-1}$ (C). * indicates significant difference from pre- to post-exercise. Dash lines with open circles
472 represent mean eccKF responses.

473 **References**

- 474 1. Azidin, R. F., Sankey, S., Robinson, M. A., & Vanrenterghem, J. (2013). Treadmill versus
475 overground soccer-specific fatigue: The effect on hamstring and quadriceps strength and frontal
476 plane peak knee joint moments in side-cutting.
- 477 2. Baird, M. F., Graham, S. M., Baker, J. S., & Bickerstaff, G. F. (2012). Creatine-kinase-and
478 exercise-related muscle damage implications for muscle performance and recovery. *Journal of*
479 *nutrition and metabolism*, 2012.
- 480 3. Barrett, S., Midgley, A. W., Towlson, C., Garrett, A., Portas, M., & Lovell, R. (2016). Within-
481 match PlayerLoad™ patterns during a simulated soccer match: potential implications for unit
482 positioning and fatigue management. *International journal of sports physiology and*
483 *performance*, 11(1), 135-140.
- 484 4. Besomi, M., Hodges, P. W., Clancy, E. A., Van Dieën, J., Hug, F., Lowery, M., & Carson, R.
485 G. (2020). Consensus for experimental design in electromyography (CEDE) project: Amplitude
486 normalization matrix. *Journal of electromyography and kinesiology*, 102438.
- 487 5. Bradley, P. S., Sheldon, W., Wooster, B., Olsen, P., Boanas, P., & Krstrup, P. (2009). High-
488 intensity running in English FA Premier League soccer matches. *Journal of sports sciences*,
489 27(2), 159-168.
- 490 6. Brownstein, C. G., et al., (2017). Etiology and recovery of neuromuscular fatigue following
491 competitive soccer match-play. *Frontiers in physiology*, 8, 831.
- 492 7. Brughelli, M., & Cronin, J. (2008). Preventing hamstring injuries in sport. *Strength &*
493 *conditioning journal*, 30(1), 55-64.
- 494 8. Castellano, J., Blanco-Villaseñor, A., & Alvarez, D. (2011). Contextual variables and time-
495 motion analysis in soccer. *International journal of sports medicine*, 32(06), 415-421.
- 496 9. Croisier, J. L., Ganteaume, S., Binet, J., Genty, M., & Ferret, J. M. (2008). Strength imbalances
497 and prevention of hamstring injury in professional soccer players: a prospective study. *The*
498 *American journal of sports medicine*, 36(8), 1469-1475.
- 499 10. Chambers, R., Gabbett, T. J., Cole, M. H., & Beard, A. (2015). The use of wearable
500 microsensors to quantify sport-specific movements. *Sports medicine*, 45(7), 1065-1081.

- 501 11. Chumanov, E. S., Schache, A. G., Heiderscheit, B. C., & Thelen, D. G. (2012). Hamstrings are
502 most susceptible to injury during the late swing phase of sprinting. *BMJ publishing group ltd*
503 *and British association of sport and exercise medicine*.
- 504 12. Coratella, G., Bellin, G., Beato, M., & Schena, F. (2012). Hamstrings are most susceptible to
505 injury during the late swing phase of sprinting. *British journal of sports medicine*. 46: 90.
506 33(12).
- 507 13. Cormack, S. J., Mooney, M. G., Morgan, W., & McGuigan, M. R. (2013). Influence of
508 neuromuscular fatigue on accelerometer load in elite Australian football players. *International*
509 *journal of sports physiology and performance*, 8(4), 373-378.
- 510 14. Di Salvo, V., Gregson, W., Atkinson, G., Tordoff, P., & Drust, B. (2009). Analysis of high
511 intensity activity in Premier League soccer. *International journal of sports medicine*, 30(03),
512 205-212.
- 513 15. Ekstrand, J., Hägglund, M., & Waldén, M. (2011). Epidemiology of muscle injuries in
514 professional football (soccer). *The American journal of sports medicine*, 39(6), 1226-1232.
- 515 16. Field, A., Corr, L. D., Haines, M., Lui, S., Naughton, R., Page, R. M., & Harper, L. D. (2020).
516 Biomechanical and Physiological Responses to 120 min of Soccer-Specific Exercise. *Research*
517 *quarterly for exercise and sport*, 1-13.
- 518 17. Gibson, A. S. C., Lambert, M. I., & Noakes, T. D. (2001). Neural control of force output during
519 maximal and submaximal exercise. *Sports medicine*, 31(9), 637-650.
- 520 18. Graham, S., Zois, J., Aughey, R., & Duthie, G. (2020). The peak player load™ of state-level
521 netball matches. *Journal of science and medicine in sport*, 23(2), 189-193.
- 522 19. Goodall, S., et al., (2017). The assessment of neuromuscular fatigue during 120 min of
523 simulated soccer exercise. *European journal of applied physiology*, 117(4), 687-697.
- 524 20. Greig, M. (2008). The influence of soccer-specific fatigue on peak isokinetic torque production
525 of the knee flexors and extensors. *The American journal of sports medicine*, 36(7), 1403-1409.
- 526 21. Hader, K., Mendez-Villanueva, A., Ahmaidi, S., Williams, B. K., & Buchheit, M. (2014).
527 Changes of direction during high-intensity intermittent runs: neuromuscular and metabolic
528 responses. *BMC sports science, medicine and rehabilitation*, 6(1), 2.

- 529 22. Harper, L. D., Stevenson, E. J., Rollo, I., & Russell, M. (2017). The influence of a 12%
530 carbohydrate-electrolyte beverage on self-paced soccer-specific exercise performance. *Journal*
531 *of science and medicine in sport*, 20(12), 1123-1129.
- 532 23. Harper, L. D., Fothergill, M., West, D. J., Stevenson, E., & Russell, M. (2016). Practitioners'
533 perceptions of the soccer extra-time period: Implications for future research. *Plos one*, 11(7).
- 534 24. Hills, S. P., Radcliffe, J. N., Barwood, M. J., Arent, S. M., Cooke, C. B., & Russell, M. (2020).
535 Practitioner perceptions regarding the practices of soccer substitutes. *Plos one*, 15(2),
536 e0228790.
- 537 25. Hewit, J., Cronin, J., Button, C., & Hume, P. (2011). Understanding deceleration in
538 sport. *Strength & conditioning journal*, 33(1), 47-52.
- 539 26. Hughes, G., & Watkins, J. (2008). Lower limb coordination and stiffness during landing from
540 volleyball block jumps. *Research in sports medicine*, 16(2), 138-154.
- 541 27. Jonkers, I., Stewart, C., & Spaepen, A. (2003). The complementary role of the plantarflexors,
542 hamstrings and gluteus maximus in the control of stance limb stability during gait. *Gait &*
543 *posture*, 17(3), 264-272.
- 544 28. Konrad, P. (2005). The abc of emg. *A practical introduction to kinesiological*
545 *electromyography*, 1(2005), 30-5.
- 546 29. Lovell, R., Knox, M., Weston, M., Siegler, J. C., Brennan, S., & Marshall, P. W. (2018).
547 Hamstring injury prevention in soccer: before or after training?. *Scandinavian journal of*
548 *medicine & science in sports*, 28(2), 658-666.
- 549 30. Magalhaes, J., Oliveir, A. J., Ascensao, A., & Soares, J. (2004). Concentric quadriceps and
550 hamstrings isokinetic strength in volleyball and soccer players. *Journal of sports medicine and*
551 *physical fitness*, 44, 119-125.
- 552 31. Mirzayev, J. A. (2017). Muscle damage: Scientific fundamentals. *Journal of applied*
553 *physiology*, 122(4), 1052-1052.
- 554 32. Mohr, M., Krstrup, P., & Bangsbo, J. (2005). Fatigue in soccer: a brief review. *Journal of*
555 *sports sciences*, 23(6), 593-599.

- 556 33. Nicoletta, D. P., Torres-Ronda, L., Saylor, K. J., & Schelling, X. (2018). Validity and reliability
557 of an accelerometer-based player tracking device. *Plos one*, *13*(2).
- 558 34. Opar, D. A., Williams, M. D., & Shield, A. J. (2012). Hamstring strain injuries. *Sports*
559 *medicine*, *42*(3), 209-226.
- 560 35. Orchard, J. W., Driscoll, T., Seward, H., & Orchard, J. J. (2012). Relationship between
561 interchange usage and risk of hamstring injuries in the Australian Football League. *Journal of*
562 *science and medicine in sport*, *15*(3), 201-206.
- 563 36. Page, R. M., Marrin, K., Brogden, C. M., & Greig, M. (2015). Biomechanical and physiological
564 response to a contemporary soccer match-play simulation. *The journal of strength &*
565 *conditioning research*, *29*(10), 2860-2866.
- 566 37. Page, R. M., Marrin, K., Brogden, C. M., & Greig, M. (2019). Physical Response to a Simulated
567 Period of Soccer-Specific Fixture Congestion. *The journal of strength & conditioning*
568 *research*, *33*(4), 1075-1085.
- 569 38. Pincivero, D. M., Aldworth, C., Dickerson, T., Petry, C., & Shultz, T. (2000). Quadriceps-
570 hamstring EMG activity during functional, closed kinetic chain exercise to fatigue. *European*
571 *journal of applied physiology*, *81*(6), 504-509.
- 572 39. Paquette, M. R., Peel, S. A., Schilling, B. K., Melcher, D. A., & Bloomer, R. J. (2017).
573 Soreness-related changes in three-dimensional running biomechanics following eccentric knee
574 extensor exercise. *European journal of sport science*, *17*(5), 546-554.
- 575 40. Peñas, C. L., Dellal, A., Owen, A. L., & Gómez-Ruano, M. Á. (2015). The influence of the
576 extra-time period on physical performance in elite soccer. *International journal of performance*
577 *analysis in sport*, *15*(3), 830-839. doi:10.1080/24748668.2015.11868834
- 578 41. Place, N., Maffiuletti, N. A., Martin, A., & Lepers, R. (2007). Assessment of the reliability of
579 central and peripheral fatigue after sustained maximal voluntary contraction of the quadriceps
580 muscle. *Muscle & nerve: official journal of the American association of electrodiagnostic*
581 *medicine*, *35*(4), 486-495.

- 582 42. Rahnama, N., Lees, A., & Bambaecichi, E. (2005). A comparison of muscle strength and
583 flexibility between the preferred and non-preferred leg in English soccer
584 players. *Ergonomics*, 48(11-14), 1568-1575.
- 585 43. Rahnama, N., Lees, A., & Reilly, T. (2006). Electromyography of selected lower-limb muscles
586 fatigued by exercise at the intensity of soccer match-play. *Journal of electromyography and*
587 *kinesiology*, 16(3), 257-263.
- 588 44. Rahnama, N., Reilly, T., Lees, A., & Graham-Smith, P. (2003). Muscle fatigue induced by
589 exercise simulating the work rate of competitive soccer. *Journal of sports science*, 21(11), 933-
590 942.
- 591 45. Russell, M., Sparkes, W., Northeast, J., & Kilduff, L. P. (2015). Responses to a 120 min reserve
592 team soccer match: a case study focusing on the demands of extra time. *Journal of sports*
593 *sciences*, 33(20), 2133-2139.
- 594 46. Setuain, I., Lecumberri, P., & Izquierdo, M. (2017). Sprint mechanics return to competition
595 follow-up after hamstring injury on a professional soccer player: A case study with an inertial
596 sensor unit based methodological approach. *Journal of biomechanics*, 63, 186-191.
- 597 47. Small, K., McNaughton, L., Greig, M., & Lovell, R. (2010). The effects of multidirectional
598 soccer-specific fatigue on markers of hamstring injury risk. *Journal of science and medicine in*
599 *sport*, 13(1), 120-125.
- 600 48. Stegeman, D. F., Blok, J. H., Hermens, H. J., & Roeleveld, K. (2000). Surface EMG models:
601 properties and applications. *Journal of electromyography and kinesiology*, 10(5), 313-326.
- 602 49. Stevenson, E. J., Watson, A., Theis, S., Holz, A., Harper, L. D., & Russell, M. (2017). A
603 comparison of isomaltulose versus maltodextrin ingestion during soccer-specific exercise.
604 *European journal of applied physiology*, 117(11), 2321-2333. doi:10.1007/s00421-017-3719-
605 5.
- 606 50. Thomas, K., Goodall, S., Stone, M., Howatson, G., Gibson, A. S. C., & Ansley, L. (2015).
607 Central and peripheral fatigue in male cyclists after 4-, 20-, and 40-km time trials. *Medicine &*
608 *science in sports & exercise*, 47(3), 537-546.

- 609 51. Thomas, K., Dent, J., Howatson, G., & Goodall, S. (2017). Etiology and recovery of
610 neuromuscular fatigue after simulated soccer match play. *Medicine & science in sports &*
611 *exercise*, 49(5), 955-964.
- 612 52. Van Hooren, B., Fuller, J. T., Buckley, J. D., Miller, J. R., Sewell, K., Rao, G., & Willy, R. W.
613 (2020). Is Motorized Treadmill Running Biomechanically Comparable to Overground
614 Running? A Systematic Review and Meta-Analysis of Cross-Over Studies. *Sports*
615 *medicine*, 50(4), 785-813.
- 616 53. Verheul, J., Nedergaard, N. J., Vanrenterghem, J., & Robinson, M. A. (2020). Measuring
617 biomechanical loads in team sports—from lab to field. *Science and medicine in football*, 1-7.
- 618 54. Wilk, B. R., Nau, S., & Valero, B. (2009). Physical therapy management of running injuries
619 using an evidenced based functional approach. *Journal of the American medical athletic*
620 *association*, 22(1), 5-7.
- 621 55. Winder, N., Russell, M., Naughton, R. J., & Harper, L. D. (2018). The Impact of 120 Minutes
622 of Match-Play on Recovery and Subsequent Match Performance: A Case Report in Professional
623 Soccer Players. *Sports*, 6(1), 22.
- 624 56. Yao, J., Guo, N., Xiao, Y., Li, Z., Li, Y., Pu, F., & Fan, Y. (2019). Lower limb joint motion
625 and muscle force in treadmill and over-ground exercise. *Biomedical engineering online*, 18(1),
626 1-12.

627
628
629
630
631
632
633
634

Table 1. The activity profile of an individual 15-minute bout of the soccer-specific exercise simulation

Locomotion category (velocity)	Number of repetitions	Duration (s)	Gradient (%)
Standing (0 km·h ⁻¹)	29	7.0	1.0
Walking (4 km·h ⁻¹)	65	6.4	1.0
Jogging (8 km·h ⁻¹)	53	3.0	1.0
Low speed running (11.6 km·h ⁻¹)	48	2.6	1.0
Moderate speed running (15 km·h ⁻¹)	17	2.2	2.0
High speed running (18 km·h ⁻¹)	12	2.1	2.0
Sprinting (25 km·h ⁻¹)	7	2.0	2.5

635
636
637
638
639
640
641
642
643
644
645
646

Table 2. Muscle excitation and PlayerLoad™ responses throughout the 120 min soccer simulation (Mean ± SE)

Variable	Time							
	E1 (0—15 min)	E2 (15—30 min)	E3 (30—45 min)	E4 (45—60 min)	E5 (60—75 min)	E6 (75—90 min)	E7 (90—105 min)	E8 (105—120 min)
EMG _{RF} (%)	100 ± 4	99 ± 4	97 ± 4	100 ± 4	95 ± 4	93 ± 4	95 ± 4	87 ± 4 95% CI = -24 to -1 ^a ; -23 to -2 ^b ; -23 to -1 ^d
EMG _{BF} (%)	100 ± 3	100 ± 3	102 ± 3	104 ± 3	103 ± 3	99 ± 4	101 ± 3	103 ± 4
PL-T (a.u)	218 ± 7	221 ± 7 95% CI = 1 to 7 ^a	221 ± 7	226 ± 7 95% CI = 2 to 13 ^a ; 1 to 8 ^c	230 ± 7 95% CI = 5 to 18 ^a ; 3 to 14 ^b ; 4 to 13 ^c ; 1 to 7 ^d	231 ± 7 95% CI = 6 to 20 ^a ; 3 to 16 ^b ; 5 to 16 ^c ; 1 to 10 ^d	234 ± 7 95% CI = 3 to 13 ^a ; 3 to 12 ^b ; 4 to 12 ^c ; 2 to 9 ^d ; 1 to 6 ^c ; 1 to 4 ^f	236 ± 7 95% CI = 3 to 14 ^a ; 2 to 12 ^b ; 3 to 12 ^c ; 1 to 9 ^d
PL-V (a.u)	115 ± 5	116 ± 5	116 ± 5	119 ± 5 95% CI = 1 to 5 ^c	121 ± 5 95% CI = 1 to 9 ^a ; 1 to 8 ^b ; 2 to 7 ^c	121 ± 5 95% CI = 1 to 11 ^a ; 1 to 9 ^b ; 1 to 9 ^c	124 ± 5 95% CI = 3 to 14 ^a ; 2 to 12 ^b ; 4 to 12 ^c ; 1 to 9 ^d ; 1 to 6 ^c ; 1 to 4 ^f	124 ± 5 95% CI = 3 to 14 ^a ; 2 to 12 ^b ; 3 to 12 ^c ; 1 to 9 ^d
PL-AP (a.u)	52 ± 3	54 ± 3 95% CI = 1 to 3 ^a	54 ± 3 95% CI = 1 to 3 ^a	54 ± 3 95% CI = 1 to 4 ^a	56 ± 3 95% CI = 2 to 5 ^a ; 1 to 4 ^b ; 1 to 4 ^c ; 1 to 3 ^d	57 ± 3 95% CI = 2 to 6 ^a ; 1 to 4 ^b ; 1 to 4 ^c ; 1 to 3 ^d	57 ± 3 95% CI = 3 to 7 ^a ; 1 to 5 ^b ; 2 to 5 ^c ; 1 to 4 ^d	58 ± 3 95% CI = 4 to 8 ^a ; 2 to 6 ^b ; 3 to 6 ^c ; 2 to 5 ^d ; 1 to 3 ^e ; 1 to 3 ^f
PL-ML (a.u)	50 ± 3	51 ± 3	51 ± 3	52 ± 3	53 ± 3	53 ± 3	54 ± 3	54 ± 3

Note. EMG_{RF} = Mean electromyography for rectus femoris; EMG_{BF} = Mean electromyography for bicep femoris; PL-T = PlayerLoad total; PL-V = PlayerLoad vertical; PL-AP = PlayerLoad anterior-posterior; PL-ML = PlayerLoad medial-lateral; CI 95% = 95% confidence intervals for the difference.

^{a-g} Indicates significant differences from E1–E7 ($p \leq 0.05$), respectively.

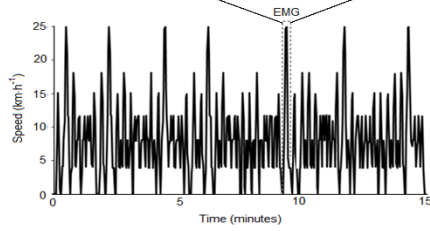
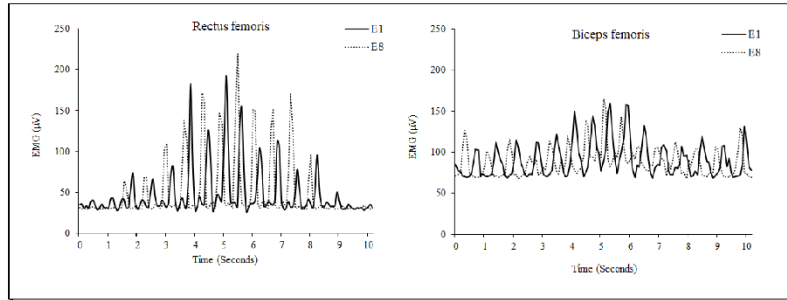
647

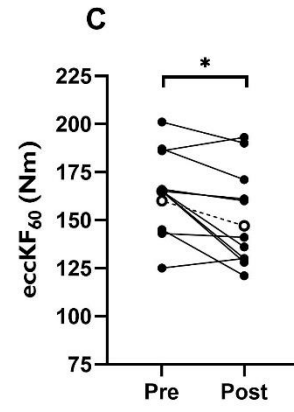
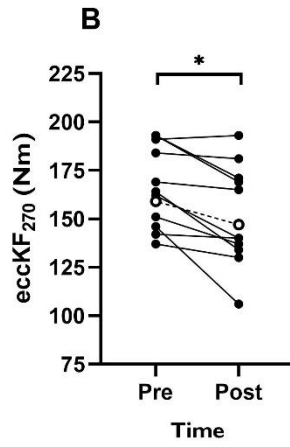
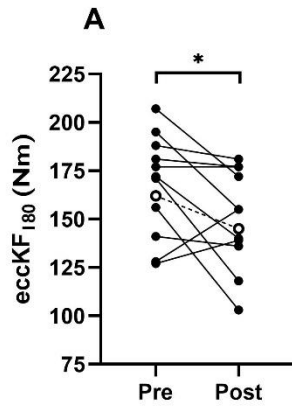
648

649

650

651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682





683