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Temporal differences in the myoelectric activity of lower limb muscles during rearfoot and forefoot running

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2	rearfoot and forefoot running: A statistical parametric mapping approach
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32 Abstract

33 Forefoot (FF) and rearfoot (RF) running techniques can induce different lower-limb muscle 34 activation patterns. However, few studies have evaluated temporal changes in the 35 electromyographic activity (EMG) of lower limb muscles during running. The aim of this study 36 was to compare temporal changes in EMG amplitude between RF and FF running techniques. 37 Eleven recreational runners ran on a treadmill at a self-selected speed, once using a RF strike 38 pattern and once using a FF strike pattern (randomized order). The EMG of five lower limb 39 muscles [rectus femoris (RFe), biceps femoris (BF), tibialis anterior (TA), medial and lateral 40 gastrocnemius (MG and LG)] was evaluated, using bipolar electrodes. EMG data from the RF 41 and FF running techniques was then processed and compared with statistical parametric 42 mapping (SPM), dividing the analysis of the running cycle into stance and swing phases. The 43 MG and LG muscles showed higher activation during FF running at the beginning of the stance 44 phase and at the end of the swing phase. During the end of the swing phase, the TA muscle's 45 EMG amplitude was higher, when the RF running technique was used. A higher level of coactivation between the gastrocnemius and TA muscles was observed in both stance and swing 46 phases using RF. The myoelectric behaviour of the RFe and BF muscles was similar during 47 48 both running techniques. The current findings highlight that the two running techniques 49 predominately reflect adjustments of the shank and not the thigh muscles, in both phases of the 50 running cycle.

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52 Highlights

- Statistical parametric mapping (SPM) can reveal temporal differences in muscle
 activity between running techniques.
- The medial and lateral gastrocnemius muscles were more active at specific time instants of the initial stance and late swing phases during forefoot (FF) running
 compared to rearfoot (RF) running.
- Higher activation was observed for the tibialis anterior muscle at the end of the swing
 phase during RF running
- Contrary to the muscle activity differences observed in the leg muscles, the muscle
 activity of the thigh muscles was similar during RF and FF running.
- 62
- 63 **Keywords:** Statistical parametric mapping, running, surface electromyography.
- 64
- 65

- 66 Introduction
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In recent years, running has become one of the most popular physical activities, as it is a 68 simple, cost-efficient solution for many people who wish to maintain a healthy lifestyle (e.g., 69 70 improve their cardiovascular fitness and/or reduce stress levels) (Landreneau, Watts, 71 Heitzman, & Childers, 2014). Unfortunately, the increase in the popularity of running has 72 been followed by an increase in the prevalence of running-related injuries (Daoud et al., 73 2012). Running is commonly performed by both amateur and elite athletes (Andersen, 2020), 74 however, the most common cohort within the running community, are probably recreational 75 runners, i.e., people that run exclusively for fun and rarely participate in running competitions 76 (Hespanhol Junior, Pena Costa, & Lopes, 2013). Training characteristics play an important 77 role in the incidence of running-related injuries in recreational runners, as training errors can 78 lead to overloading of the musculoskeletal tissues and predispose them to injury (Hespanhol 79 Junior et al., 2013). An example of training characteristics that has a huge effect on running 80 biomechanics and thus, the distribution of the biomechanical loads across the lower limbs, is the foot strike pattern employed during running (Xu et al., 2021). Runners commonly use 81 82 rearfoot (RF) or forefoot (FF) running techniques, which are characterised by landing on the heel or by landing on the ball of the foot respectively (Yong et al., 2020). 83

84 A common way to evaluate changes in lower limb neuromuscular behaviour during different running techniques, and possibly understand the development and risk of injuries, is 85 86 by using surface electromyography (sEMG) (Landreneau et al., 2014). sEMG is a non-87 invasive technique that has been widely used in sporting environments as a fundamental tool 88 to quantitively evaluate and record the electrical activity of multiple muscles, during different 89 sport activities (e.g., soccer, volleyball, basketball, outdoor sports), including running 90 (Cavalcanti Garcia & Vieira, 2011; Landreneau et al., 2014). Many studies have previously evaluated the sEMG activity (commonly measured as sEMG amplitude) of lower limb 91 92 muscles during running (Lucas-Cuevas et al., 2016; Nüesch, Roos, Egloff, Pagenstert, & 93 Mündermann, 2019; Valencia et al., 2020; Yong et al., 2020), using measures of centrality 94 and dispersion, such as the mean and standard deviation of the interference sEMG signal 95 (Landreneau et al., 2014; Olin & Gutierrez, 2013; Trégouët, Merland, & Horodyski, 2013). 96 For example, one study compared RF and FF running techniques by calculating the mean 97 difference in sEMG amplitude and reported significant differences in the sEMG amplitude of 98 the medial, lateral gastrocnemius, and tibialis anterior muscles (Lucas-Cuevas et al., 2016). 99 However, an important limitation of these measures is that they just provide a general

overview of the myoelectric behaviour of the leg muscles for the full running cycle, not
allowing the identification of changes at different time-points or phases during the running
cycle (Pataky, Robinson, & Vanrenterghem, 2016; Robinson, Vanrenterghem, & Pataky,
2015). Therefore, it is important to employ signal-processing techniques which allow the
evaluation of temporal differences in muscle activity during the entire time series of a task
(e.g., full running cycle), rather than comparing ensemble averages for the full running cycle,
which provides results with poor temporal resolution.

107 A statistical-processing technique that has allowed biomechanical variables to be 108 examined in function of the time series of a task, is statistical parametric mapping (SPM) 109 (Pataky, 2010; Pataky et al., 2016). This technique was first described by Friston et al. (1995), 110 and then validated by Pataky based on kinematic and kinetic data (Pataky, 2010; Pataky et al., 111 2016). SPM is based on an inferential method, where hypothesis testing is directly applied to 112 the signal (Pataky et al., 2016). More specifically, random field theory determines the appropriate threshold to maintain alpha at 0.05 across the time-series, where the null 113 hypothesis is either accepted or rejected if the experimentally observed test statistic {t} 114 exceeds this threshold. SPM has been recently used to evaluate temporal differences during 115 116 the whole cycle of several tasks, including gait (Abbasi et al., 2020), jumping (Moisan, 117 Mainville, Descarreaux, & Cantin, 2020), and running (Nüesch et al., 2019). In terms of the 118 running task, SPM has already been used to compare curves of kinematic, kinetic, and sEMG 119 data during running (Abbasi et al., 2020; Nüesch et al., 2019; Yong et al., 2020). However, 120 only a few studies have focused on assessing temporal differences in the activity of lower 121 limb muscles (i.e., gastrocnemius) when comparing different types of running techniques, 122 such as RF and/or FF running (Luciano, Zilianti, Perini, Guzzardella, & Pavei, 2020; Valencia 123 et al., 2020). Additionally, to date no studies have evaluated temporal differences in the 124 behaviour of the thigh muscles during RF and FF running. Since these muscles are one of the 125 main muscle groups used during running, this evaluation could provide information regarding 126 the effect of the strike pattern on their activity throughout the running cycle. Importantly, even 127 though many studies have commonly used the ratios between agonist/antagonist muscle 128 activity to describe the levels of co-activation during dynamic tasks (e.g., gait, trunk and hip 129 movements) (Aslan, Batur, & Meray, 2020; Rojas-Quinchavil et al., 2021; Tretriluxana, 130 Nanbancha, Sinsurin, Limroongreungrat, & Wang, 2021; Vanderstukken, Borms, Berckmans, 131 Spanhove, & Cools, 2020), there are currently no studies evaluating co-activation using the 132 whole time series of a task by using SPM.

133 Therefore, the aim of this study is to compare the temporal shape of the electromyographic 134 amplitude of thigh and calf lower limb muscles, between RF and FF running, considering the 135 stance and swing phases of the running cycle. The current study will also evaluate differences 136 in the ratio of the gastrocnemius/tibialis anterior activity (co-activation) during the different 137 phases of RF and FF running. We hypothesised that (1) the muscle activity of the lower limb 138 muscles will differ between the FF and RF running techniques, in both phases of the running 139 cycle and (2) the level of co-activation between the gastrocnemius and TA muscles will be higher during RF running. 140

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142 Methods

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144 Participants

145 Eleven healthy recreational runners (7 men and 4 women; age: 22.3±2.4 years; mass: 146 66.8±5.6 kg; height: 1.7±0.1 m) from the University XX, XX, XX were recruited for this 147 observational, cross-sectional study. The sample size was calculated based on data collected 148 previously from the tibialis anterior muscle (Valencia et al., 2020), considering an effect size of 1.33, alpha of 0.05, and power of 80%. The GPower software (version 3.1.9.2, Kiel 149 150 Universität, Germany) was used to perform the power calculation. A minimum sample size 151 of 8 runners was required for this study; however, 11 runners were recruited. Participants were 152 eligible to participate in this study if they run $(1) \ge 3$ times/week and (2) for at least 5km each 153 day. All volunteers routinely used the RF technique during running. However, this was not a requirement of the current study, but an unintended characteristic of the recruited sample. 154 155 Participants were excluded from the study if they had a musculoskeletal injury or surgery in their lower limbs over the last 6 months. All participants provided written informed consent 156 157 before evaluation. Ethical approval was obtained by a local ethics committee (CEC201905). 158 This study was conducted in accordance with the Declaration of Helsinki.

159

160 Experimental protocol

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Prior to the laboratory visit, all participants were advised to wear athletic clothing and their personal running shoes, which should have been used for at least one month. At the beginning of the experiment, all participants were given a few minutes to familiarise themselves on a treadmill (H/P/Cosmos®, Model LE200 CE, Germany). All volunteers routinely used the RF technique. Then, the principal investigator trained each participant on how to run, using the 167 two different running techniques (i.e., RF and FF) on the treadmill for five minutes. During this process, each participant's preferred running speed was also calculated (Nüesch et al., 168 169 2019; Yong et al., 2020), based on the average of three consecutive trials (the average self-170 selected running speed of all participants was 8.6 ± 1.3 km/h). More specifically, the treadmill 171 speed was progressively increased by the investigator, up to the participant's desired level (i.e., 172 the point that the participant felt comfortable to run for 5 minutes). The participant was blinded 173 to the treadmill speed during this process. Once the participant's preferred running speed was 174 calculated and felt comfortable to run with both techniques, each volunteer ran for five minutes, 175 once using the RF and once using the FF running techniques at the same speed. The order in 176 which the runners had to perform each technique was randomised. They were then asked to 177 perform three 5s isometric maximal voluntary contractions (MVCs) for each muscle separately. 178 During this procedure, all participants were verbally motivated in a similar manner. Each trial 179 was separated by 1 min of rest. For the assessment of tibialis anterior (TA), medial (MG) and 180 lateral (LG) gastrocnemius muscles' MVCs, all participants were in a prone lying position with 181 their dominant foot strapped to a custom-made metal structure and their ankle at a neutral 182 position. From this position, they were instructed to perform ankle dorsi flexion/extension 183 MVCs to assess the gastrocnemius and TA muscles, respectively. For the evaluation of rectus 184 femoris (RFe) and biceps femoris (BF) muscles' MVCs, all participants were seated on a quadriceps bench, with their hips at 90° of flexion and their knees at 50° of flexion. From this 185 186 position, they were instructed to perform knee extension/flexion MVCs to assess the RFe and BF muscles, respectively. The highest MVC value for each muscle was used as a reference to 187 188 normalise the electromyographic signals (%MVC), considering as maximum the average value 189 of a window of 10ms around the peak.

190 sEMG and kinematic data were acquired simultaneously from the dominant lower limb of 191 all participants while they were running on the treadmill. Participants were asked to perform a 192 dynamic task (i.e. to kick a soccer ball), in order to determine the lower limb dominance 193 (Brown, Zifchock, & Hillstrom, 2014). Data (i.e., sEMG signals and kinematic marker 194 trajectories) were recorded during the last minute of each running trial (i.e., between minutes 195 4-5) and for 20 running cycles. This process was performed once while participants were 196 running using the RF technique and once while they were running using the FF technique (i.e., 197 40 cycles in total).

198

199 Kinematics

200 Kinematic data were captured using a 3D motion system with eight infrared cameras (T-Series, Vicon Motion Systems, Oxford, UK) at 200 Hz. Two reflective markers (14mm 201 202 diameter) were firmly attached on the shoe of all participants over the calcaneus (rearfoot) and 203 on the base of the second metatarsal phalangeal joint (forefoot), as described previously 204 (Landreneau et al., 2014). This enabled us to export information about the time that the foot 205 contacted the treadmill, as well as on the time that the foot was lifted from the treadmill (defined 206 as foot strike and foot off in the software NEXUS, Vicon®). Thus, we were able to determine 207 the running cycle, including both the stance and swing phases. This information was then used 208 for the sEMG analysis.

209

210 Electromyography recording

211 Simultaneously with the kinematic measurements, sEMG signals were recorded in single differential mode using a BagnoliTM 16-channel sEMG system (Delsys® Inc., Boston, MA, 212 USA; sampling frequency: 1kHz, converter 12-bit A/D), with a common-mode rejection ratio 213 214 of 92 dB, input impedance > 1015 Ohms, estimated noise \leq 1.2 mV, overall amplification of 100–10000 (v/v) and bandwidth 20-450Hz. The signals were acquired at 1kHz using bipolar 215 216 electrodes (parallel-bar Ag/AgCl, contact dimension:10x1mm, interelectrode distance:10mm). 217 The electrodes were placed over the muscle bellies of the RFe, BF, TA, MG, and LG 218 respectively muscles, in accordance with the SENIAM protocol guidelines (Hermens, Freriks, 219 Disselhorst-Klug, & Rau, 2000). Prior to electrode placement, the skin was shaved and then 220 cleaned with alcohol cotton swabs to reduce electrode-skin impedance. The kinematic and 221 sEMG signals were synchronised with the 3D motion capture system (Vicon®).

222

223 Data processing

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225 The sEMG data were processed based on the selection of ten central running cycles 226 (defined as two consecutive foot-strikes of the same foot on the ground treadmill) for each of the two running techniques (i.e., 10 for RF and 10 for FF). The vertical axis of the trajectories 227 228 recorded by the two reflective markers which were located on the participants' shoes, was 229 used to identify the stance and swing phases, using the events of foot strike and foot off. This 230 was manually performed using the Nexus software (version 2.8, Vicon Motion Systems, 231 Oxford, UK). The raw sEMG signals of all muscles were rectified and filtered with a lowpass filter (Butterworth; 4th order; cutting off frequency 20Hz) (Flores-Leon, Soto, Araneda, 232 233 Guzman-Venegas, & Berral de la Rosa, 2018). The signals of each muscle were then

234 normalised to its MVC and were cut according to the stance and swing phases, generating 101 235 data points per phase. The function spmld.util.interp (SPM1D, www.spmld.org) was used to 236 do this, as presented previously (Nüesch et al., 2019). Once the results for each participant 237 were acquired, an average curve from 10 running cycles was calculated for each muscle (RFe, 238 BF, MG, LG, and TA). Additionally, the level of co-activation between MG + LG and TA 239 during the two running techniques was calculated. For this purpose, we employed two 240 formulas, first we used MG activity + LG activity (total gastrocnemius activity, defined as GAS)/TA * 100, when co-activation was calculated during the swing phase and second, 241 242 TA/GAS * 100, when co-activation was calculated during the stance phase. Co-activations 243 were determined in this way considering which muscle was acting as agonist or antagonist 244 during the running cycle (i.e., TA is predominately active during the end of the swing phase 245 and GAS muscles are predominately active at the beginning of the stance phase, see results). 246 The levels of co-activation were calculated only for the temporal regions that GAS and TA showed significant differences when running with a RF or a FF strike pattern (revealed by the 247 SPM analysis). 248

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251 Statistical analysis

253 Descriptive statistics were used to report the anthropometrics characteristics of the eleven 254 participants (i.e., mean \pm standard deviation). A paired-sample t-test using the open-source Statistical Parametric Mapping 1D package (SPM1D, www.spm1d.org) was applied to 255 compare the electromyographic activity (RFe, BF, MG, LG and TA) between running 256 257 techniques (RF vs FF) during the stance and swing phase and its respective temporal variation 258 in one dimension (1D). This was calculated using a threshold value estimated by SPM {t}, 259 where the null hypothesis was rejected if the trajectory of the 1D data exceeded the critical 260 value. The threshold t-value was estimated by using an α of 0.05, similarly to others (Moisan 261 et al., 2020; Pataky et al., 2016; Yong et al., 2020). Our null hypothesis for each muscle 262 measured was that there will be no differences in 1D sEMG data between the two different 263 running techniques (i.e., RF and FF). All SPM analyses were implemented using the Python 264 3.5 software (Van Rossum, 2016). Moreover, a Shapiro Wilk test was performed to assess if 265 the ratios between antagonist muscles (GAS/TA) for both techniques follow a normal 266 distribution. Once the normality of this data set was confirmed, the ratios between the RF and 267 FF techniques were compared with a t-test or Wilcoxon for paired data. The level of
268 significance α, was set at 0.05 (GraphPad 9v Software, San Diego, California, USA).

270 271

272 **Results**

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274 SPM analysis - stance phase

For the MG muscle we observed that two supra-threshold clusters exceeded the critical 276 277 value t' = 4.195 at the beginning of the stance phase, indicating greater MG activity during FF 278 running compared to RF running at the same time-instant (RF, initial contact; 0-13%, p<0.001 279 and 18-19.5%, p=0.041; figure 1). Similarly, for the LG muscle, two supra-threshold regions 280 (critical value t' = 4.138) were observed, suggesting greater activation of the LG muscle during 281 the beginning of the stance phase, when the FF running technique was used (0-6%, p=0.008 and13.5-19%, p=0.012; figure 1). No significant differences between RF and FF running were 282 observed in the activation of the RFe, BF, and TA muscles (figure 1) during stance phase 283 284 (p>0.05).

285

286 SPM analysis - swing phase

287 For the MG muscle we observed that one supra-threshold region exceeded the critical 288 289 value t' = 4.593, suggesting a higher activation of the MG muscle at the end of the swing phase 290 during FF running (66-100%, p<0.001). The LG muscle showed two supra-threshold regions 291 which exceeded the critical value t' = 4.704 (figure 1) at the end of the swing phase, suggesting 292 a higher activation of the LG muscle during FF running (75-93% and 95-100%, both with 293 p<0.001). Two infra-threshold regions were observed for the TA muscle, during the swing 294 phase, one between 59% and 60% of the running cycle, and one between 82-94% (p=0.04 and 295 p<0.001, respectively). Both exceeded the critical value t' = 4.387, indicating a higher activity 296 of the TA muscle when the RF running technique was used (figure 1). No differences in the 297 activity of the RFe and BF muscles between the two running techniques were observed 298 (p>0.05). 299

300

*** Add Figure 1 here, please***

301 Co-activation

302

Considering that the muscle activity of GAS and TA (antagonistic muscles), differed significantly between the two running techniques, the co-activation was calculated for the beginning of the stance phase (0-19%) and end of the swing phase (82-100%). The results showed a higher level of co-activation (both GAS/TA and TA/GAS) with the use of RF, described in both phases (stance phase: FF= $5.102 \pm 3.95\%$ vs RF= $14.76 \pm 8.92\%$; 95% confidence interval= 3.38 to 15.93; p=0.0029; swing phase: FF= $8.56 \pm 6.47\%$ vs RF= $41.23 \pm$ 20.94%; 95% confidence interval= 17.59 to 47.74; p=0.0007 figure 2)

310 311

*** Add Figure 2 here, please***

312 Discussion

313 We investigated temporal differences in muscle activity of a group of lower limb 314 muscles (LG, MG, TA, RFe, and BF) during RF and FF running, using SPM. When 315 comparing the two running techniques, SPM revealed differences in the muscle activity of the 316 leg muscles (LG, MG, and TA), during both stance and swing phases of the running cycle. 317 The SPM analysis revealed that the LG and MG muscles' activity was higher during FF 318 running, for both the stance and swing phases. More specifically, in terms of the stance phase, 319 temporal differences in the activation of MG and LG were identified at the initial contact 320 (approximately between the 0-20% phase of the running cycle). This suggests that both the 321 gastrocnemius heads were more active at the beginning of the stance phase (initial contact). 322 This finding is in line with previous observations (Lieberman et al., 2010; Lucas-Cuevas et 323 al., 2016; Xu et al., 2021) and likely suggests that both the MG and LG muscles significantly 324 increase their activity during this phase of the running cycle, possibly to improve the control 325 of the ankle joint at the initial contact of the forefoot with the ground. More specifically, this 326 higher activation could improve the position of the leg-foot segments by placing it in a more 327 plantar flexed position, which enables the absorption of the ground forces at the initial foot 328 contact, through the decelerating eccentric (lengthening) contraction of those muscles and 329 storage of elastic energy (Lieberman et al., 2010; Xu et al., 2021; Yong et al., 2020). 330 Considering that a pre-activation phase was observed only during FF running and then there 331 was a similar activation of the gastrocnemius muscles between FF and RF running (40-100% 332 of the stance phase, or also described as impulse region), this could suggest that the 333 gastrocnemius muscles are activated for a longer time during FF running. This is an interesting 334 finding, and even though quite speculative, it could suggest that RF running does not 335 sufficiently activate the triceps surae and could possibly explain a less use of elastic energy 336 with the RF technique, as also proposed by others (Yong et al., 2020). Nonetheless, another

337 strategy that could also be used by the RF technique to improve the stability of the ankle is to 338 increase the co-activation between antagonist muscles, which could be a consequence of the 339 greater time of contact of the foot with the ground (38% stance in RF vs 28% stance in FF, 340 according to our results). This factor could be in concordance with a higher co-activation level 341 observed at the beginning of the stance phase (0-19%).

342 Moreover, the SPM analysis revelated significant differences in the activation of the MG, LG and TA muscles between the two running techniques, at the end of the swing phase 343 344 (i.e., between 80-100% of the running cycle). These findings could indicate that both 345 gastrocnemius portions contribute to high mechanical demand developed during the final 346 phase of the swing phase (temporally greater for MG, between 66 and 100%). This could be 347 possibly seen as a pre-activation strategy, which aims to achieve the optimal foot position 348 prior to initial contact. In this context, the findings from the MG are similar to those observed 349 in a recent study, which reported a higher activation of this muscle with the FF technique, 350 however, in a smaller range of the swing phase (91-100% of the running cycle) (Yong et al., 351 2020). For the TA muscle, the SPM analysis revealed two temporal regions during which TA 352 muscle's activation was higher when the RF running technique was used, during the swing 353 phase (between 59-60% and 82-94% respectively). This finding is likely related to the greater 354 ankle dorsiflexion observed before the initial contact of the foot with the ground, preventing 355 the drop of the forefoot during heel strike. The higher level of co-activation between GAS/TA 356 observed during the swing phase with RF running, could also reflect a (stiffening) strategy to 357 improve ankle control before of the initial contact of the foot with the ground. Previous studies 358 have also reported similar findings, but their results were based on simple measures of 359 centrality and dispersion (i.e., comparing mean values of EMG amplitude) and not based on 360 SPM analysis which considers the full time series of a task (Clarke, Frederick, & Cooper, 361 1983; Lucas-Cuevas et al., 2016; Yong, Silder, & Delp, 2014). Therefore, these studies were 362 not able to identify temporal differences in activation between running techniques. On the 363 contrary, in the present study we were able to identify the exact time-instants where the EMG 364 activity varied between running techniques, including thigh muscles that are not commonly 365 investigated. This highlights the usefulness and the superiority of the SPM analysis compared 366 to more simple statistical analysis approaches.

Moreover, considering the interesting differences in the muscle activity of the leg muscles during the stance and swing phase, in particular with use to the FF technique, it is important to mention that some studies have described that an increased gastrocnemius muscle activation also increases the stress in the muscle-tendon unit, causing a higher plantar flexor tendon energy storage (Yong et al., 2020). This could increase the work of the Achilles tendon
(Kernozek, Knaus, Rademaker, & Almonroeder, 2018), potentially generating serious injuries
related to the cyclical loading of the triceps surae muscle-tendon complex during longdistance running (Kernozek et al., 2018; Raichlen, Armstrong, & Lieberman, 2011; Yong et
al., 2020). Thus, future studies should try to investigate the optimum training volume for FF
running, since the cyclical demand on the Achilles tendon during a race can potentially induce
muscle-tendon injuries to this region.

378 Importantly, there is currently only one study that has assessed the temporal variation of 379 LG, MG and TA EMG amplitude during these two running techniques (Yong et al., 2020), 380 however, without assessing the behaviour of the RFe and BF (thigh) muscles. With regards to 381 the thigh muscles, our results indicated that their level of activation was similar between the 382 two running techniques across the whole running cycle (i.e., during both the stance and swing 383 phases) (figure 1). This could suggest that the mechanical adjustments required to perform each 384 of these techniques, do not affect the behaviour (i.e., activation level) of the thigh muscles. 385 This is an interesting finding, as each of the running techniques requires modification of the 386 motion patterns across the lower limb joints (Xu et al., 2021), which could possibly alter the 387 muscle activity levels of the muscles in this region. Contrary to this, our results showed that 388 the RFe and BF muscles' activity did not differ between the two running techniques. However, 389 this could be possibly attributed to the fact that the foot strike pattern has little biomechanical 390 effect on the hip and knee joints during running, with the differences being more evident in the 391 ankle-joint (Xu et al., 2021). Thus, this could partly explain the lack of differences for these 392 two muscles (RFe and BF) between running techniques.

393

394 Lastly, some limitations need to be acknowledged. Firstly, the environment where the 395 runners were evaluated did not represent the real place where they usually train. Secondly, all 396 participants routinely used the RF technique, and therefore, they were exposed to the FF 397 technique for the first time in this study and by a short time of evaluation. Although all 398 participants were familiarised and trained with the FF technique prior to the recording, we 399 cannot exclude the possibility that the results were affected by this issue to a certain extent. 400 Future studies should aim to overcome this limitation by recruiting runners who routinely use 401 both running techniques.

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403 Conclusions

404 This study extends our knowledge about lower limb muscle activity during two commonly used running techniques by using SPM analysis, which allows the identification 405 406 of the exact time-instants where differences in electromyographic activity exist. During FF 407 running, a higher LG and MG myoelectric activity was observed at the beginning of the stance 408 and at the end of the swing phases respectively. During RF running, at the same time-instant 409 that higher MG and LG muscle activation was observed, i.e., during the end of the swing 410 phase, the TA muscle's activity was also higher. Interestingly, we did not observe any 411 differences in the activity of the RFe and BF muscles, strongly suggesting that these two 412 running techniques predominately reflect adjustments of the shank and not the thigh muscles. 413 These findings highlight the importance of SPM for the accurate assessment of differences in 414 muscle activity during running, as this technique enables the identification of the exact time 415 instants when statistical differences exist.

416

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541 Figure 1: Shows the average activity of the rectus femoris (RFe), biceps femoris (BF), lateral gastrocnemius (LG), medial gastrocnemius (MG), and tibialis anterior (TA) adjusted by 542 543 %MVC (from superior and inferior image). Statistical differences were analysed with SPM{t} between running techniques (rearfoot: blue; forefoot: red) during the stance (two columns of 544

the left) and swing phase (two columns of the right). Grey bars show the regions with statistical
differences (p<0.05), concordant with the results of SPM{t}.



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Figure 2: Shows the comparison between the coactivation percentages between the gastrocnemius muscles (GAS) and tibialis anterior (TA) during rearfoot and forefoot techniques, calculated on the regions where significant differences between running techniques were identified with SPM. Accordingly, the figure shows co-activation results at 0-19% of the stance phase (A) and 82-100% of the swing phase (B) phase. *p-value value is indicated in the figure.

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