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Published in:
Journal of Electromyography and Kinesiology

DOI (link to publication from Publisher):
10.1016/j.jelekin.2021.102624

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Journal of Electromyography and Kinesiology 62 (2022) 102624

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Surface EMG variability while running on grass, concrete and treadmill

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ARTICLE INFO

Keywords:
Electromyography
Running
Treadmill
Concrete
Grass
Coefficient of variation

ABSTRACT

This study aimed to investigate whether inter-trial variability in muscle activity (electromyography, EMG) during running is influenced by the number of acquired steps and running surface. Nine healthy participants ran at preferred speed on treadmill, concrete, and grass. Tibial acceleration and surface EMG from 12 lower limb muscles were recorded. The coefficient of variation (CV) from the average EMG and peak EMG were computed from 5, 10, 25, 50 and 100 steps in each running surface. Data average stability was computed using sequential estimation technique (SET) from 100 steps. The CV for average and peak EMG was lower during treadmill running compared to running on grass ($-11 \pm 2.88\%$) or concrete ($-9 \pm 2.94\%$) ($p < 0.05$), without differences across the different number of steps. Moreover, the peak EMG CV from peroneus longus was lower on concrete ($p < 0.05$), whereas gluteus maximus presented greater variability on grass compared to concrete ($p < 0.05$). The SET analysis revealed that average stability is reached with up to 10 steps across all running conditions. Therefore, treadmill running induced greater variability compared to overground, without influence of the number of steps on EMG variability. Moreover, average stability for EMG recordings may be reached with up to 10 steps.

1. Introduction

Running biomechanics has been assessed using different techniques, such as kinematics (e.g., running speed, stride length and/or joint angles (Edwards et al., 2012) and kinetics (e.g., ground reaction forces (Cavanagh and Lafortune, 1980), towards the implementation of safer and more effective training programs (Goss et al., 2015). However, assessing state-of-the-art biomechanical variables require data acquisition in laboratory settings, leading to different running techniques compared to running outdoors (Sinclair et al., 2013, Nigg et al., 1995). There is no consensus on whether performing biomechanical analysis on treadmills and overground results in similar research outcomes (Miller et al., 2019). Therefore, it is relevant to expand the knowledge regarding running biomechanics outdoors.

Running surface can affect running biomechanics (Tillman et al., 2002, Zrenner et al., 2019, Fu et al., 2015, Zeng et al.), as runners adapt their lower limb kinematics to reduce the variability of impact forces depending on the surface (Dixon et al., 2000). Despite studies not showing differences in electromyographic (EMG) activity between treadmill and overground running (Schwab et al., 1983, Montgomery et al., 2016), vastus lateralis activation during treadmill running is reduced when compared to overground (Wank et al., 1998). In addition, there are similar spatial inter-muscular recruitment patterns between treadmill and overground running (Oliveira et al., 2016). Therefore, it is relevant to deepen our understanding on the adjustments that different running surfaces impose to lower limb muscle activity.

Movement variability is a result of complex fluctuations in the control of motor function (Stergiou et al., 2006). Despite potential effects of running surface on movement variability, the number of optimal strides when performing iterative tasks can affect the outcomes from biomechanical analyses. It has been previously proposed that acquiring > 25 steps/running cycles may maximize data average stability and statistical power in various biomechanical parameters (Oliveira and Pirscoveanu, 2021). However, such recommendation does not account for EMG activity, for which there is no recommendation concerning an optimal amount of running steps for data analysis. It is known that EMG presents distinct variability when compared to running kinematics/kinetics (O'Connor and Hamill, 2004). Therefore, it is plausible that large number of running steps (>25) could be relevant to reduce EMG variability regardless of the running surface.

Assessing muscle activity during running is highly relevant to deepen our understanding on motor control strategies applied in different

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https://doi.org/10.1016/j.jelekin.2021.102624
Received 13 July 2021; Received in revised form 30 October 2021; Accepted 30 November 2021
Available online 8 December 2021
1050-6411/

scenarios. However, little is known regarding the effects that different running surfaces impose to the variability of lower limb muscle activity. Therefore, the aim of this study was to investigate whether the lower limb EMG inter-trial variability during running may be influenced by the number of acquired steps and running surface such as grass, concrete or treadmill. We hypothesized that: 1) There is lower EMG variability during treadmill running when compared to concrete and grass, as treadmill running is performed under fixed running speed. 2) The EMG variability is reduced as a function of the number of steps used to compute an average, regardless of the running surface.

2. Methods

2.1. Participants

Nine healthy physically active male (age: 21.4 ± 2.1, body mass: 74.3 ± 7.6, height: 174.9 ± 10.1, weekly running volume: 26.3 km) participated in this experiment. Participants reported to be right dominant and rearfoot runners, without lower limb musculoskeletal injuries within 6 months prior to the experiment. Previous experience with treadmill running was an inclusion criterion. Participants received verbal and written information regarding the experiment prior to consenting to participate. All experimental methods were carried out in accordance with the relevant guidelines and regulations, and the experimental procedures of the present study were in accordance and approved by the Ethical Committee of North Jutland (Region Nordjylland).

2.2. Experimental design

In a single session, participants performed running while wearing their preferred running shoes. The experiment was conducted at a gymnasium containing a room with a treadmill and an outdoor area. The outdoor run was conducted at the outdoor area containing a 120-m long flat and straight section of grass and concrete side-by-side. Initially, participants were familiarized to the treadmill (WoodwayPro, Foster Court Waukesha, USA) by jogging at 9–10 km/h for 5 min. The preferred running speed was determined using a protocol based on Jason et al. (Jordan et al., 2007). Subsequently, participants performed 5-min treadmill running at the target speed, while stride frequency and lower limb EMG were acquired.

In addition, after a 3–5 min familiarization to running outdoors, participants ran continuously for 5 min along the 120-m track, leading to 5–6 laps on the concrete and on grass at the target speed. A metronome was used to help participants to replicate their stride frequency from treadmill running. A GPS watch (Forerunner 745, Garmin, Olathe, Kansas, USA) was used to set and record running speed. The test was stopped in case participants lost pace. A 3-minute rest period between conditions was imposed, and the order of overground tasks was randomized.

2.3. Data recordings

2.3.1. Surface electromyography

EMG signals were recorded using a wired EMG amplifier (Biovision, Wehrheim, Germany, 2,000 Hz, 12 bits), which acquired bipolar EMG through pairs of Ag/AgCl electrodes (AmbuNeuroline 720 01-K/12; Ambu, Ballerup, Denmark) with 22 mm of center-to-center spacing. Prior to electrode placement, the skin was shaved and lightly abraded. Surface EMG were recorded from tibialis anterior (TA), peroneus longus (PER), soleus (SO), gastrocnemius lateralis (GL), gastrocnemius medialis (GM), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), semitendinosus (ST), gluteus maximus (GX), and gluteus medius (GME) of the right side according to Barbero et al. (Barbero et al., 2012). A reference EMG electrode was placed on the right tibia. Vertical acceleration of the right shank was recorded using a uni-axial accelerometer connected to the EMG amplifier. The accelerometer was placed at 1/3 distal from the knee joint, on the medial face of the tibia, tightly fixed using surgical tape. Participants ran using stretching pants to fixate EMG and accelerometer cables. The EMG amplifier and the recording personal computer were stored on a backpack that runners carried during the test.

2.3.2. Data analysis – Accelerometry

The vertical acceleration data was low-pass filter (60 Hz) and used to segment the EMG signals into running cycles as described elsewhere (Oliveira et al., 2016). The peak vertical acceleration (PK_{ACC}) was defined as the positive peak of the derivative immediately prior to the minimum acceleration defined previously (Oliveira et al., 2016). Data regarding changes in direction was removed by excluding peaks falling below 90% of the median PK_{ACC} across the entire recording.

2.3.3. Data analysis – Electromyography

The raw EMG was initially band-pass filtered (10–500 Hz, 4th order Butterworth), full-rave rectified and low-pass filtered (10 Hz). The time indexes from the accelerometer data were used to segment the EMG into running steps. Gait cycles showing erroneous EMG envelopes in comparison to expected curves were excluded by visual inspection. Indeed, EMG signals of each participant and condition were visually checked for unexpected envelopes, e.g., if there was no activity for gastrocnemius medialis muscle during mid-stance, that cycle was considered an erroneous cycle and discarded from the next processing steps. Subsequently, running cycles were time-normalized to 200 data points (Oliveira and Pirscoveanu, 2021). We reported data only from the first 100 running steps of each participant, as the use of 125, 150, 175 or 200 continuous steps showed similar results to using only 100 steps. The average EMG, peak EMG and PK_{ACC} were computed from the 100 EMG envelopes and acceleration curves of each participant.

2.3.4. Coefficient of variation

The coefficient of variation (CV, as %) from the average vertical tibial acceleration (TIB_{CV}), average EMG CV (AVR_{CV}) and peak EMG CV (PK_{CV}) were computed from 100,000 random samples of 5, 10, 25, 50 and 100 steps for each runner for all three running surfaces (Knudson, 2017). These 100,000 CV values were averaged for each runner.

2.3.5. Sequential estimation technique (SET)

SET determines the point of mean stability of a variable (Taylor et al., 2015). The 100 steps were averaged to create the target stability, from which a ± 25% bandwidth was determined. Subsequently, a moving average starting from the first two points and including a subsequent point at each iteration was computed until all 100 steps were included. The first point that settles within the bandwidth along with all subsequent points recorded is defined as the stability point. SET was calculated for the average EMG (AVR_{SET}), peak EMG (PK_{SET}), and peak vertical tibial acceleration (TIB_{SET}).

2.4. Statistics

Kolmogorov–Smirnov test of normality was used to verify and confirm normal distribution of running speed, AVR_{CV}, PK_{CV}, TIB_{CV}. A one-way repeated measures ANOVA was used to assess the effect of running surface (treadmill *vs* concrete *vs* grass) on running speed. A Linear mix model was used to assess the within-subject effect of surface (treadmill *vs* concrete *vs* grass) and the between-subject effect of number of steps (5 *vs* 10 *vs* 25 *vs* 50 *vs* 100) on TIB_{CV}, AVR_{CV} and PK_{CV}. Cohen's D effect size (ES) was computed for all comparisons. A post-hoc test (Bonferroni) was applied in case of main effect of surface was found. Non-parametric Kendall's W test was used to assess the effect of surface (treadmill *vs* concrete *vs* grass) on the AVR_{SET}, PK_{SET}, and TIB_{SET} during running. We used Benjamini-Hochberg procedure to correct p values for multiple comparisons. The significance level was set at $P < 0.05$ for all statistical tests.

3. Results

3.1. Running speed

Running speed was similar across running conditions (TRD: 3.19 ± 0.19 m/s; CCT: 3.19 ± 0.18 m/s; GRA: 3.21 ± 3.18 m/s, $P > 0.05$).

3.2. Vertical tibial acceleration

Twenty running steps were required to reach average stability for TIB_{SET} for running on concrete and grass, whereas treadmill running required approximately 60 steps. However, no significant main effect of condition was found for TIB_{SET} ($P < 0.05$, Fig. 1A), due to large inter-subject variability. There was a significant main effect of running surface on TIB_{CV} ($F_{2,80} = 18.22$, ES = 0.31, $P_{adj} < 0.001$, Fig. 1B). The *Post-hoc* analysis revealed that TIB_{CV} from treadmill running (13.02 ± 0.53%, averaged across all number of steps) was lower than the TIB_{CV} from grass (16.83 ± 0.79%, $P_{adj} < 0.001$) and concrete (14.97 ± 1.0%, $P_{adj} = 0.05$). No main effect of number of steps ($P_{adj} > 0.05$) or condition *vs* number of steps interaction ($P_{adj} > 0.05$) were found.

3.3. Average EMG CV

There were significant main effects of condition for all muscles, except BF and GME (Fig. 2, and Supplementary Table 1 for statistical outcomes). The *post-hoc* analysis revealed lower AVR_{CV} (5–31% reduction, $P < 0.05$) during treadmill running when compared to grass and concrete for TA, PL, SO, GM, VM, and RF. In addition, there was a lower AVR_{CV} (13–27% reduction, $P < 0.05$) for treadmill running when compared to grass for GL, ST and GX. In addition, there was a greater AVR_{CV} (10–12% increase, $P < 0.05$) during running on grass when compared to concrete for TA and GX. No effects of number of steps were found for all the muscles ($P > 0.05$).

3.4. Peak EMG CV

There were main effects of condition for TA, PL, SO, GM, GX, and GME (Fig. 3, and Supplementary Table 2 for statistical outcomes). The *post-hoc* analysis revealed greater PK_{CV} running on grass when compared to concrete for PL (15 ± 3.28%) and GX (13 ± 4.32%). Conversely, SO presented lower PK_{CV} running on grass when compared to concrete (−8 ± 4.32%). Moreover, there was a lower PK_{CV} for concrete when compared to treadmill running for PL (−11 ± 2.51%), and greater PK_{CV} during concrete when compared to treadmill running for GME (13 ± 9.03%). Finally, PK_{CV} was greater during grass compared to treadmill running for GME (6 ± 6.76%). No effects of number of steps were found for all the muscles ($p > 0.05$).

3.5. Average EMG SET and peak EMG SET

There were no significant main effects of condition for both AVR_{SET} (Fig. 4A, $P_{adj} > 0.05$) and AVR_{SET} (Fig. 4B, $P_{adj} > 0.05$) across running surfaces (Fig. 4, Supplementary Table 3 for statistical outcomes). In addition, stable averages through SET calculation were reached predominantly with <10 steps across all lower limb muscles.

4. Discussion

The main finding of this study was that running on grass and concrete increases tibial acceleration and lower limb EMG variability when compared to treadmill running. However, different number of running steps does not influence variability. Moreover, the data average stability for the mean and peak EMG was reached with up to 10 steps. Therefore, overground running either on soft or hard surface increases EMG variability when compared to treadmill running. Nonetheless, the use of up to10 running steps seems appropriate to represent average and peak EMG regardless of the running surface.

4.1. Tibial vertical acceleration

The greater variability for tibial acceleration during the overground conditions compared to treadmill running corroborates a previous study assessing differences in muscle synergies between treadmill and overground running (Oliveira et al., 2016). The constant belt speed act as a task constraint during treadmill running, leading to inherently lower movement variability (Paquette et al., 2017). Conversely, outdoor running allows free adjustments of posture and speed, for which runners can use distinct motor control strategies. Tibial acceleration may be influenced by running speed and technique (Sheerin et al., 2019), consistently increasing as a function of running velocity (Lafortune et al., 1995). Although running speed was strictly controlled across conditions in our study, participants might have changed their running kinematics, especially on the treadmill. It has been reported that treadmill speed can be maintained with a shorter propulsive phase when compared to overground running (Baur et al., 2007). Moreover, a reduction in the braking phase duration during treadmill running

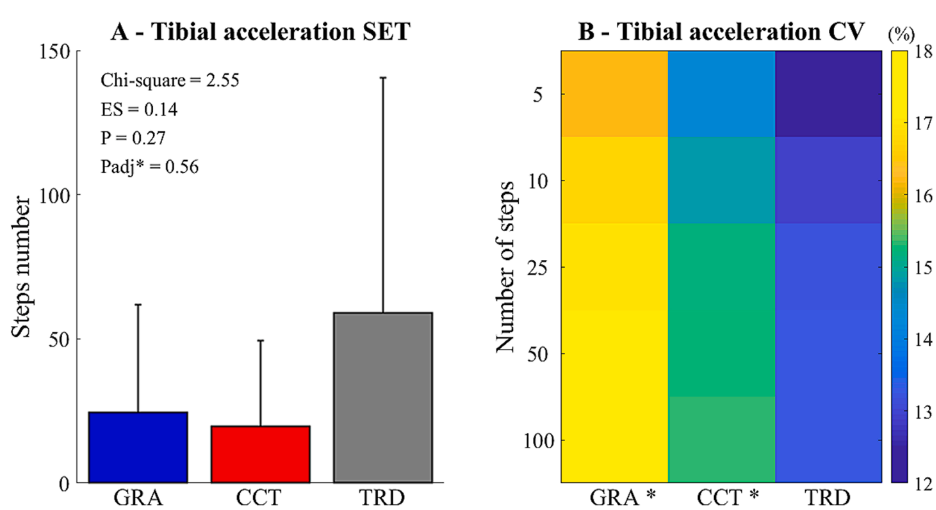

Fig. 1. Comparison tibial acceleration for TIB_{SET} during running on different surfaces (A) and TIB_{CV} during running on different surfaces with different number of steps (B). *, significant different from treadmill.

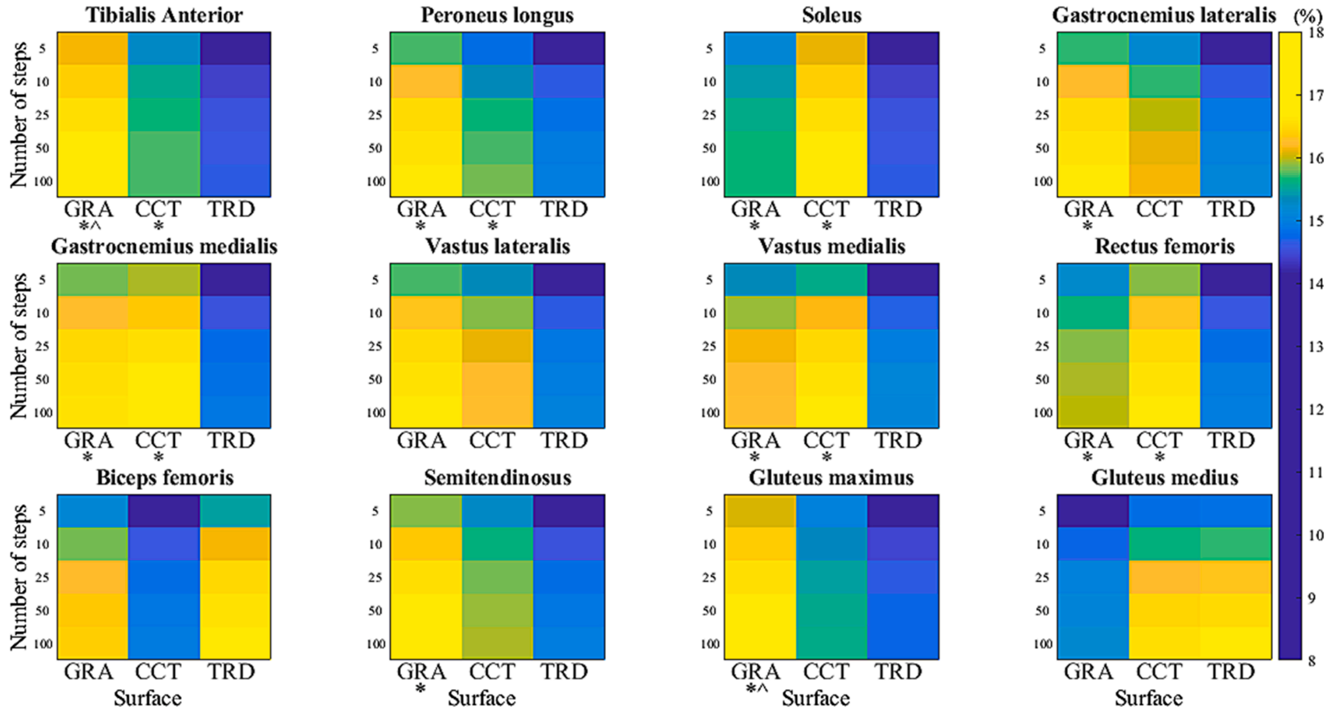

Fig. 2. Colormap illustrating the average step-to-step coefficient of variation from the average EMG (AVR_{CV}) of lower limb muscles during running on grass (GRA), concrete (CCT) and treadmill (TRD) when using 5, 10, 25, 50 or 100 running steps. * denotes significant different from treadmill ($P < 0.05$); ^ denotes significant different from concrete ($P < 0.05$).

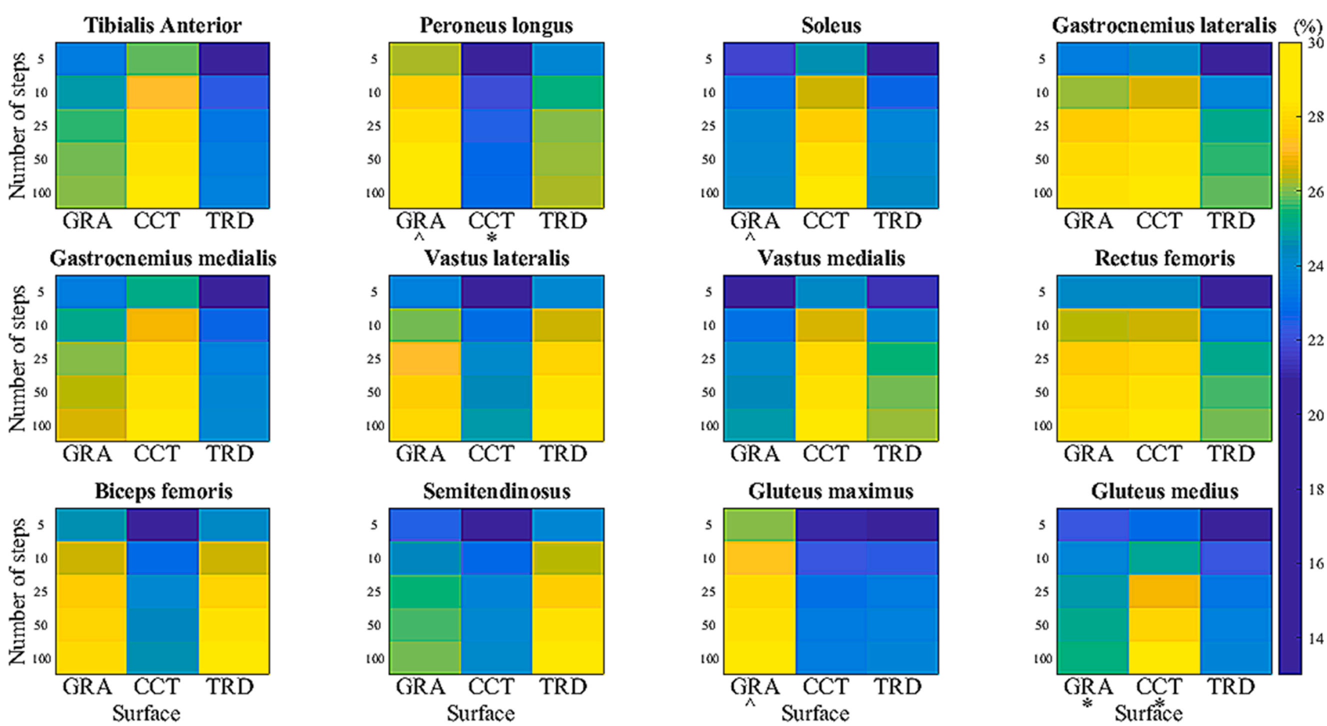

Fig. 3. Colormap illustrating the average step-to-step coefficient of variation from the peak EMG (PK_{CV}) of lower limb muscles during running on grass (GRA), concrete (CCT) and treadmill (TRD) when using 5, 10, 25, 50 or 100 running steps. * denotes significant different from treadmill ($P < 0.05$); ^ denotes significant different from concrete ($P < 0.05$).

minimizes backward and forward motion due to the moving belt (García-Pérez et al., 2014). These facts may partially explain the reduced TIB_{CV} during treadmill running.

4.2. Average and peak EMG CV

Our result showed greater AVR_{CV} and PK_{CV} of gluteus maximus during grass compared to treadmill or concrete. An important function of gluteus maximus is to stabilize the trunk against flexion during

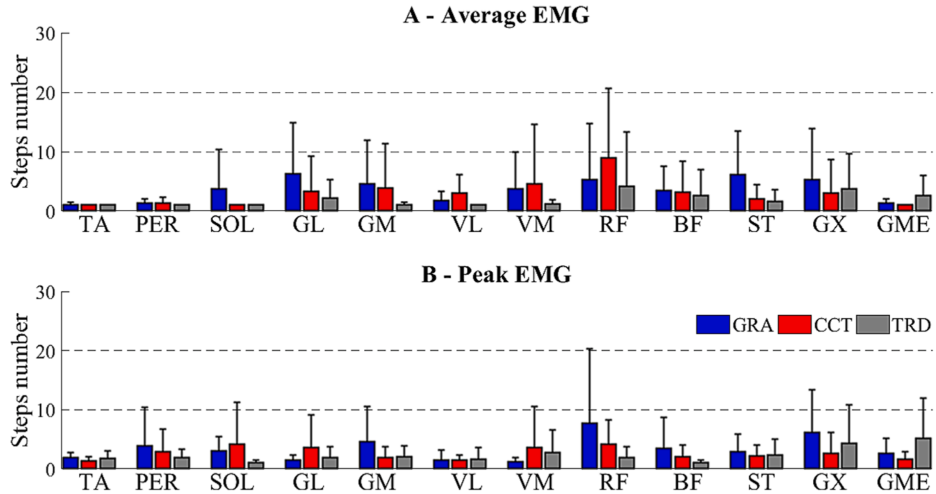

Fig. 4. Mean (SD) sequential estimate technique (SET) outcomes from the average EMG (AVR_{SET}) and peak EMG (PK_{SET}) extracted for 12 lower limb muscles during running on grass (GRA), concrete (CCT) and treadmill (TRD).

running (Marzke et al., 1988). The gluteus maximus is activated at moderate to strong levels at the end of swing phase and during the first third of stance (Zeitoune et al., 2020), reaching peak activation prior to initial contact during running (Jönhagen et al., 1996). This mechanical characteristic may amplify the demand for constant updates on the gluteus maximus muscle activation during running on grass. On the other hand, gluteus medius presented greater variability for overground conditions only for PK_{CV}. The eccentric gluteus medius activity is relevant during early stance to control internal rotation and adduction of the femur (Torry et al., 2006). Moreover, it has been shown that overground running induces greater hip rotation (~8°) at the transverse plane during initial contact when compared to treadmill running (Sinclair et al., 2013). Subsequently, it is necessary to increase gluteus medius activation during overground running.

There were distinct results for soleus and peroneus longus for AVR_{CV} and PK_{CV}. The soleus PK_{CV} was greater on concrete compared to grass, while AVR_{CV} increased on concrete and grass compared to treadmill. A previous study assessing plantar forces during running reported similar maximal plantar forces for different overground surfaces (concrete, synthetic rubber, and grass) (Wang et al., 2012). However, running on grass is the least demanding on lower leg muscles when compared to asphalt or gravel. Therefore, the soleus variability may be associated with the stiffness of the running surfaces, as concrete lead to greater variability than grass. Regarding peroneus longus, running on concrete induced the lowest PK_{CV}, whereas the lowest AVR_{CV} was found for treadmill running. Peroneus longus activation during running is related to medial–lateral ankle stability, counteracting unintended foot inversions (Santilli et al., 2005). The concrete surface is more stable than grass or treadmill for running, potentially increasing the confidence of our participants to perform initial contact. Therefore, greater peroneus longus EMG variability in unstable surface conditions is related to the need for adjustments to mechanical demands that may vary at every step.

The muscles tibialis anterior, gastrocnemius lateralis, and gastrocnemius medialis showed lower AVR_{CV} variability during treadmill running, which may be related to distinct postural control strategies when the running speed is imposed by the moving belt (Baur et al., 2007). In addition, the greater AVR_{CV} for tibialis anterior during running on grass compared to concrete may be related to greater need for ankle stability on grass. Moreover, vastus medialis and rectus femoris presented the lowest variability during treadmill running when compared to overground conditions. This fact may be related to a greater shock absorption provided by the treadmill, which consequently reduces the amount of energy returned to the runner (Colino et al., 2020). Furthermore, the hamstring muscles are involved in motor preparation to landing and the control of early stance (Van Hooren et al., 2020). Therefore, an increased variability in semitendinosus AVR_{CV} during grass running may suggest greater need of re-adjustments on motor strategies to maintain running patterns on unstable surfaces.

4.3. Variability across different number of running steps

It has been recently reported that a minimum of 25 running steps may be ideal to achieve appropriate data stability and statistical power to evaluate running kinematics/kinetics variables (Oliveira and Pirscoveanu, 2021). Determining the minimum number of steps is highly relevant to assess and adequately report running biomechanical variables, being also relevant to optimize experimental protocols. Moreover, fewer number of steps demands an increase in sample size to ensure adequate statistical power (Owings and Grabiner, 2003). It is noteworthy that the present study investigated changes in EMG variability instead of kinematics/kinetics variables, limiting the direct comparison to previous literature. We observed similar muscle activity among different sequence of steps (5 up to 100 steps, and even up to 200 steps from preliminary analysis), demonstrating that muscle activity over short durations is less affected by the repetitive nature of running when compared to kinematics/kinetics variables.

4.4. SET analysis

Contrary to our expectation, no difference was found for AVR_{SET}, PK_{SET}, or TIB_{SET}. A previous study demonstrated that at least 15 steps may be required to reach average stability in different running kinematics/kinetics variables (Oliveira and Pirscoveanu, 2021). The EMG follows closely the temporal pattern of the average profile, while the amplitudes differ some 15–25% per step (Gazendam and Hof, 2007). Previous study assessing the effect of using 2 to 40 steps on walking motor modules showed that at least 20 steps are necessary to capture most of the step-by-step variability (Oliveira et al., 2014). In addition, the use of 3 to 10 walking steps provides distinct results depending on the walking speed. The EMG patterns may become more stable at faster locomotion speeds (Cappellini et al., 2006), explaining the data average stability being defined with up to 10 steps. Therefore, our results suggest that it is not necessary to record extended periods of data to represent EMG during running, regardless of the running surface.

4.5. Limitations

Firstly, there is a limited sample size in in our study (n = 9), and future studies comparing the stability of EMG variables from different running conditions from a larger sample would be highly relevant to confirm our preliminary results. Secondly, running technique may influence muscle activation, as forefoot running reduces tibialis anterior EMG activity during late swing phase when compared to rearfoot running (Yong et al., 2014). In addition, medial and lateral gastrocnemius present greater EMG activity during late swing in forefoot striking runners (Yong et al., 2014). Therefore, extrapolating these results to forefoot runners must be done with caution. Finally, our study did not assess kinematic parameters from running in different conditions, limiting our analysis regarding potential differences in movement patterns across these running conditions. Previous studies have shown kinematic differences when running on different surfaces (Zhou et al., 2021), as well as between treadmill and overground running (Sinclair et al., 2013). Therefore, it is plausible that different kinematic patterns could be found between the three investigated running conditions. Combining EMG and motion capture in future studies can help deepen our understanding on the neuromechanical differences of running in different surfaces. Moreover, it could be established whether the inter-trial variability in EMG and kinematics variables are similarly influenced by running technique and running surface.

5. Conclusions

In summary, this study revealed that EMG variability for lower limb muscles is increased when running on concrete and grass compared to treadmill running. Moreover, evaluating EMG data using as low as 5 steps does not compromise the inter-trial variability when compared to 100 steps. Finally, mean and peak EMG data stability was achieved using up to 10 running steps regardless of the running surface. Our results may serve as guidelines to assist researchers in designing optimal experimental protocols to investigate running biomechanics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2021.102624.

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