

## Article

# The Symmetry of Fatigue of Lower Limb Muscles in 400 m Run Based on Electromyography Signals

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**Abstract:** Background: This study assesses curved track effects on fatigue symmetry and lower limb muscle activity while taking maximum velocity running kinematics into account. Methods: Polish master class athletes were examined (age  $24.6 \pm 3.67$  years, bm  $78.9 \pm 6.02$  kg, and bh  $186.1 \pm 6.63$  cm). The measurements were made on a 400 m synthetic surface athletics track. The DelSys 16 channel system was employed to measure the activity of the right and left leg muscles. The kinematic variables of the run were obtained using a 3-axis accelerometer built into the recorder. Results: The study revealed curved track effects on asymmetric muscle activity and running kinematics in the first two sections of the run. On the first curve, the symmetry index (SI) was 8.1%, while in on straight, it was 11.5%. Moreover, significantly lower values of the fatigue index  $b$  were found for the right limb ( $F_{(3,36)} = 6.504$ ;  $p = 0.0152$ ). Conclusions: A reduction of asymmetric muscle activity is linked with compensatory muscle stimulation triggered by the nervous system and with adjusting running kinematics to changing external conditions. Therefore, the main focus further research should be on the optimal interaction between stride length and frequency in relation to the muscle activity corresponding to the track geometry.



**Citation:** Iwańska, D.; Tabor, P.; Grabowska, O.; Mastalerz, A. The Symmetry of Fatigue of Lower Limb Muscles in 400 m Run Based on Electromyography Signals. *Symmetry* **2021**, *13*, 1698. <https://doi.org/10.3390/sym13091698>

Academic Editor: Robert Sainburg

Received: 5 August 2021

Accepted: 9 September 2021

Published: 14 September 2021

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**Keywords:** electromyography; fatigue; symmetry; run

## 1. Introduction

Numerous studies have indicated that athletics track geometry affects running kinematics. This is connected, among other things, to the fact that a standard 400 m athletics track consists of curved and straight sectors, which constitute approximately 42% and 58% of the track, respectively [1]. Many researchers have revealed significant differences in running kinematics in those sectors [2–7]. During curve running, together with an increase velocity, there is a decrease in stride duration [7–10] and in ground contact time [7,9]; it also indicates that maintaining the body in the lane is possible due to proper muscle activity. Additionally, changes in the running direction result in movement asymmetry [2,3,9,11]. The effect of the curve on these differences is even more profound when the inward body inclination is greater due to running velocity and the radius of the curve [12]. Taboga et al. [8] reported that during radius curve sprinting, stride length and stride frequency decreased, while ground contact time was 8% longer for the inside leg compared to the outside leg. Significant strength asymmetry was also noted in foot evtor and invertor muscles [13]. The authors associate this asymmetry with the specificity of track running. In addition, other studies have observed that faster running speed is achieved with greater ground forces and shorter ground contact times [14] and are related with the increased activity of the lower limb muscles [15]. Kyrolainen et al. [16] attribute enhanced muscle activity in the pre-contact phase to increased tendomuscular stiffness in the braking and propulsive phases. As a consequence, athletes need to develop effective muscle activity strategy over the course of the whole run. The above studies indirectly indicate that diverse running track geometries affect muscle activity, i.e., different muscle activity means that

fatigue is different in the inside and outside leg. This may lead to overloading effects as well as injuries in one of the limbs. Nonetheless, the effect can be completely reversed. By learning to cope with repeated changes in running conditions, the brain may adjust to covering particular sections of the run without producing asymmetry in muscle activity. However, it is hard to prove this hypothesis.

No comprehensive analysis has ever been performed regarding muscle activity during curve and straight running. Therefore, this study sought to at least partially verify this hypothesis and to assess curved track effects on fatigue symmetry and lower limb muscle activity while taking into account the maximum velocity running kinematics of elite Polish athletes.

## 2. Materials and Methods

### 2.1. The Inclusion Criteria

In order to take part in the research, the subjects had to manifest no asymmetries related to the length and strength of the lower limbs. For this reason, the height of their bony landmarks (sy-b, tro-b, ti-b, sph-b) as well as the muscle strength of the hip, knee, and ankle joints of both limbs were measured in static conditions. Individuals who demonstrated differences exceeding 0.5% in the length parameters and 3% in the strength parameters between the right and left lower limbs were excluded from the study [17]. In addition, only athletes of the highest sports class with a minimum 6 years of training experience could take part in the study.

### 2.2. Material

Ultimately, 11 elite (master class) male athletes (400–800 m runners) from the Polish national team participated in the study. Their mean age was  $24.6 \pm 3.67$  yrs, their body mass was  $78.9 \pm 6.02$  kg, and their body height was  $186.1 \pm 6.63$  cm. The number of participants was estimated on previous experiments. The a priori sample size was calculated by the G\*Power software (version 3.1.9.4, Düsseldorf, Germany) for the group by means of time interaction comparison (F test, ANOVA for repeated measures, within-between interaction with the following criteria: alpha level = 0.05, power = 0.80, f effect size = 0.25). Based on that procedure the estimated number of subjects was 10. To fulfil these requirements and to accommodate dropouts (~10–20%) in the training studies, a total of 11 men were recruited.

The study was conducted during a competition period. Prior to commencing the procedure, all of the athletes gave their written informed consent to participate in the study.

All participants gave their informed consent and were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of Józef Piłsudski University of Physical Education in Warsaw (SKE 01-02/2017, research project number N RSA4 05354).

### 2.3. Method

All of the measurements were made on a 400 m synthetic surface athletics track (IAAF class 1 athletic stadium). Before the tests, the participants performed a standard warm-up. To motivate the athletes to give their best possible performance, competition-like conditions were created, in which each athlete covered the distance accompanied by another competitor who did not take part in the experiment. The run began with a crouch start, and the time was registered using a professional measurement system used in national-level sporting events.

Surface electrodes (Trigno™ Wireless EMG: 4 bar contacts, 99.9% Ag,  $5 \times 1$  mm, 10 mm inter-electrode distance, CMMR > 80 dB, signal-to-noise ratio <  $0.75 \mu\text{V}$ ) were placed over the muscle bellies in line with fibre orientation to avoid muscle crosstalk [18]. Four muscles were selected for testing: the tibialis anterior (TA), lateral gastrocnemius (GA), rectus femoris (RF), and biceps femoris (BF). Inter electrode distance and electrode

placement procedure, as well as skin preparation were done in accordance with Hermans et al. and SENIAM recommendations [19]. EMG activities were recorded using a wireless system (Trigno™ Personal Monitor; Delsys Inc., Boston, MA, USA). Detection of heel-strike events were based on measurement of the accelerometers located in two Trigno sensors positioned at the ankle over the Achilles tendons [20,21]. All of the sensors were secured with elastic wrap. The EMG and accelerometer signals were digitally sampled at 1926 sa/s.

Afterwards, analysis was performed with the use of the fast Fourier transform (FFT). The data prepared in this manner were used to set:

- MPF—mean power frequency of the EMG signal

$$MPF = \frac{\sum_{i=1}^N f_i PSD_i}{\sum_{i=1}^N PSD_i}$$

where  $P_i$  is the EMG power spectrum at the frequency bin  $i$ ,  $f_i$  is the frequency value of EMG at the frequency bin  $i$ , and  $N$  is the length of frequency bin ( $N = 512$ ).

- RMS—root mean square.

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^N v_i^2}$$

where  $v_i$  is the voltage value of EMG channel at  $i$ th sampling, and  $N$  is the number of the samples in a segment.  $N$  was set to 512, and the EMG sampling rate was set to 2 kHz.

Normalization of EMG signals was performed by dividing the EMG signals from a given muscle and the EMG recorded from the same muscle during a maximal voluntary isometric contraction.

Within the given MPF time frames of the successively covered 100 m sections of the run (1st curve, 1st straight, 2nd curve, 2nd straight), the approximation of the signal was performed using the slopes ( $b$ ) of the regression lines estimated by the method of least squares, and the fatigue index  $b$  was calculated for the right- and left-leg muscles separately.

Muscle activity (RMS) was assessed separately for the right and left leg. 100% normalized values of muscle activity in particular sections of the track (1st curve, 1st straight, 2nd curve, 2 straight) were analyzed.

In addition, the symmetry index (SI) was calculated by normalizing the differences between the parameter values for the right and left leg with respect to the values obtained for the dominant leg [22].

For the kinematic variables, left stride duration ( $t$ ) was defined as the time between placing the right and left foot on the ground. Measurements were made using a 3-axis accelerometer built into the Delsys as well as the accelerometers found in the EMG electrodes placed on the tibialis anterior (TA) and the lateral gastrocnemius (GA) of the left and right limbs. The signal was processed using 20 Hz low pass Butterworth filter. Knowing the instantaneous acceleration value and ground contact time, it was possible to calculate the instantaneous velocity value of the body ( $v$ ) and its distance ( $d$ ) when the left foot was placed on the ground. The same procedure was adopted for the right limb. Knowing the number of steps performed in time units, it was possible to calculate left and right stride frequency ( $f$ ). The calculated parameters were averaged for particular sections of the run.

#### 2.4. Statistical Analysis Methods

The changes in the variables under investigation were assessed using ANOVA for repeated measures. The factors included in the analysis were the trajectories of the track divided into the 1st curve, 1st straight, 2nd curve, and 2nd straight as well as the right limb (R-outside) and the left limb (L-inside). Mauchly's test was applied to evaluate the sphericity assumptions. In the event of variables violating the sphericity assumptions, the results were evaluated with the Greenhouse–Geiser (G-G) correction. If the effects of the interactions between the examined factors were noted, Tukey's HSD test was used

for further analysis. All of the statistical analyses were performed using STATISTICA software (v.12).

### 3. Results

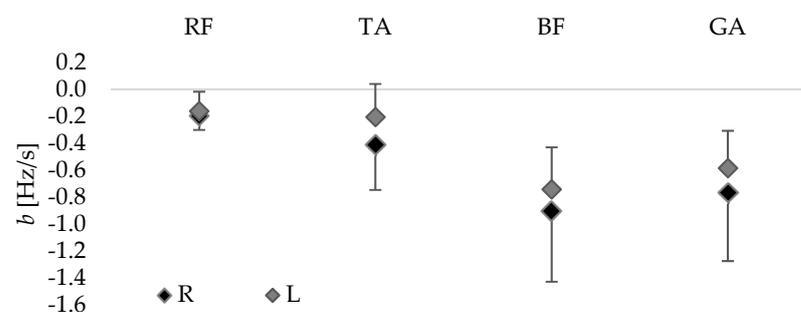
ANOVA for repeated measures revealed no effects of the interactions between the examined factors, i.e., the right and left lower limbs as well as the curved and straight sections of the track ( $F_{(3,27)} = 1.869$ ;  $p = 0.195$ ). Means  $\pm$  SD of the relative RMS values for the right (R) and left (L) limb obtained in the curved and straight sections of the track surface are shown in Table 1.

**Table 1.** Mean values  $\pm$ SD of the relative RMS values for the right (R) and left (L) limbs obtained in the curved and straight sections of the track.

Data	Limb	1st Curve	1st Straight	2nd Curve	2nd Straight
RMS %	R	76 $\pm$ 20.1	79 $\pm$ 18.8	89 $\pm$ 5.0	99 $\pm$ 1.7
	L	82 $\pm$ 7.9	88 $\pm$ 6.9	92 $\pm$ 6.8	98 $\pm$ 5.5

The asymmetry analysis of the relative RMS values for the right and left limbs during the run revealed the highest symmetry index (SI) in the first two sections of the run (1st curve and 1st straight). In Section 1 (curve), the SI was 8.1%, while in Section 2 (straight), the SI was 11.5%. In both cases, the left (inside) limb manifested greater muscle activity. However, this asymmetry was not significant. In turn, a significant increase was observed in the relative RMS values for both limbs in the other sections ( $F_{(3,27)} = 15.96$ ,  $p < 0.001$ ). The largest change in the RMS was noted in Section 3 (2nd curve) and Section 4 (2nd straight), which were both for the right and left limb. However, these changes were much greater for the left limb, and, between the sections, they totaled 3%, 13.8% ( $p < 0.01$ ), and 11.3% ( $p < 0.001$ ) for the right limb and 6.2%, 5.2%, and 6.4% for the left limb.

Afterwards, the muscle fatigue index values ( $b$ ) were analyzed. Lower values of this index point to greater fatigue. The mean index  $b$  values for particular right and left limb muscles are shown in Figure 1.



**Figure 1.** Mean  $\pm$  SD index  $b$  values for particular right (R) and left (L) limb muscles (RF—rectus femoris; TA—tibialis anterior, BF—biceps femoris, GA—lateral gastrocnemius).

Significantly lower index values  $b$  (which point to greater fatigue) were found for the right limb ( $F_{(3,36)} = 6.504$ ;  $p < 0.05$ ). The largest asymmetry occurred for the tibialis anterior, as the SI amounted to as much as 66%, which indicated greater right-side fatigue. For the other muscle groups, the SI was not as large; however, it was still significant (RF—19%; BF—19%; GA—26%).

The analysis revealed the effect of the muscle type on the index values  $b$  ( $F_{(3,36)} = 11.159$ ;  $p < 0.001$ ). Furthermore, observation power of this effect was significantly higher ( $\alpha = 0.998$ ) than it was in the case of the limb-related effect ( $\alpha = 0.699$ ).

The lowest  $b$  values were noted for the BF both in the right and left limbs. Significant differences in the  $b$  values were found between the BF and RF ( $p < 0.001$ ) as well as in the

TA ( $p < 0.05$ ). Compared to the RF, significantly lower  $b$  values were also observed for the GA in the right limb ( $p < 0.01$ ).

Further analyses focused on evaluating the effects of track trajectory on  $b$  in particular muscles of the right and left limbs. The mean  $b$  values are presented in Table 2.

**Table 2.** Mean values  $\pm$ SD of the relative RMS value for the right (R) and left (L) limbs obtained in the curved and straight sections of the track.

Muscle	Limb	1st Curve	1st Straight	2nd Curve	2nd Straight
RF	R	$-0.57 \pm 0.93$	$-0.44 \pm 0.87$	$-0.20 \pm 0.29$	$0.01 \pm 0.30$
	L	$-0.81 \pm 1.47$	$-0.18 \pm 0.48$	$-0.41 \pm 0.28$	$0.08 \pm 0.76$
TA	R	$-1.80 \pm 2.28$	$-0.65 \pm 1.02$	$-0.18 \pm 0.67$	$-0.18 \pm 0.41$
	L	$-2.97 \pm 2.94$	$-0.08 \pm 0.48$	$0.17 \pm 0.54$	$-0.11 \pm 0.88$
BF	R	$-1.81 \pm 2.24$	$-0.83 \pm 1.05$	$-0.40 \pm 0.79$	$-0.39 \pm 2.89$
	L	$-0.86 \pm 2.08$	$-1.18 \pm 1.12$	$-0.71 \pm 0.73$	$-1.15 \pm 0.93$
GA	R	$-0.28 \pm 1.49$	$-0.61 \pm 0.58$	$-1.03 \pm 1.57$	$-0.50 \pm 1.22$
	L	$-0.67 \pm 1.39$	$-0.47 \pm 0.97$	$-0.64 \pm 0.51$	$-0.17 \pm 0.64$

The multifactorial analysis of variance revealed significant effects resulting from the interactions between the examined factors (muscles, limbs, track trajectory) on  $b$  ( $F_{(9,108)} = 2.166$ ;  $p < 0.05$ ). The lowest  $b$  values were found in the first curve. In each subsequent sections of the run, the index  $b$  was considerably higher (yet not significantly different) for particular muscles ( $F_{(9,108)} = 2.253$ ;  $p = 0.056$ ). In the first curve, the highest  $b$  values were noted for the TA of the left limb and the BF of the right limb. The index  $b$  values for the TA were significantly higher compared to the other muscles ( $p < 0.001$ ). For this muscle, the effects of interactions between the track curve and the limb on  $b$  were found ( $F_{(3,27)} = 4.458$ ;  $p < 0.05$ ). It was revealed that fatigue changed while running through particular sections, and these changes differed for the right and left limbs. A different characteristic of fatigue was noted for GA. The lowest index values  $b$  were observed in Section 3 of the run (2nd curve) for the right limb and in Sections 1 and 3 (1st and 2nd curve) for the left limb. A different degree of fatigue was also noted for the BF of the left limb. The lowest index values  $b$  were observed in Sections 2 and 4 (1st and 2nd straight). Moreover, the extreme fatigue of this muscle was noted throughout the whole run.

In addition to the aforementioned data, the analysis included the kinematic variables of the run: stride duration ( $t$ ), stride length ( $d$ ), running velocity ( $v$ ), and stride frequency ( $f$ ) in particular sections. The mean values  $\pm$  SD of the variables are illustrated in Table 3.

**Table 3.** Mean values  $\pm$  SD of the relative RMS value for the right (R) and left (L) limbs obtained in the curved and straight sections of the track.

Data	Limb	1st Curve	1st Straight	2nd Curve	2nd Straight
$t$ [s]	R	$0.257 \pm 0.029$	$0.273 \pm 0.017$	$0.275 \pm 0.017$	$0.280 \pm 0.022$
	L	$0.248 \pm 0.022$	$0.258 \pm 0.019$	$0.265 \pm 0.021$	$0.273 \pm 0.021$
$d$ [m]	R	$2.27 \pm 0.21$	$2.43 \pm 0.19$	$2.33 \pm 0.18$	$2.14 \pm 0.19$
	L	$2.24 \pm 0.19$	$2.35 \pm 0.20$	$2.26 \pm 0.22$	$2.09 \pm 0.17$
$v$ [m/s]	R	$8.90 \pm 0.78$	$8.95 \pm 0.65$	$8.52 \pm 0.74$	$7.68 \pm 0.79$
	L	$9.04 \pm 0.70$	$9.13 \pm 0.77$	$8.52 \pm 0.75$	$7.69 \pm 0.77$
$f$ [Hz]	R	$3.9 \pm 0.43$	$3.7 \pm 0.23$	$3.7 \pm 0.22$	$3.6 \pm 0.29$
	L	$4.1 \pm 0.35$	$3.9 \pm 0.28$	$3.8 \pm 0.30$	$3.7 \pm 0.28$

No effects resulting from the interactions between the examined factors (the limb and the track trajectory) on any of the kinematic variables of the run were found. However, the effects on the obtained results were revealed for these factors when analyzed separately. For the first variable (stride duration), a significant limb effect was noted ( $F_{(1,9)} = 31.95$ ;  $p < 0.001$ ). The stride duration ( $t$ ) of the right (outside) leg was significantly longer than that of the left (inside) leg. Right-side asymmetry was in all of the sections of the run (average value SI = 4%). The greatest changes that occurred as a result of a significant track

trajectory effect ( $F_{(3,27)} = 26.78$ ;  $p < 0.001$ ) were observed between the 1st curve and the 1st straight, both for the left and right limbs. As for the other sections, the changes were not considerable.

The analysis of the stride length ( $d$ ) and stride frequency ( $f$ ) only revealed limb effects ( $F_{(1,9)} = 25.99$ ;  $p < 0.001$  for stride length;  $F_{(1,9)} = 29.77$ ;  $p < 0.001$  for stride frequency). A longer stride (average value SI = 3%) was observed for the outside leg. Simultaneously, lower stride frequency (average value SI = 4%) was manifested by the athletes. Despite the lack of significant effects caused by the track trajectory, the comparison of the stride length in particular sections of the run revealed the greatest positive change between the 1st curve and the 1st straight, and this change was bigger for the right limb (7.1%) than for the left one (4.7%). It was also noted that in the other sections, the stride length and stride frequency were lower.

Similar observations were made for the registered changes in running velocity ( $v$ ). The highest (and almost identical) velocity was noted in Sections 1 and 2 of the run. In Section 3 (2nd curve) and Section 4 (2nd straight), however, the running velocity was significantly lower. Between the last two sections, the mean velocity differed by nearly 10%. The effect noted here was significant ( $F_{(3,27)} = 21.26$ ;  $p < 0.001$ ). In turn, no significant differences were found between the right and left legs in terms of velocity. The SI did not exceed 2%.

#### 4. Discussion

Based on the findings of numerous studies, it was noted that fatigue in trained 400 m runners stemmed from overloading the musculoskeletal system [23]. However, the effect of fatigue was only observed when running at maximum velocity [24]. According to Wright and Weyand [25], the energetic cost while running increases together with a rise in the ground force application and muscle activity in the support phase. In turn, covering the curved section is associated with greater ground reaction forces for the outside leg [26]. Both of these observations indicate that the outside leg will manifest greater fatigue than the inside leg, which may lead to more frequent injuries. However, the question arises as to whether the specificity of training in elite athletes may contribute to the development of compensatory effects that would act as preventive measures, e.g., different running kinematics in particular sections resulting from different muscle activity adjusted to external conditions. Therefore, the study sought to assess curved track effects on fatigue symmetry and lower limb muscle activity in elite Polish athletes. Kinematic variables such as stride length, stride duration, stride frequency, and running velocity were also taken into account in the analysis.

Muscle fatigue was assessed based on index  $b$  of the regression line slope that illustrates the speed of changes in mean power frequency (MPF) of the EMG signal. A greater slope points to extreme fatigue. Thus, an attempt was made to assess if and to what extent fatigue affects the symmetry of muscle activity and if it has anything to do with the track trajectory.

It was stated that energetic cost was the most considerable in the first curve, i.e., during the acceleration phase until the maximum running speed was reached. Hanon and Gajer [27] reported that world-class athletes adopt an aggressive pacing strategy, and they achieve 96% of their maximum velocity in the first 200 m. The lower fatigue index and lower muscle activity noted in the current study confirm increased energetic cost.

This probably stems from the fact that in the acceleration phase, the body has to deal with extra load, i.e., inertial force. The greatest muscle fatigue assessed by the rate of change of the EMG mean power frequency ( $b$ ) was observed in the first 100 m for the tibialis anterior and the biceps femoris, and it was different for the right and left limbs. Greater TA fatigue was noted for the left limb. Conversely, the first curve was more exhausting for the BF of the right limb. In the other sections, a lower muscle fatigue index and greater activity point to the occurrence of compensatory effects. This is probably connected to the activation of more and more muscle units. After 300 m, the values of the calculated index did not change so much, whereas the muscle activity continued to

increase with a simultaneous decrease in running velocity. This may indicate that any further compensation was not possible.

It should be stated that muscle fatigue leads to the focus of the EMG signal spectrum in the low-frequency range, which is mainly associated with a decrease in the speed of spreading action potentials. When analyzing force generated by lower limb muscles, [23] also reported its decrease in the first 100 m of the run followed by an increase in muscle activity in the form of compensatory effects in the next 200–300 m. Completely different changes in fatigue were noted for the lateral gastrocnemius. The fatigue of this muscle in the right limb increased with each subsequent section of the run, while in the case of the left limb, it was the greatest in the curved sections of the track.

The above findings were confirmed by the kinematic variables of the run in the final section (2nd straight). The stride duration was the longest, whereas the frequency of the stride length and stride decreased. Similar observations were made by Hanon and Gajer [27]. They found that in world-class runners, a velocity decrease between 200 and 300 m is attributable to shorter stride length, while a velocity decrease between 300 and 350 m is attributable to both a shorter stride length and a lower stride frequency. The velocity decrease in the last 50 m of the run was mainly influenced by stride frequency, which is in line with the findings of Nummela et al. [23]. According to Hanon and Gajer [27], maximum stride length was reached between 100 and 150 m, while the maximum stride frequency was achieved between 50 and 100 m.

The findings of the present study are consistent with the aforementioned observations. Therefore, it can be stated that training specificity requires developing a certain running strategy in order to achieve the best performance possible. The strategy adopted during the run is linked with the changing trajectory and the asymmetric overloading of the musculoskeletal system in the straight and curved sections.

Churchill et al. [3] revealed that changes in the running direction result in movement asymmetry. Thus, the increased energetic cost associated with greater ground reaction forces is visible for the outside leg in the curved sections of the run [25,26]. Additionally, Chang and Kram [4] as well as Ishimura and Sakurai [12] point to asymmetry in the resultant ground reaction forces. The outside leg generated higher values of both propulsive and braking forces as well as higher values of lateral ground reaction forces than the inside leg [4].

The present study revealed greater fatigue of the outside leg in the first 100 m (1st curve), and increased energetic cost was also noted in the second section (1st straight). This may be linked with the smooth transition and inertial effect. In the other sections, no significant differences between the limbs were noted. However, the comparison of muscle activity revealed that compensation for fatigue through increased muscle activity during the run was observed to a larger extent in the outside leg. Moreover, greater track trajectory effects were noted for the same limb. Changes in the RMS values were significantly different in particular curved and straight sections. In turn, changes in the activity of the inside leg remained at the same level and did not exceed 6%. Therefore, we may presume that the characteristics of the track lane significantly affect muscle activity asymmetry. We may also presume that higher activity for the inside (left) leg in the first two sections (1st curve—by 8%, 1st straight—by 11%) may indicate greater outside leg strength.

The study conducted by Beukeboom et al. [13] may be treated as the confirmation of these theories. They revealed significant strength asymmetry in foot evtor and invertor muscles, which they associate with the specificity of track running. However, it ought to be emphasized that in the current study, asymmetry was mainly noted in the first two sections. Thus, this points to muscle activity adjustment and adaptation to changing conditions rather than muscle strength asymmetry. When analyzing ground reaction forces in particular sections, [3] noted that compared to straight running, lower values of the vertical and resultant forces were obtained for the inside leg during curve running. As for the outside leg, no changes were observed, or, in some cases, an opposite tendency could be seen, which points to differences in muscle activity. These findings also indicate that in

order to estimate differences between the limbs, one should compare ground contact times since, as Ammann and Wyss [28] reported, acceleration occurs during this phase.

The above data were confirmed by the kinematic variables analyzed in the present study. It was found that the first two sections of the run are fundamental because stride length and stride duration asymmetry were noted then. Similar to the findings of Taboga and Kram [8], it was observed that during curve running, the stride length was significantly longer for the outer limb. The researchers also revealed that the ground contact time was 8% longer for the inside leg, which contributed to increases in the running velocity [10]. The present study did not focus on ground contact time; however, the maximum velocity of the run registered in Section 2 (100–200 m) was attributed to longer strides and their higher frequency. Mero et al. [15] also revealed that a rise in velocity occurs due to an increase in both the stride frequency and the stride length. In addition, they noted that with a velocity higher than 7 m/s, any further acceleration mainly results from an increment in the stride frequency rather than in the stride length. In the current study, the athletes reached a higher maximum running velocity (9.13 m/s), and this was registered when stride length was greater.

The findings of the present study make it difficult for the authors to fully verify the hypotheses. However, it was revealed that the influence of track geometry on asymmetric muscle activity and running kinematics was only visible in the first two sections. This was probably linked to the acceleration phase (in the unnatural conditions of the curved track) until the maximum running speed was reached. It seems obvious that if the first section were straight, no asymmetry would be found. Therefore, we may conclude that the decreased asymmetry in further sections of the track was probably connected to the compensatory stimulation of the muscles triggered by the nervous system and to an ability to adjust running kinematics to changing external conditions. However, further research is needed to confirm these conclusions, especially the EMG power spectrum analyzed with regard to the kinematic variables of the run in particular sections. This seems crucial due to the fact that coaches often make use of the results obtained in laboratory settings, i.e., they take steps which, on the one hand, aim to decrease the asymmetry of muscle activity, but on the other hand, they may produce contrary effects. For this reason, an in-depth analysis of what happens in terms of neuromuscular coordination and the effects of running kinematics is an indispensable element that helps to enhance the performance of elite athletes and becomes a preventative strategy.

A certain limitation of the study was group size. Therefore, conclusions can be drawn only for this group of women. There was also no control group, which would have strengthened the conclusions. For this reason, research should be continued on the in-depth analysis of running kinematic variables in relation to the bioelectrical activity of the muscles, and these results should be compared with physically inactive people.

## 5. Conclusions

The study revealed curved track effects on asymmetric muscle activity and running kinematics in the first two sections of the run. This was probably connected with the acceleration phase (in unnatural conditions of the curved track) until the maximum running speed was reached.

The greatest activity and fatigue were noted in the case of the biceps femoris (BF). This muscle also played the most significant role in the acceleration phase. Moreover, the greater fatigue of the BF in Section 1 (1st curve) resulted in the occurrence of asymmetric muscle activity in the lower limbs that lasted until the end of Section 2 (1st straight). Thus, differences were revealed between the right and left side of the body in terms of muscle loading and fatigue. This effect may contribute greatly to the disturbance of the movement structure in a 200-m race, which was confirmed by the observations of the movement kinematics.

Thus, it is presumed that asymmetric muscle activity occurs at the maximum velocity of the run, while its reduction is linked with compensatory muscle stimulation triggered by the nervous system and with adjusting running kinematics to changing external conditions.

Analysis of the results obtained from those particular sprinters may be of great importance for trainers and coaches, as it implies work on stride frequency and stride length in order to reach a higher speed value. Therefore, it is noteworthy that in some sprint races it is also important to specify the optimal interaction between the stride length and the stride frequency in relation to muscle activity and track geometry

**Author Contributions:** Conceptualization, A.M., D.I. and P.T.; methodology, A.M., D.I. and P.T.; formal analysis, D.I., P.T., O.G. and A.M.; investigation, D.I., P.T., O.G. and A.M.; resources: D.I., P.T., A.M. and O.G.; writing—original draft preparation, D.I., A.M., P.T. and O.G.; writing—review and editing, D.I., A.M., P.T. and O.G.; supervision: D.I., A.M. and P.T.; project administration, A.M.; funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the Ministry of Science and Higher Education (<https://www.gov.pl/web/nauka/>) (March 2020) in 2020/2022 as part of the Scientific School of the University of Physical Education in Warsaw—SN No. 5 “Biomedical determinants of physical fitness and sports training in adult population” and scientific program in the year 2018 (N RSA4 05354). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

**Institutional Review Board Statement:** The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of Józef Piłsudski University of Physical Education in Warsaw (SKE 01-02/2017, research project number N RSA4 05354).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** This study did not report any data.

**Conflicts of Interest:** The authors of the work confirm the above-mentioned participation in the creation of the article. At the same time, they declare that they have no conflict of interest related to the research and publication of this work. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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