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ORIGINAL

Vertical Ground Reaction Force Asymmetry in Prolonged Running

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Objective: The purpose of this study was to determine the asymmetry of vertical ground reaction force (GRF) components between dominant and non-dominant legs in rested and fatigued states in prolonged running.

Method: Twenty healthy men, heel strikers, were included (age: 24.00 ± 5.0 years; height: 176.1 ± 6.0 cm; body mass: 69.0 ± 6.0 kg) in this study. Subjects ran on an instrumented treadmill for 130 minutes. During treadmill running, GRF data (1,000 Hz) were collected for 20 strides at five minutes (rested) and 125 minutes (fatigued) running while they were unaware of collecting data. Asymmetry indexes (ASI) were calculated to quantify the asymmetry magnitude in rested and fatigued states. Paired *t*-test was used to verify the differences between dominant and non-dominant legs in rested and fatigued states. In addition, one-way repeated measure analysis of variance was applied for comparison of ASI of both states. The level of significance was set at $p < .05$.

Results: Passive force peak magnitude, loading rate, and impulse affecting the development of running injury were found significantly greater in dominant leg than in non-dominant leg at rested state ($p < .05$). However, passive force peak time and active force peak magnitude were found significantly different between legs in fatigued state ($p < .05$). To determine changes in percentage of asymmetry between legs in both states, ASI was used. ASI for all variables increased in fatigued state; however, no significant differences were found between both states.

Conclusion: This study found that fatigue did not affect differences in vertical GRF between dominant and non-dominant legs and asymmetry changes.

Keywords: Asymmetry, VGRF, Dominant and non-dominant legs, Fatigue, Prolonged running, Treadmill running

INTRODUCTION

Prolonged running is known to improve physical fitness, such as general endurance and muscular endurance, because aerobic metabolism is mostly used during long-distance running (Kerr, Beauchamp, Fisher, & Neil, 1983); however, 19~79% of long-distance runners (Bredeweg & Buist, 2011) experience a variety of lower extremity injuries every year, including tendinitis, stress fracture, plantar fasciitis, chondromalacia, and shin pain (Dickinson, Cook, & Leinhardt, 1985).

Fatigue is one of the causes of injuries induced by prolonged running (Burr, 1997; Dickinson et al., 1985; Grimston & Zernike, 1993; Nyland, Shapiro, Stine, Horn, & Ireland, 1994). Individuals who are fatigued from prolonged running are highly vulnerable to injury, as fatigue tends to alter or lower neuromuscular response (Dutto & Smith, 2002). Therefore, the incidence of injury caused by prolonged running is likely to rise later in the exercise when fatigue has been accumulated (Whiting & Zerinicke, 1998).

The kinematic factors related to injury caused by prolonged running in a fatigued state have been extensively studied. Many studies have been conducted to analyze the changes of shock and loading in a fatigued state (Avela, Kyröläinen, Komi, & Rama, 1999; Christina, White, & Gilchrist, 2001; Gerlach et al., 2005; Gerritsen, van den Bogert, & Nigg, 1995; Jean-Benoit, Pierre, & Guillaume, 2011; Nicol, Komi, & Marconnet, 1991; Ryu, 2013; Ryu, 2014; Willson & Kernozek, 1999), the effects of fatigue on the size and absorption of shock (Derrick, Dereu, & McLean, 2002; Lafortune, Hennig, & Lake, 1996; Mizrahi, Verbitsky, & Isakov, 2000; Voloshin, Mizrahi, Verbitsky, & Isakov, 1998), and the stiffness in fatigued states (Mizrahi, Verbitsky, Isakovet, & Daily, 2000; Dutto & Smith, 2002). Although multiple studies have attempted to anticipate potential injuries in fatigued states caused by prolonged running, most of them had analyzed variables only in one leg under the premise that movements of both legs are equal. Consequently, few studies that examined physical asymmetry, a known cause of injury (Croisier, Forthomme, Namurois, Vanderthommen, & Crielaard, 2002; Knapik, Bauman, Jones, Harris, & Vaughn, 1991), in fatigued states caused by prolonged running are currently available.

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From a kinematic perspective, prolonged running asymmetry refers to the degree of agreement of dynamic variables between the left and right legs. In general, the absolute symmetry index is used to determine the asymmetry, where 0 indicates perfect symmetry and any deviation from this value indicates asymmetry (McElveen, Riemann, & Davies, 2010; Munro & Herrington, 2011). Kinematic asymmetry between the right and left legs is highly likely to cause overuse injuries in musculoskeletal tissues by inflicting more stress on one leg (Zifchock, Davis, Higginson, McCaw, & Royer, 2008; Zifchock, Davis, & Hamill, 2005).

To date, the studies on locomotor asymmetry have taken a variety of perspectives, including differences between the dominant and non-dominant legs (Pappas, Paradisis, & Vagenas, 2015), features of the moving ground (Vagenas & Hoshizaki, 1988; Yoon, 2008), anatomical differences between the lower extremities (Perttunen et al., 2004; Vagenas & Hoshizaki, 1992), moving velocity and intensity (Carpes, Mota, & Faria, 2010; Lee, Sutter, Askew, & Burkett, 2010; Plotnik, Bartsch, Zeev, Giladi, & Hausdorff, 2012), lower extremity injuries (Bredeweg, Buist, & Kluitenberg, 2013; Croisier et al., 2002; Zifchock et al., 2005), and fatigue (Radzak, Putnam, Tamura, & Hetzler, 2017).

Zifchock et al. (2008) predicted that fatigue would intensify asymmetry, while Arampatzis, Bruggemann and Metzler (1999) and Zifchock et al. (2008) argued that asymmetry is not evident in the early stage of exercise, but occurs in a fatigued state and gradually increase. However, there is a relative lack of studies that investigated asymmetry in a fatigued state caused by prolonged running. Radzak et al. (2017) examined asymmetry of dynamic factors of the lower extremity joints, as well as active force and loading rate of ground reaction force (GRF) components in stable and fatigued states induced by a temporary exhaustion protocol. However, one of the limitations of this study was the difficulty in realizing natural steps and the limited number of steps for analysis due to a limited running course. Further, Brown, Zifchock and Hillstrom (2014) investigated the three-dimensional angle and moment of the dominant and non-dominant legs in stable and fatigue stages, but the reliability of the data was undermined, because fatigue was induced on a treadmill, while actual data were collected on a running course.

Kinematic variables, such as accumulated impulse and loading rate from prolonged running, have a grave impact on the musculoskeletal system; thus, an asymmetry of these variables in the leg may potentially cause injury or morbidity (Seeley, Umberger, & Shapiro, 2008). Therefore, assessment of the asymmetry of kinematic variables, such as passive force peak, active peak, and loading rate, which have been found to contribute to injury during prolonged running (Stefanyshyn, Stergiou, Meeuwisse, Worobets, & Lun, 2006) and to determine potential injury (Hreljac, Marshall, & Hume, 2000; Milner, Ferber, Pollard, Hamill, & Davis, 2006; Pohl, Hamill, & Davis, 2009; Ryu, 2013), has meaningful implications, pertaining to injuries caused by prolonged running (Bredeweg et al., 2013). In particular, quantifying asymmetry in a fatigued state, another cause of physical injury, is meaningful in terms of determining the possibility of injury from prolonged running, as well as understanding clinical, coaching, and technical aspects (Exell, Gittoes, Irwin, & Kerwin, 2012). Therefore, it is necessary to investigate leg asymmetry, a known risk factor of sports injury, in a fatigued state.

In this context, this study aimed to investigate the asymmetry of vertical GRF components (indicator of impact) of both legs in a rested state and fatigued state caused by prolonged running in an attempt to predict the potential injuries caused by prolonged running. For this purpose, this study set the following specific objectives: first, the support time, size of passive force peak, passive force peak time, active force peak time, active force peak time, impulse, and loading rate were compared between the dominant and non-dominant legs in a rested state and fatigued state caused by prolonged running; second, the asymmetry coefficients of these factors were analyzed to observe the effects of fatigue on the asymmetry between the two legs. This study hypothesized significant differences between a fatigued state and rested state and an increase in the asymmetry between the right and left legs induced by fatigue.

METHODS

1. Participants

Twenty healthy adults in their 20s and 30s who practiced heel strike running and had no history of physical injury were enrolled (age: 24.00 ± 5.0 yrs.; height: 176.1 ± 6.0 cm; body mass: 69.0 ± 6.0 kg). All participants provided an informed consent prior to inclusion. In addition, all participants had an experience of running at least two hours at their preferred speed (mean: 9 ± 0.0 km/hr).

2. Measurements

After a sufficient warming-up, the participants performed a prolonged running for two hours and ten minutes at their preferred speed on an instrumented dual belt treadmill (Bertec Corp., Columbus, OH, USA). While they were running, the signals for ten left and right steps needed for optimal GRF analysis (Hamill & MacNiven, 1990) were collected at five minutes (rested state) and 125 minutes (fatigued state) (Wilmore & Costill, 1994). Sampling rate was set to 1,000 Hz.

3. Data processing

GRF components obtained from the experiment were used to extract vertical GRF components through the following process. First, vertical GRF signals were filtered by computing the cutoff frequency for the participants' trials. After computing the power spectrum density for each signal (Ryu, 2013), the cutoff frequency was used as the maximum frequency in the bandwidth up to 99.9% of the accumulation (Stergiou, Giakas, Byrne, & Pomeroy, 2002). After filtering the signals with a fourth-order low-pass Butterworth filter using this cutoff frequency (Ryu, 2013), the first 10 points of the signals were averaged to subtract the average value from all signals to eliminate any inherent biases (Ryu, 2013). The analysis range was set to the support phase, from the moment the feet touched the ground to the moment of takeoff. The range of the support phase was set to greater than 5 N at touchdown and less than 5 N at takeoff, and a rectangular window was used for this phase for the final analysis (Ryu, 2013). The variables computed for analysis were

support time, passive force peak size, passive force peak time, active force peak size, active force peak time, loading rate (passive force peak size divided by passive force peak time), and impulse (integral of vertical reaction force for weight with respect to time). All variables other than time were standardized to weight. The variables were distinguished between the dominant and non-dominant legs to calculate the asymmetry index. The leg the participant used to kick a ball was considered the dominant leg and the other leg was considered the non-dominant leg (Damholt & Termansen, 1978). Asymmetry index (ASI) was computed using the following formula (Zifchock et al., 2006)

$$\mathrm{ASI} = \frac{|X_{Pref} - X_{Nonpref}|}{0.5(X_{Pref} + X_{Nonpref})} \times 100$$

where X_{Pref} was a parameter for the dominant leg and $X_{Nonpref}$ was a parameter for the non-dominant leg. ASI was calculated in percentages. ASI for each parameter was determined using the average of the ten steps taken by the dominant and non-dominant legs at five minutes (rested state) and 125 minutes (fatigue state) of running (Pappas et al., 2015).

4. Statistical analysis

All variables were presented as mean and standard deviation to compare the dominant and non-dominant leg, and paired *t*-test was used to examine the difference between the rested and fatigued state. One-way repeated measure analysis of variance was performed for calculated ASI to quantify the asymmetries of parameters in rested and fatigued states. Statistical significance level was set to p = .05.

RESULTS

Table 1 shows the means, standard deviations, and percentages of dominant and non-dominant leg parameters in rested and fatigued states. Figure 1 shows the vertical GRF signals of the dominant and non-dominant legs at a rested and fatigued state, and Figures 2~7 show the dispersion of individuals variables for the tens steps. Based on the analysis, the passive force peak size, lading rate, and impulse in

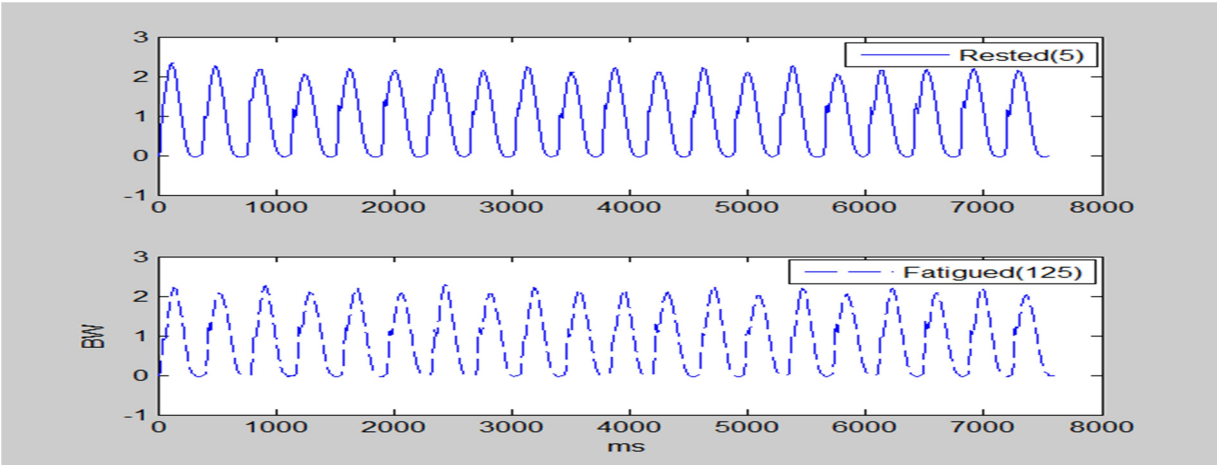

Figure 1. Example of vertical ground reaction force signals between dominant and non-dominant legs in rested and fatigued states for an individual.

Table 1. Comparison of parameters between dominant and non-dominant legs in rested and fatigued state

	Rested (5 min)				Fatigued (125 min)			
	Dominant	Non-dominant	Δ%	*p*-value	Dominant	Non-dominant	Δ%	*p*-value
Passive peak time (s)	0.050 (0.008)	0.051 (0.008)	-2.0	.1169	0.042 (0.009)	0.044 (0.011)	-4.7	.0013*
Passive peak (BW)	1.494 (0.224)	1.454 (0.223)	2.7	.0093*	1.412 (0.302)	1.429 (0.226)	-1.2	.4768
Loading rate (BW/s)	30.71 (8.65)	29.15 (7.58)	5.3	.0054*	34.67 (8.97)	33.64 (7.71)	3.0	.1156
Active peak time (s)	0.128 (0.017)	0.129 (0.015)	-0.8	.4649	0.124 (0.015)	0.124 (0.016)	0.0	1.0000
Active peak (BW)	2.267 (0.188)	2.267 (0.187)	0	.9530	2.276 (0.181)	2.256 (0.157)	0.8	.0048*
Impulse (BW*s)	0.371 (0.020)	0.369 (0.022)	0.5	.0049*	0.373 (0.032)	0.373 (0.034)	0.0	.4527
Support time (s)	0.321 (0.029)	0.321 (0.028)	0.0	0.8266	0.310 (0.037)	0.310 (0.040)	0.0	0.7199

*: p <. 05.

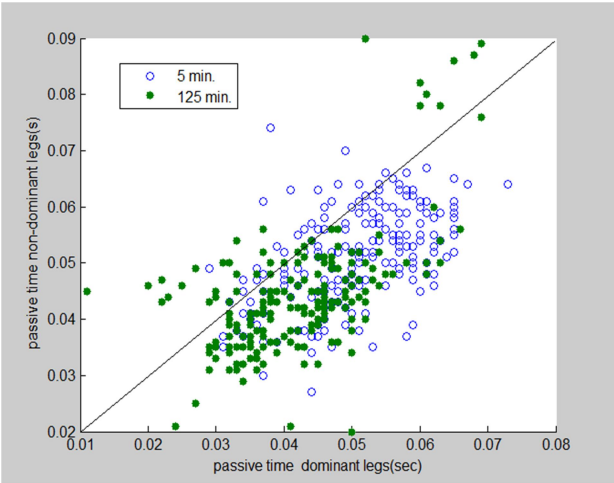

Figure 2. Scatter plot of passive peak time between dominant and non-dominant legs in rested and fatigued states.

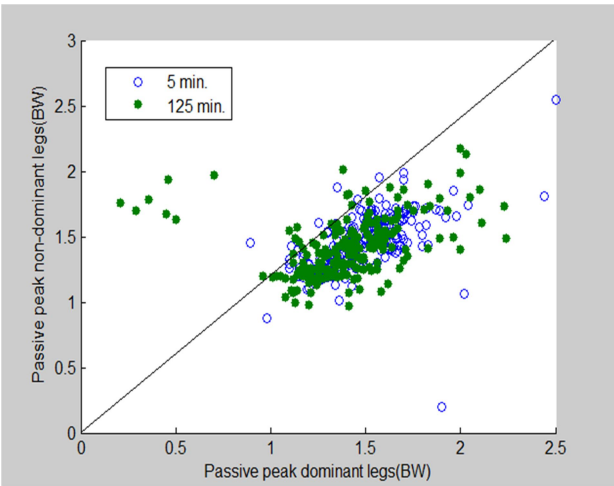

Figure 3. Scatter plot of passive peak magnitude between dominant and non-dominant legs in rested and fatigued states.

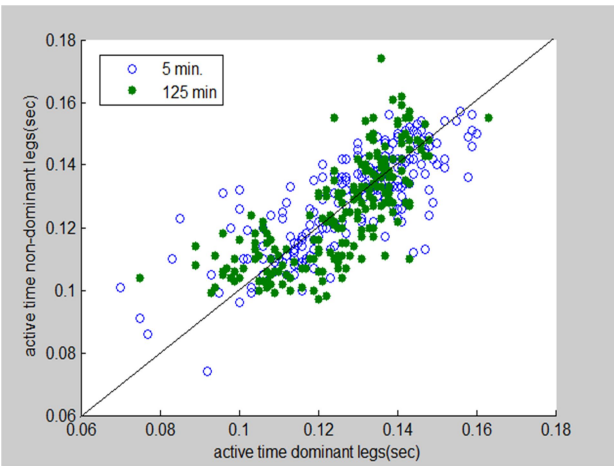

Figure 4. Scatter plot of active peak time between dominant and non-dominant legs in rested and fatigued states.

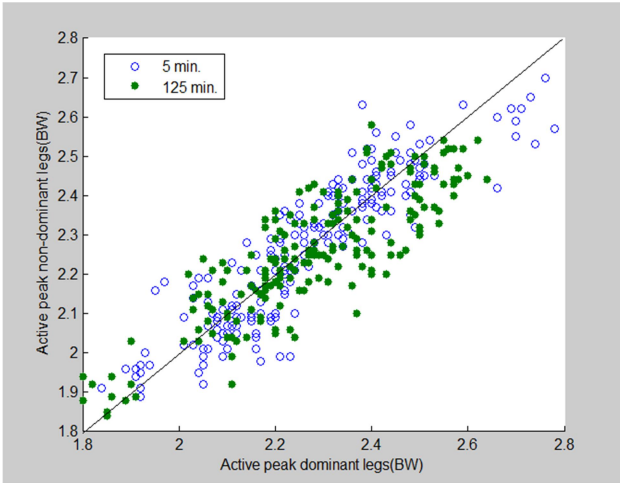

Figure 5. Scatter plot of active peak magnitude between dominant and non-dominant legs in rested and fatigued states.

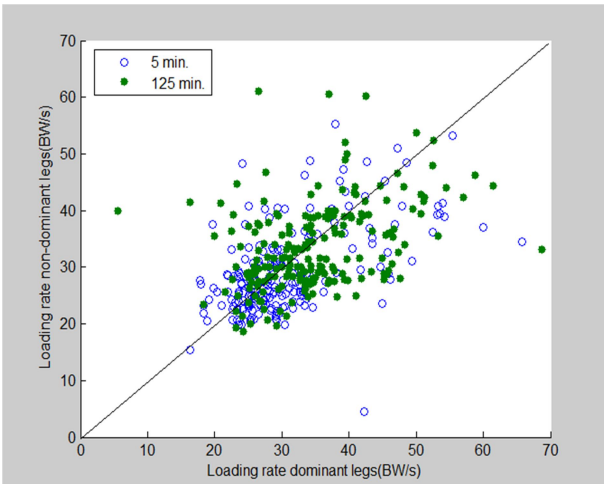

Figure 6. Scatter plot of loading rate between dominant and non-dominant legs in rested and fatigued states.

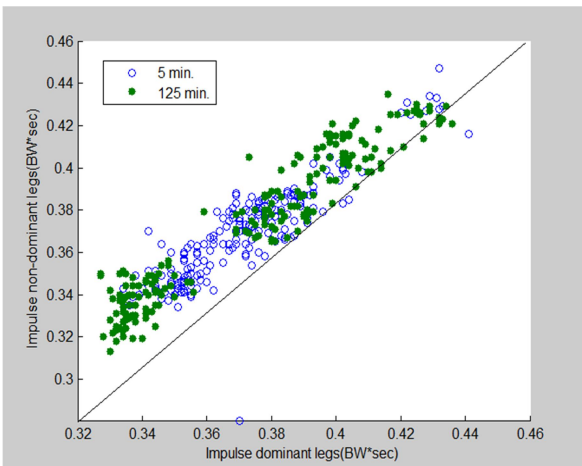

Figure 7. Scatter plot of impulse between dominant and non-dominant legs in rested and fatigued states.

Table 2. Asymmetry indexes for 5 and 125 minutes running and their statistic test results

Parameters	5 min	125 min	Absolute mean difference (%)	*F*-values (*p*)
Passive peak time (s)	3.37 (1.14)	4.05 (2.40)	0.68	1.37 (.254)
Passive peak (BW)	2.40 (1.51)	3.63 (4.30)	1.23	1.56 (.225)
Loading rate	4.66 (2.00)	4.95 (2.61)	0.31	0.14 (.709)
Active peak time (s)	1.61 (0.84)	1.83 (0.71)	0.22	1.53 (.230)
Active peak (BW)	0.72 (0.29)	0.87 (0.39)	0.15	2.09 (.164)
Impulse (BW*s)	0.50 (0.21)	0.54 (0.17)	0.04	0.47 (.498)
Support time (s)	0.95 (0.26)	1.11 (0.61)	0.16	1.21 (.284)

rested state were significantly greater in the dominant leg than those in the dominant leg (p < .05); however, support time, active force peak, and active force peak time did not significantly differ between the two legs. In the fatigued state, however, passive force peak time was significantly more delayed in the non-dominant leg (p < .05), while active force peak was greater in the dominant leg (p < .05). No significant differences were found between the two legs in passive force peak size, active force peak time, impulse, and support time.

The means, standard deviations, absolute difference of mean, and statistical significance of the differences for all variables in the rested and fatigued states were calculated to analyze the effects of fatigue on asymmetry of both legs (Table 2). As shown in the table, the ASI was higher for all variables in a fatigued state than those in a rested state; however, the differences were not statistically significant.

DISCUSSION

This study quantified the vertical GRF components of the dominant and non-dominant legs in a rested and fatigued state and analyzed the effects of fatigue on the ASI of both legs.

Our results showed that passive peak size, loading rate, and impulse were significantly greater in the dominant leg than in the non-dominant leg. This phenomenon is speculated to be attributable to the fact that the dominant leg inflicts more support against the gravity (Hirokawa, 1989) when making movements to propel the body forward during prolonged running (Winter, 1990). Our findings are in line with a previous argument that healthy individuals clearly show an asymmetry of some dynamic parameters between their dominant and non-dominant legs during prolonged running. Radzak et al. (2017) reported that the right foot has a significantly lower loading rate and peak GRF in a rested state. Although it is difficult to directly compare our findings with their findings due to the differences in determination of leg dominance, standardization of variables, and type of running shoes used for the experiment (Vagenas & Hoshizaki, 1992), we could definitely state that both studies showed an asymmetry of dynamic variables between the dominant and non-dominant legs. Our study demonstrated that the loading rate, which has been found associated with tibial stress fracture (Milner et al., 2006), showed the greatest difference between the two legs in rested state. This seems to be related to the difference in length and functional dominance between the legs (Perttunen et al., 2004); however, more specific studies are needed to evaluate this finding. In particular, considering the results of studies that reported a significant asymmetry between injured and non-injured legs in runners who have incurred an overuse injury in one leg (Zifchock et al., 2006; Zifchock et al., 2008), further studies that will prospectively investigate lower extremity injuries are needed.

In our study, significant differences of passive peak size, loading rate, and impulse between the dominant and non-dominant legs in the rested state were not evident in the fatigued state. However, in a fatigued state, the dominant leg reached the passive force peak faster than the non-dominant leg; moreover, the dominant leg showed a significantly greater active force peak. As shown here, the changes in the asymmetry of dynamic variables between the dominant and non-dominant legs in a stable and fatigued state were in line with finings of previous studies (Radzak et al., 2017). Although the factors that influence these variables should be examined in more detail in order to understand the cause of these findings, the fact that the dominant leg had a larger active force peak in a fatigued state is speculated to be largely attributable to the maintenance of muscular contractibility in the dominant leg due to its superior functional feature.

In a similar previous study, Brown et al. (2014) argued the absence of significant differences in the three-dimensional angle and moments of the lower limb joints between the dominant and non-dominant legs in rested and fatigued states. These results seem to show that the interaction between the dominant and non-dominant leg could differ in relation to the analyzed variables, and that the degree of effects of lower limb dominance on the differences of lower limb mechanics differ across variables.

Fatigue has been frequently hypothesized to cause injury resulting from prolonged running (Baker, Frankel, & Burnstein, 1972; Burr, 1997; Dickinson et al., 1985; Grimston & Zernike, 1993; Nyland et al., 1994). Zifchock et al. (2008) theorized that fatigue would increase the incidence of asymmetry, while Zifchock et al. (2006) argued that asymmetry in a fatigued state would induce a greater, repeated shock on the limbs of one side. Asymmetrical locomotion is theoretically described to aggravate abnormal and injurious loading on the leg (Radzak et al., 2017). Based on these theories, the present study was particularly interested in predicting injury from prolonged running by comparing the size of ASI

between a rested and fatigued state. When the effects of fatigue on the asymmetry between legs were analyzed, the ASI was larger in the fatigued state than in the rested state in all variables, but the differences were not statistically significant. Based on the results of a previous study stating that an ASI of 0 indicates perfect symmetry and 10~15% deviances indicate asymmetry between the right and left legs (McElveen et al., 2010; Munro & Herrington, 2011), our findings of ASI below 5% for all variables in the rested and fatigued states seem to suggest that fatigue caused by prolonged running did not alter the asymmetry between the two legs. In particular, the fact that the changes of asymmetry of loading rate and passive force peak, which are two of the vertical GRF components that are related to injuries caused by prolonged running, were not significant suggests that asymmetry in a transient fatigued state is not a determinant of potential injury of one leg.

CONCLUSION

This study identified the differences in vertical GRF components of both legs between a rested and fatigued state during prolonged running and analyzed the effects of fatigue on the magnitude of asymmetry between the two legs. Based on our results, we concluded that a certain degree of asymmetry of some vertical GRF components do exist between a rested and fatigued state during prolonged running, but the asymmetry of vertical GRF components between the rested and fatigued states did not differ significantly. Furthermore, fatigue did not significantly affect the asymmetry of vertical GRF components between the two legs, suggesting that asymmetry in a fatigued state during prolonged running is not a determinant of potential injury. Further studies that would quantify the asymmetry between the two legs in consideration of the body's structure, the participant's proficiency with prolonged running, sex differences, and lower limb muscle strengths are necessary.

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