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ORIGINAL

Gender Dfferences in Ground Reaction Force Components

Sang-Kyoon Park[1], Seungbum Koo[2], Suk-Hoon Yoon[3], Sangheon Park[4], Yongcheol Kim[2], Ji-Seon Ryu[5]

[1]Department of Physical Education, Korea National Sport University, Seoul, South Korea
[2]Biomechanics Lab, Chung-ang University, Seoul, South Korea
[3]Department of Community Sport, Korea National Sport University, Seoul, South Korea
[4]Institute of Sport Science, Korea National Sport University, Seoul, South Korea
[5]Department of Health and Exercise Science, Korea National Sport University, Seoul, South Korea

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Corresponding Author
Ji-Seon Ryu
Department of Health and Exercise Science, Korea National Sport University, 1239, Yangjae-daero, Songpa-gu, 05541, Seoul, South Korea
Tel : +82-10-8944-6306
Fax : +82-2-418-1877
Email : jiseon@knsu.ac.kr

Objective: The aim of this study was to investigate gender differences in ground reaction force (GRF) components among different speeds of running.

Method: Twenty men (age=22.4±1.6 years, mass=73.4±8.4 kg, height=176.2±5.6 cm) and twenty women (age=20.7±1.2 years, mass=55.0±8.2 kg, height=163.9±5.3 cm) participated in this study. All participants were asked to run on an instrumented dual belt treadmill (Bertec, USA) at 8, 12, and 16 km/h for 3 min, after warming up. GRF data were collected from 30 strides while they were running. Hypotheses were tested using one-way ANOVA, and level of significance was set at p-value <.05.

Results: The time to passive peaks was significantly earlier in women than in men at three different running speeds (p<.05). Further, the impact loading rates were significantly greater in women than in men at three different running speeds (p<.05). Moreover, the propulsive peak at 8 km/h, which is the slowest running speed, was significantly greater in women than in men (p<.05), and the vertical impulse at 16 km/h, which is the fastest running speed, was significantly greater in men than in women (p<.05). The absolute anteroposterior impulse at 8 km/h was significantly greater in women than in men (p<.05). In addition, as the running speed increased, impact peak, active peak, impact loading rate, breaking peak, propulsive peak, and anteroposterior impulse were significantly increased, but vertical impulse was significantly decreased (p<.05).

Conclusion: The impact loading rate is greater in women than in men regardless of different running speeds. Therefore, female runners might be exposed to the risk of potential injuries related to the bone and ligament. Moreover, increased running speeds could lead to higher possibility of running injuries.

Keywords: Running, Gender, Speed, GRF, Loading rate

INTRODUCTION

Running is one of the most popular exercises that is performed throughout the lifetime as it has relatively fewer spatial restrictions compared with other exercises. Running regularly has many physiological benefits but can also cause chronic overuse injuries. About 20~80% of all skeletal injuries are reported to be due to running (Bredeweg & Buist, 2011; Lun, Meeuwisse, Stergiou, & Stefanyshyn, 2004; Taunton et al., 2003; van Gent et al., 2007). Running injuries are caused by various factors. They are affected by internal factors such as dynamic abnormalities, previous injuries, gender, and body mass index and by external factors such as training frequency, intensity, and duration; muscle strength; flexibility; and shoes (Taunton et al., 2003; van Mechelen, 1992).

Of the factors that affect running injuries, gender difference is an important topic of research. Robinson and Nee (2007) claimed that female athletes are at increased risk of chronic injuries due to running compared with male athletes of the same age. Geraci and Brown (2005) and Taunton et al. (2002) reported that the risk of running injuries such as patellofemoral pain syndrome, iliotibial band syndrome, and injuries of the gluteus medius muscle is two times higher among women than among men. Lopes, Hespanhol, Yeong, and Costa (2012) reported that patellofemoral pain syndrome is the most common injury that occurs during running and that its incidence and prevalence are higher among women. Taunton et al. (2003) and van Gent et al. (2007) further characterized the different sites of injury between men and women by claiming that injuries of the calves and feet due to running are more common among men, whereas those of the hip are more common among women.

In addition to research aimed at understanding the properties of running injuries in men and women, various approaches have been used to identify the dynamic mechanism of running injuries. Atwater (1990) claimed that female adults have lower height, mass, and body

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fat percentage compared with men and differences exist in dynamic factors between men and women during running. They hypothesized that the differences in the dynamic factors may be what gives rise to the injury characteristics observed in women and, therefore, assessed the gender difference in the body structure as a cause of running injuries.

In addition, several researchers performed kinematic analysis and comparison of movements to investigate the gender differences in running injuries. Sinclair, Greenhalgh, Edmundson, Brooks, and Hobbs (2012) claimed that whereas women used large knee abduction, internal rotation, and ankle eversion, men showed large back flexion. Ferber, Davis, and Williams (2003) reported that women show greater hip adduction and internal rotation and greater peak knee abduction compared with men. Sinclair and Taylor (2014) reported that the peak calcaneal eversion and peak angle of internal rotation of the tibia during the stance phase were significantly higher among female athletes. Malinzak, Colby, Kirkendall, Yu, and Garrett (2001) investigated the gender differences during knee exercises in the frontal, and sagittal planes and claimed that women have smaller peak knee flexion and knee range of motion. In addition, Chumanov, Wall-Scheffler, and Heiderscheit (2008) claimed that women show greater internal rotation of the hip while running and walking compared with men, and Simoneau, Hoenig, Lepley, and Papanek (1988) claimed that women show greater peak internal rotation and adduction of the hip while running. Schache, Blanch, Rath, Wrigley, and Bennell (2003) reported that, although women have greater pelvic inclination in the erect position compared with men while running, there was no gender difference in the relative stride length. Sinclair, Chockalingam, and Vincent (2014) reported that men experience greater changes in the plantar fascia and have a greater peak calcaneal eversion while running compared with women and the risk of potential injuries due to mechanisms associated with these characteristics is high.

Studies have also investigated the kinetic differences between men and women while running. Sinclair et al. (2012) compared the major components of the ground reaction force (GRF) during running at 4 m/s by using a pressure plate attached to the ground and reported no difference in these components between both genders. Willson, Loss, Willy, and Meardon (2015), in their study on exhaustive running, compared the peak contact load on the patellofemoral joint, patellofemoral stress, hip abduction impulse, knee abduction impulse, mean vertical reaction force, and step length changes and reported no significant difference in these factors between both genders.

Although numerous anatomical, kinematic, and epidemiological studies on the gender differences in running movements and mechanisms of running injuries have been conducted, those investigating the gender differences in kinetic factors are relatively rare.

In today's world where many women run to enhance their health, research on the dynamic patterns of the running mechanism in women has theoretical and practical significance. In other words, understanding the differences in the running mechanism between men and women will provide insights that may be useful in devising ways to prevent running injuries by identifying the patterns and causes of running injuries and in developing shoes and assistive equipment (Sinclair et al., 2012; Ferber et al., 2003). Understanding the gender differences in kinetic factors such as peak impact, active peak, and impact loading rate (Ryu, 2005; Milner, Ferber, & Pollard, 2006; Pohl, Mullineaux, Milner, Hamill, & Davis, 2008; Hamill, Miller, Noehren, & Davis, 2008), all of which induce certain running injuries during the acceleration phase in which dynamic loads such as impulse increase (Belli, Kyrolainen, & Komi, 2002), is necessary in understanding the gender differences in the running mechanism and the properties of running injuries. Moreover, considering the differences in the female and male body structures between Asian and Western populations (Schache et al., 2003), research on the gender differences in the running mechanism is even more necessary.

This study was aimed at characterizing the gender differences in the components of the GRF at increasing running speeds. The aims of this study were to 1) analyze the impact force, impact loading rate, and impulse in the vertical GRF during the stance phase of running and 2) evaluate the breaking force, propulsive force, and impulse in the anteroposterior GRF.

METHODS

1. Participants

Twenty men (age=22.4±1.6 years, mass=73.4±8.4 kg, height=176.2 ±5.6 cm) and twenty women (age=20.7±1.2 years, mass=55.0±8.2 kg, height=163.9±5.3 cm) participated in this study. All participants were rearfoot strike runners and had not experienced any physical injuries in six months before the start of this study. Informed consent was obtained from the participants before their participation began in accordance with the regulations of the Institutional Review Board of the university.

2. Measurements and data processing

All participants performed sufficient warm-up before the experiment and wore the same type of shoes provided by the researcher (Prospecs Flash101-103). They ran at fixed speeds of 8, 12, and 16 km/h on a treadmill equipped with a force plate (instrumented dual belt treadmills, Bertec, USA) for 3 min. The fixed speeds were determined by measuring the maximum speed that can be maintained for 3 min (16 km /h) by women who have relatively lower running abilities and decreasing the speed by 4 km/h. Prior to running at fixed speeds, the running speed was gradually increased for 30 s until the target speed was reached, and a subject ran for 30 s for a warm-up to get used to the target speed. Next, the subject ran at the fixed speed for 120 s. GRF signals were collected from 30 steps at a sampling frequency of 1,000 Hz without the subject's awareness. Data were randomly collected for the three different speed conditions. For data analysis, of the 30 steps made by the right and left feet, each, the fifth and tenth steps of the right foot were analyzed as shown in (Figures 1 and 2), and their mean was obtained. Collected data were subjected to fourth-order low-pass Butterworth filtering, and the values of selected variables were obtained. The cut-off frequency was determined by calculating the power spectrum densities (PSD) of the vertical and anteroposterior GRF signals and

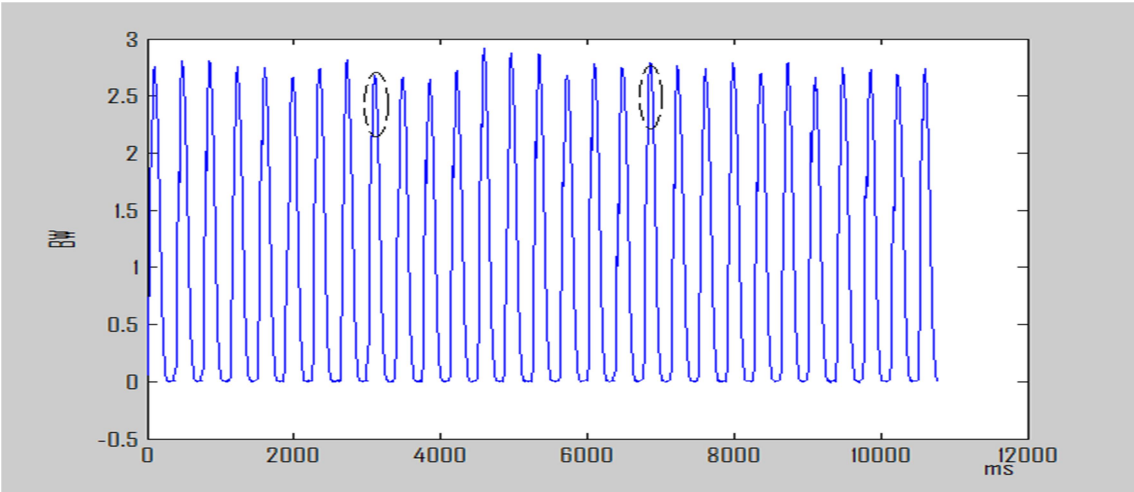

Figure 1. Vertical reaction forces of one running speed condition of an individual. Dot circles that indicated the fifth and tenth steps of the right foot were used in the analysis.

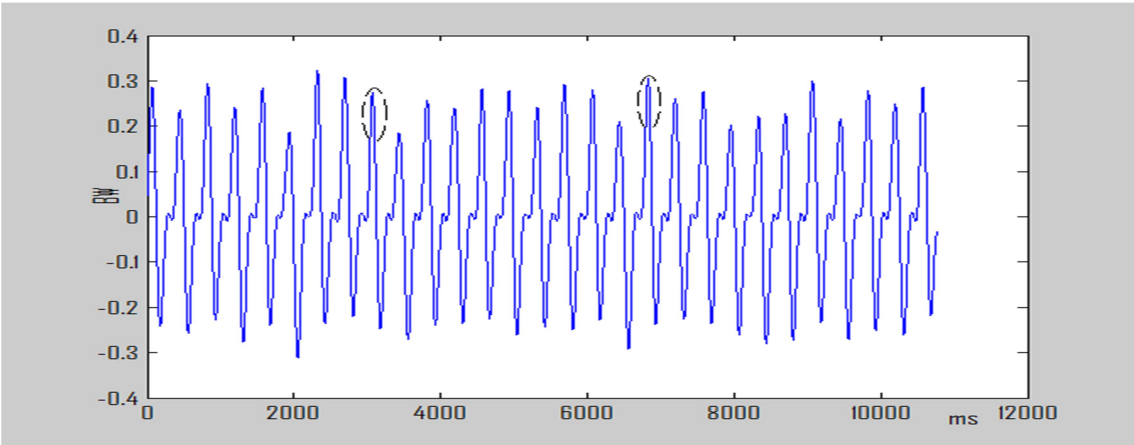

Figure 2. Anteroposterior reaction forces of one running speed condition of an individual. Dot circles that indicated the fifth and tenth steps of the right foot were used in the analysis.

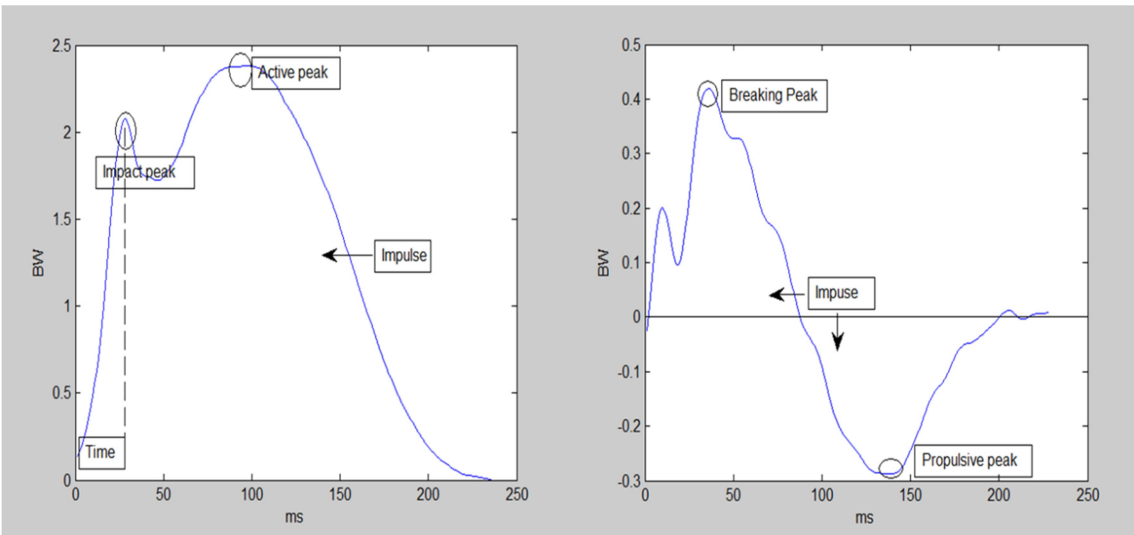

Figure 3. Analyzed components of the vertical and anteroposterior reaction forces

Table 1. Mean and SD (standard deviation) of variables and the results of the statistical test within and between genders by running speed

		Ip (BW)	Ap (BW)	T (1/1,000 s)	Ilr (BW/s)	Bp (BW)	Pp (BW)	Vm (BW·s)	Ym (BW·s)
8 km/h	Male	1.41±0.18	2.20±0.19	39.75±7.38	37.09±10.32	0.23±0.04	0.13±0.02	0.37±0.01	0.02±0.00
	Female	1.40±0.17	2.12±0.18	30.10±8.24	51.25±20.32	0.25±0.02	0.15±0.03	0.37±0.02	0.03±0.00
	p-value	.8557	.1971	**.0004**	**.0085**	.0974	**.0255**	.6800	**.0359**
12 km/h	Male	1.66±0.23	2.46±0.20	33.5±8.7	53.04±16.20	0.36±0.05	0.23±0.03	0.35±0.01	0.03±0.00
	Female	1.70±0.16	2.36±0.19	21.90±5.49	82.88±23.83	0.36±0.05	0.23±0.04	0.34±0.02	0.03±0.01
	p-value	0.4662	0.1047	**0.0001**	**0.0004**	0.9979	0.6608	0.0766	0.9405
16 km/h	Male	2.06±0.24	2.58±0.22	30.60±6.18	72.10±26.28	0.48±0.09	0.31±0.02	0.33±0.01	0.04±0.00
	Female	2.09±0.23	2.47±0.19	22.60±8.12	105.70±41.50	0.51±0.06	0.33±0.04	0.31±0.02	0.04±0.01
	p-value	0.6825	0.0910	**0.0012**	**0.0040**	0.2548	0.0501	**0.0160**	0.1572
8-12-16	Male *p*-value	**0.001**	**0.0001**	**0.001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
	Female *p*-value	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**

Abbreviations: Ip, impact force peak; Ap, active force peak; T, time to passive peak; Ilr, impact loading rate; Vm, vertical impulse; Bp, breaking force peak; Pp, propulsive force peak; Ym, absolute anteroposterior impulse

finding the maximum frequency at which the cumulative frequency of all these signals reached 99.9% (Ryu, 2013). Ground contact was defined as a vertical GRF of 5 N or greater.

The selected variables were the impact force peak of the vertical GRF; active force peak; time to passive peak; impact loading rate, which is calculated by dividing the impact force peak by the time to passive peak; and vertical impulse, which is the integral of the vertical GRF signal with respect to a time function (Figure 3). For the anteroposterior GRF force, the anteroposterior GRF signals were integrated with respect to the breaking force peak, propulsive force peak, and time function to calculate the absolute anteroposterior impulse(Figure 3). All variables except for time are expressed in terms of weights.

3. Statistical analysis

One-way ANOVA was used to investigate the differences in the variables at different running speeds within and between genders. The level of statistical significance was set at *p*-value<.05.

RESULTS

The results of the statistical analysis on the mean values and standard deviations of the variables analyzed under different speed conditions between and within genders are shown in Table 1. The impact peak that occurs at the moment the foot touches the ground while running was greater in women than in men at the relatively fast running speeds of 12 and 16 km/h, but not by a significant difference (Figure 4). The maximum active force peak per body mass, which is a vertical GRF that occurs at the moment the foot leaves the ground while running, was greater in men than in women at all running speeds, but not by a significant difference (Figure 5).

However, the mean time to maximum impact force peak was significantly shorter in women (8 km/h=30.10 ms, 12 km/h=21.90 ms, 16 km/h=22.60 ms) than men (8 km/h=39.75 ms, 12 km/h=33.5 ms, 16 km/h=30.06 ms) at all running speeds ($p<.05$, Figure 6). The mean loading rate obtained by dividing the vertical impulse peak by the time to peak was significantly higher in women (8 km/h=51.25 BW/s, 12 km/h=82.88 BW/s, 16 km/h=105.70 BW/s) than men (8 km/h=37.09 BW/s, 12 km/h=53.04 BW/s, 16 km/h=72.10 BW/s) at all running speeds ($p<.05$, Figure 7).

There was no significant difference in the propulsive force peak that occurred in the posterior direction when the foot came in contact with the ground between both genders at all running speeds (Figure 8). However, the mean propulsive force peak in the anterior direction was significantly greater in women (0.15 BW) than in men (0.13 BW) at the slowest running speed of 8 km/h ($p<.05$, Figure 9). No significant difference in the mean propulsive force peak in the anterior direction was observed for the other running speeds.

No significant difference in the vertical impulse, which is calculated by the area under the vertical GRF curve over time in the stance phase, during which the feet are in contact with the ground, was observed at 8 and 12 km/h. However, the mean vertical impulse was significantly higher in men (0.33 BW·s) than in women (0.31 BW·s) ($p<.05$, Figure 10).

The anteroposterior impulse, which is calculated by the absolute area under the anteroposterior GRF curve in the stance phase, was significantly higher in women (0.03 BW·s) than in men (0.02 BW·s) at 8 km/h, but no significant difference was observed at the other running speeds (Figure 11).

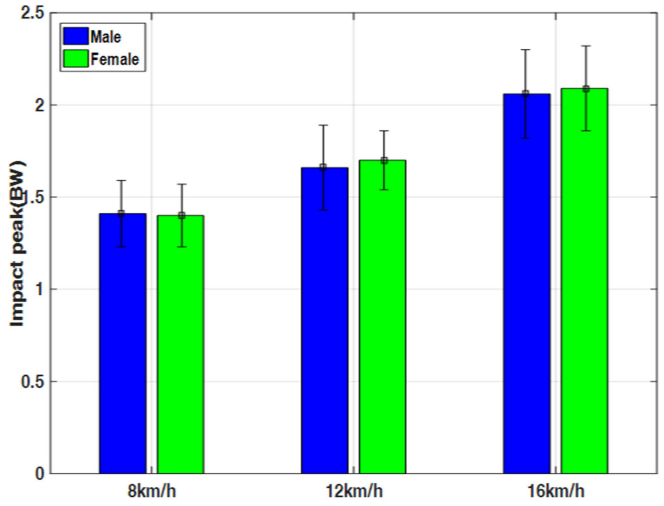

Figure 4. Gender differences in impact peak at each running speed

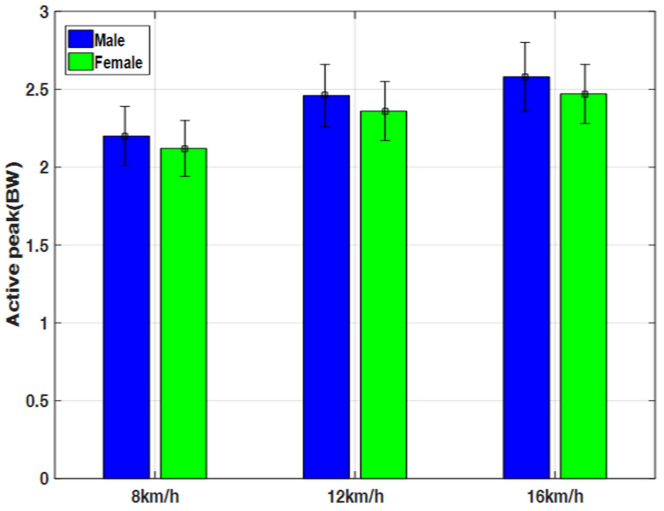

Figure 5. Gender differences in active peak at each running speed

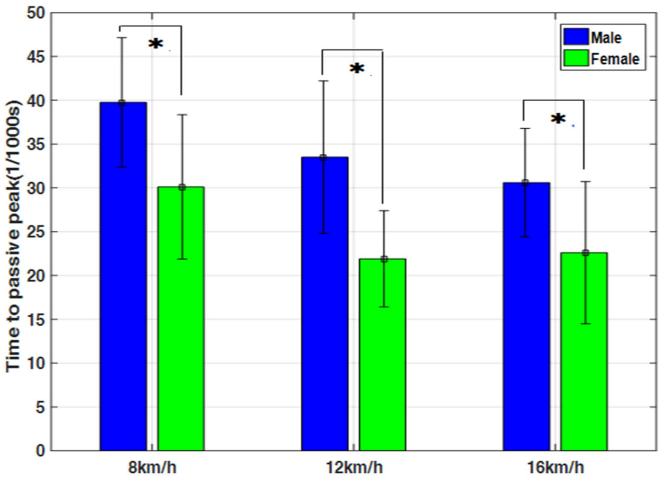

Figure 6. Gender differences in time to passive peak at each running speed (* indicates p<.05)

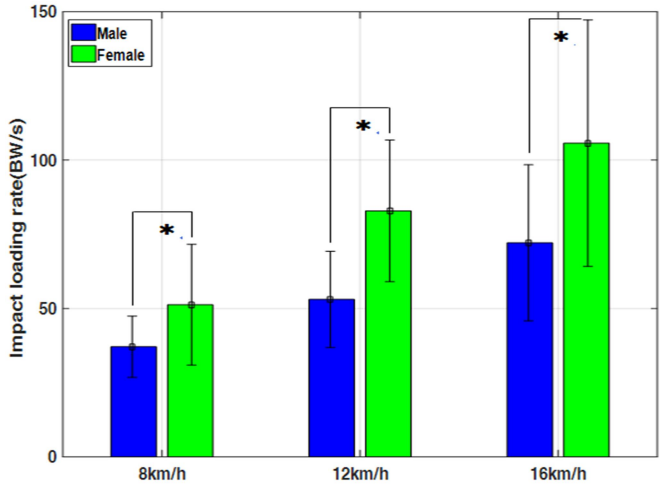

Figure 7. Gender differences in impact loading rate at each running speed

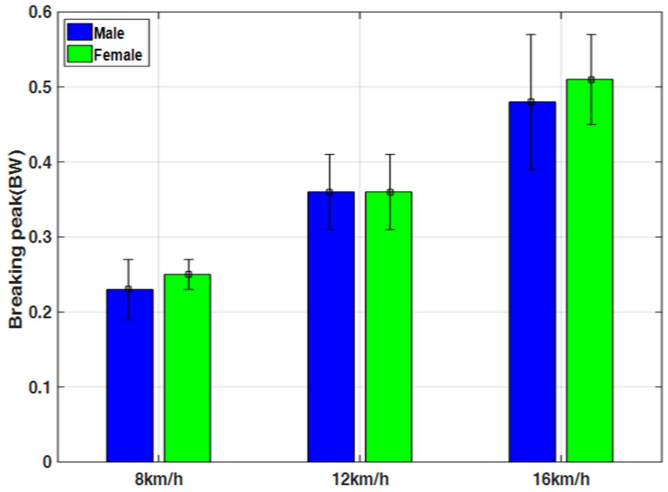

Figure 8. Gender differences in breaking peak at each running speed

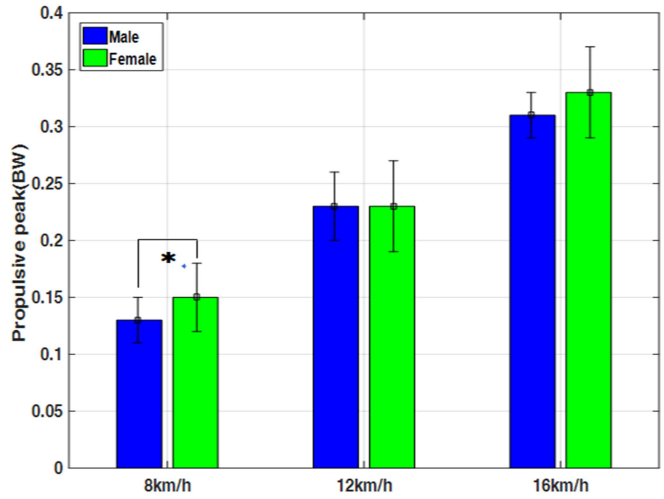

Figure 9. Gender differences in propulsive peak at each running speed

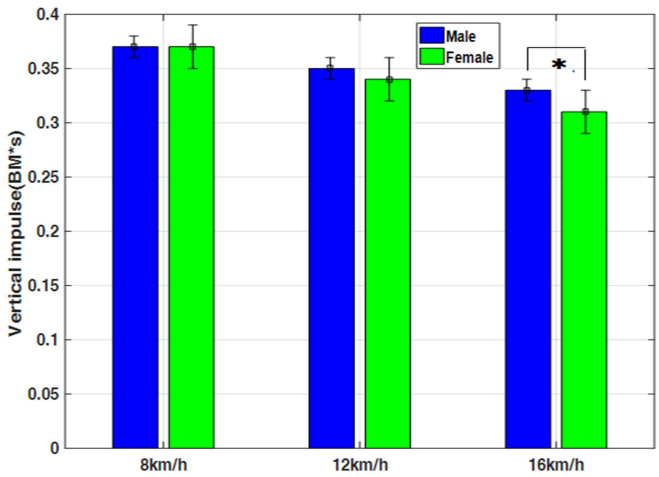

Figure 10. Gender differences in vertical impulse at each running speed

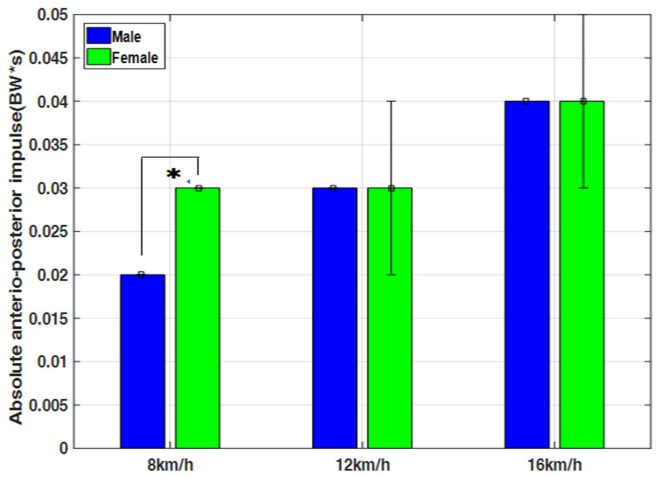

Figure 11. Gender differences in absolute anteroposterior impulse at each running speed

The impact force peak, active force peak, impact loading rate, breaking force peak, propulsive force peak, and absolute anteroposterior impulse significantly increased in men and women as the running speed increased ($p<.05$). However, the vertical impulse significantly decreased in men and women as the running speed increased ($p<.05$).

DISCUSSION

This study was conducted to characterize the gender differences in GRF components, which are important determinants of running, that occur as the running speed is increased.

In this study, the time to impact force peak that occurs at the moment the foot is in contact with the ground was shorter in women than in men at all running speeds. Although a more detailed analysis on this gender difference is necessary, this finding is related to a previous report that women, who have relatively short statures, run at higher frequency rates than men at fixed running speeds and thus experience a shorter stance phase (Ferber et al., 2003). It is also possible that the time to impact force peak was shorter in women since they have shorter strides than men due to the height difference (Elliott & Blanksby, 1979). The peak value of impact force, which is known as an important factor to be studied to understand the cause of running injuries (Dorn, Schache, & Pandy, 2012), increased in proportion to the running speed in both men and women. However, no difference in the impact force peak was observed between men and women at all running speeds. The linear increase in the impact force peak with respect to the running speed was consistent with a previous finding (Dorn et al., 2012). However, considering that there was no difference in the impact force peak between both genders, it appears that gender differences do not affect impact force peaks. A comparison of foot segment angles that affect the impact force peak and vertical impulse speed between men and women is needed (Kline & Williams, 2015). However, due to the shorter time to impact force peak in women compared with that in men, the impulse loading rate per body mass was higher in women than in men. This is consistent with a previous report that female athletes have higher impulse loading rates than male athletes (Milner et al., 2006; Ryu, 2005). Previous findings have shown that the impulse loading rate is associated with plantar fasciitis (Pohl et al., 2008), patellofemoral pain, medial tibial stress syndrome, lower back pain, and hip joint and knee joint pain (Pohl et al., 2008; Hamill et al., 2008) and potential tibial stress fracture as it affects the bones that absorb early impact forces that arise during the landing phase of running (Milner et al., 2006). Therefore, the lower impulse loading rates observed in women compared with those in men at all running speeds in this study suggest that the risk of fatigue fracture is higher in women (Taunton et al., 2002), who have lower bone densities and have menstrual cycles (Bennell, Matheson, Meeuwisse, & Bruker, 1999). Female athletes may also be at increased risk of running injuries such as plantar fasciitis and lower limb pain. Since there was no difference in the impact force peak between men and women in this study, it appears that women, whose lower limbs are shorter and have less mass compared with those of men, have a disadvantage in terms of the ability of their bones to absorb impact forces while running.

Considering the significant increase in the maximum active peak as the running time was increased, it can be estimated that the damage to the muscles that absorb this force is large. However, no gender difference in the level of damage to the soleus and gastrocnemius muscles that absorb the maximum active force between the genders was observed (Kline & Williams, 2015; Schache, Dorn, Williams, Brown, & Pandy, 2014).

In this study, vertical impulse was significantly higher in men than in women at 16 km/h. Vertical impulse during running is known as an important factor that increases the level of achievement by maintaining a high step rate in situations such as muscle fatigue (Hunter, Marshall, & Cnair, 2005). Thus, it appears that the lower limb muscles play a more significant role in improving the level of achievement in male than female runners at fast running speeds (Weyand, Sternlight, Bellizzi, & Wright, 2000). In this study, aside from the time variable, a variable that significantly decreased as the running speed was increased for both men and women was vertical impulse. The reason why vertical impulse

decreases as the running speed is increased may be that the leg muscles have enough time to generate a force needed to accelerate the body (Dorn et al., 2012) and create large vertical GRFs at low running speeds, whereas at relatively high running speeds, the ability of the leg muscles to generate the vertical GRFs is reduced due to the reduced time of contact with the ground (Weyand et al., 2000).

In this study, there was no difference in the maximum breaking GRF, which is created in the posterior direction in the early stance phase of running between both genders at all running speeds. However, the maximum propulsive force, which works in the anterior direction in the late stance phase, was significantly higher in women than in men at the low running speed of 8 km/h. Although detailed research on the causes of this phenomenon is necessary, a possible explanation is that female athletes extend their hip, knee, and ankle joints sufficiently at the moment their foot leaves the ground while running at low speeds (Hunter et al., 2005). It may be because of this reason that the absolute anteroposterior impulse was greater in women than in men at 8 km/h.

The significant increase in the propulsive force peak observed for both men and women as the running speed was increased is consistent with previous reports that the maximum running speed is significantly associated with the propulsive components of the anteroposterior GRF (Brughelli, Cronin, & Chaouachi, 2011; Hunter et al., 2005; Morin et al., 2012; Morin, Edouard, & Samozino, 2011; Nummela, Keränen, & Mikkelsson, 2007).

CONCLUSION

This study was aimed at characterizing the gender differences in the vertical and anteroposterior components of the GRF that occur as the running speed is increased. Considering that the impact loading rate was greater among female athletes than among male athletes, it appears that women are more exposed to the risk of potential running injuries related to the bone and ligament. It also seems that increasing the running speed may increase the risk of running injuries. Research on the association between the type of running injuries in men and women and running mechanisms may be useful in the future.

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