KJSB

Korean Journal of Sport Biomechanics 2016; 26(4): 413-420
http://dx.doi.org/10.5103/KJSB.2016.26.4.413
http://e-kjsb.org eISSN 2093-9752

ORIGINAL

Biomechanical Analysis of Muscle Fatigue and Ground Reaction Force for the Development of Outdoor Walking Shoes

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Received : 16 August 2016
Revised : 20 December 2016
Accepted : 20 December 2016

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Objective: The purpose of this study was to analyze and compare different kinds of outdoor walking shoes in terms of muscle fatigue and ground reaction force on walking, and to provide foundational data for developing and choosing outdoor walking shoes that fit the users.

Method: The study subjects were 30 healthy men. The experiment was conducted by using outdoor walking shoes with different inner and outer harnesses of the midsole, and shapes of the outsole. For data collection, electromyography was used to measure the muscle fatigue of the anterior tibial muscle and gastrocnemii, which contribute to the dorsiflexion and plantarflexion of the ankle joint, and the biceps muscle of the thigh and lateral great muscles, which contribute to the flexion and extension of the knee joint. A GRF measurement device was used to measure the *X*, *Y*, and *Z* axes.

Results: In the type A outdoor walking shoes, regarding the hardness of the midsole, the inner part was soft, while the outer part was hard. The vertical ground reaction force was the lowest, which means least impact while walking and light load to the knees and ankles. The type C outdoor walking shoes were intended to provide a good feel in wearing the shoes. The tibialis anterior, biceps femoris, and gastrocnemii indicate low fatigue, which means that during a long-distance walk, it will minimize the fatigue in the muscles of the lower limbs.

Conclusion: To sum up the study results, the different types of outdoor walking shoes indicate their unique characteristics in the biomechanical comparison and analysis. However, the difference was not statistically significant. Thus, a systematic and constant follow-up research should be conducted to cope with expanding market for outdoor walking shoes. Lastly, this study is expected to present foundational data and directions for developing outdoor walking shoes.

Keywords: Outdoor walking shoes, Muscle fatigue, GRF, Midsole hardness, EMG, Long-distance walk

INTRODUCTION

In recent years, the population that enjoys outdoor walking on various surfaces for leisure purposes, beyond normal walking or strolling, has increased. Consequently, the number of people who view the concept of walking from the perspective of leisure is also increasing. Shoes and walking are closely related, and shoes have been used for purposes of mobility and playing a role in preventing injuries by absorbing the impact generated when landing on the ground during normal walking and in protecting various body joints, including the ankles (Choi & Kwon, 2003). However, as the population that enjoys outdoor walking in various environments and surfaces has increased, efforts to scientize shoes to accentuate a specific purpose and characteristics of shoes are showing further improvement from functional, economic, and aesthetic aspects (Ryew & Hyun, 2013).

Recent trends have shown active development of shoes with newly added functionalities. The functions of shoes that have been gradually developed over a long period have become more diverse with increased purposes for use. Postural balance and stability are important elements in walking, and the structure of the insoles of shoes has an impact on gait characteristics (Landry et al., 2010; Miriam, 2015).

Previous studies on the functions and types of shoes include a comparative analysis of low extremity joint angles and load factor between walking barefoot and wearing functional shoes (Lee & Nam, 2015), and differences in the pressure distribution on different areas of the sole of the foot according to shoe type (Yi, 2010); a comparative analysis of the kinematics between functional shoes and regular sneakers (Song, Lee, & Sung, 2008); a kinematic analysis of gait according to shoe type and walking speed (Lee & Sung, 2008); and analysis of ground reaction force (GRF) and insole foot pressure distribution according to the type of trekking boots and gait pattern (Park & Lee, 2007), along with other studies on the effects of shoe sole forms on knee and ankle muscle

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activities (Yoon, Lee, & Choi, 2014) and the effects of form of the outsole on lower leg electromyography during gait (Kim & Choi, 2012).

Besides various studies that were limited to just shoes, many other studies have been conducted on the insoles of shoes as well. Previous studies on this topic include analyses of plantar foot pressure according to insole type during treadmill gait (Woo et al., 2015), the effects of raised heel insoles on the lower extremity joints of young males (Shin et al., 2012), biomechanical analysis of wearing a carbon nanotube-based insole during drop landing (Chae, Jung, & Lee, 2012), the effects of the height and quality of the material of popular heel-up insole on the mean plantar foot pressure during walking (Lee, Kim, Jung, Han, & Park, 2011), and a comparative analysis of foot pressure distribution by the functional insole that can be transformed and restored during walking (Park, Lee, Kim, Yoo & Kim, 2011). Meanwhile, most other studies have examined what impact shoes have on body movements and stability during walking or running, instead of focusing only on the shoes or insoles themselves. Many recent studies on shoes examined GRF and plantar pressure, and their findings are used in various ways as basic data for developing new shoes.

Injury prevention and protection features are generally considered important in shoes for outdoor walking, while they must also have functions that can enhance the stability of the feet and body (Stewart et al., 2007). Currently, outdoor walking shoes are being actively studied, where reports have indicated that the biomechanical effects of rocker soles based on immediate differences in gait strategies according to rocker sole configuration in outdoor walking shoes can improve gait by promoting recovery of movement of the feet or ankles with pain, deformity, or stiffness while also reducing the pressure exerted on specific areas of the sole of the feet and helping to improve balance (Yi, 2008). Moreover, with respect to the effects of functional walking shoes on foot type, balance, flexibility, and body composition, a study reported that flexibility in not only the ankles but also in the trunk and arm were improved by performing walking exercises while wearing walking shoes (Yi, 2007).

Various other studies have been conducted on walking shoes, including optimal hardness analysis of walking shoe soles with added weight (Kwak & Jeon, 2011) and the effects of elevated forefoot walking shoes on body composition, physical fitness, and qualitative health variables (Yi, 2005). Recent studies on outdoor walking shoes can be divided into fields of improvement in the hardness and external structure of the shoe midsole based on impact analysis by using a force plate, enhancing shoe stability by studying rear-foot control functions by using imaging analysis and measuring the pressure distribution in the bottom of shoes by using a pressure distribution meter (Shin, 2007).

Active efforts to improve outdoor walking shoes, as shown above, represent a positive development, but sports science studies are also desperately needed because systematic studies on the scientific functions of shoes can support public health. With the development of various outdoor walking shoes, the need for kinematic and kinetic studies on outdoor walking shoes has also emerged. As analysis and assessment of kinematic and kinetic functions are related to the basic functions of shoes, the need for such studies is especially high. Accordingly, the present study conducted a comparative analysis of kinematic variables according to the types of outdoor walking shoes and identified the optimal conditions for the development of outdoor walking shoes for the objective of using the findings in the study as the basic data for the development of outdoor walking shoes.

METHODS

1. Participants

The study participants consisted of 30 healthy men in their twenties who had a normal gait pattern and no history of low extremity diseases. The experiment was conducted after each participant received explanation on the objective and procedures of the study and voluntarily signed a consent form for participation in the experiment. Prior to any experiment, all the participants were given sufficient time for warming up. The physical characteristics of the participants are shown in Table 1.

Table 1. Subjects' characteristics (n = 30)

Items	(Mean ± SD)
Age (years)	22.10 ± 1.45
Weight (kg)	69.90 ± 5.80
Height (cm)	177.10 ± 2.85
Foot length (mm)	270 ± 0.00

2. Measurements

1) Shoes

A biomechanical analysis was performed by using 4 different types of outdoor walking shoes. The shoes used in the experiment were as shown in Figure 1.

2) Measuring instruments

(1) Muscle fatigue measurement

In the present study, the commercially available software TeleMyo DTS Telemetry and Noraxon XP, both from Noraxon (USA), were used to examine the amount of increase in fatigue in the lower extremity muscles. The equipment used is shown in Figure 2.

For analysis of muscle fatigue in the lower extremity muscles, lower extremity muscle fatigue during 60 min of walking on a treadmill at a speed of 4.2 km/h was measured by using a Bluetooth wireless electromyography (EMG) measurement system. Moreover, muscles in the 4 areas of the lower extremity that are most active were also measured, including the biceps femoris, which generates the greatest force when walking; the gastrocnemius, which maintains power and muscle endurance when walking for a long time; the vastus lateralis, which is involved in flexion and extension of the lower extremity; and the tibialis anterior, which plays a role in lifting the foot from the ground. The

Type A		The midsole hardness was soft on the inner side and hard on the outer side.
Type B		Provided feel that fits the foot shape by providing an adjustable arch height function.
Type C		A fly-fit form was used to improve breathability. The inner sole was designed to provide effective shock absorption.
Type D		Rock climbing shoe outsoles were used for better traction. The eyelet stay was designed with a curvature to prevent pressure and irritation on the top of the foot.

Figure 1. Types A, B, C, and D outdoor walking shoes

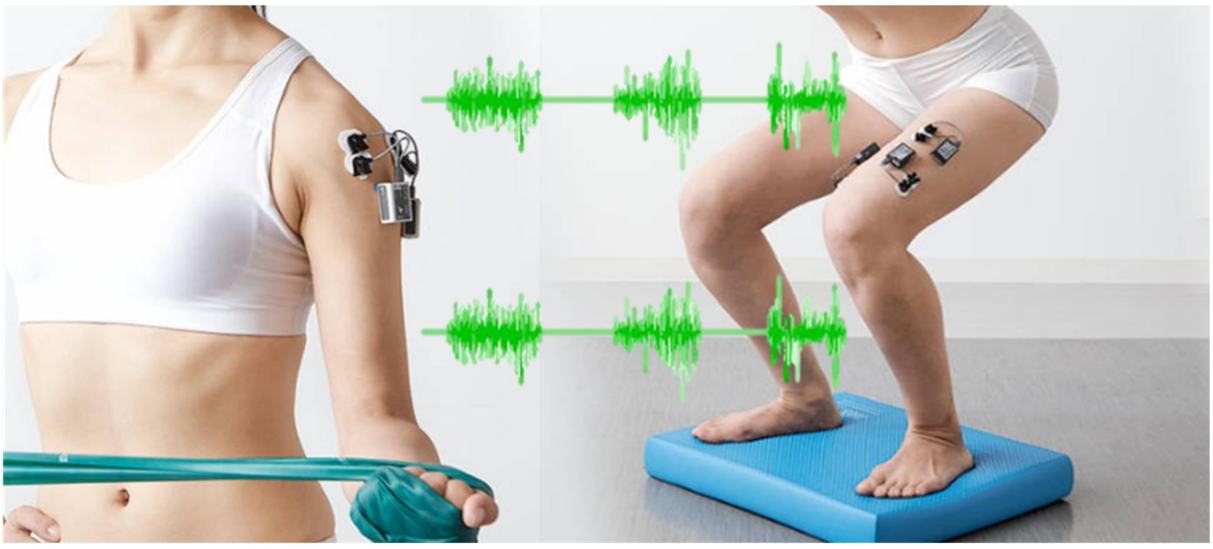

Figure 2. The wireless electromyography device of Noraxon

muscle fatigue test was performed before and after 60 min of walking, and analysis was performed after measuring the amount of change in EMG relative to the mean power frequency (MPF) values. The differences between the MPF values for each participant and muscle before walking were normalized, and the normalized MPF value was calculated by using the following equation (Figure 3):

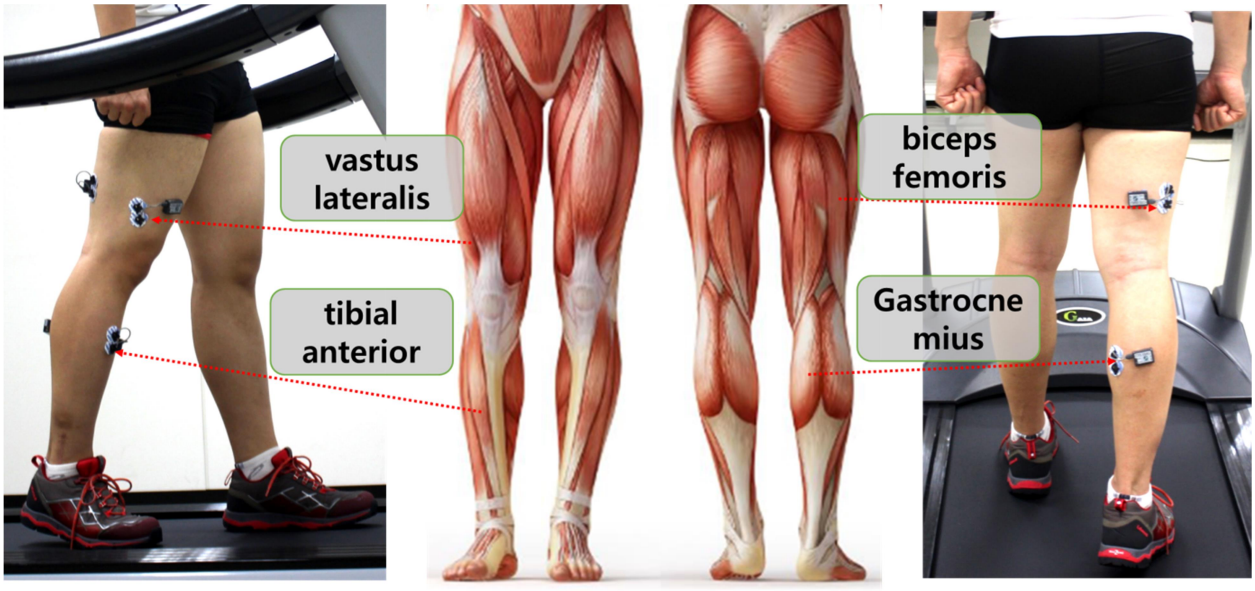

Figure 3. The surface electromyography electrode and muscle measurement placement

Normalized MPF = Mean MPF value measured after 60 min of walking/ Mean MPF value measured initially

With respect to the equation, a previous study on muscle fatigue (Kong et al., 2009; Park et al., 2010) reported that for the calculated results of muscle fatigue from which normalized MPF values were derived, an MPF value of <1 indicated a higher level of muscle fatigue, whereas an MPF value of ≥1 than the control group indicated a low fatigue level.

(2) GRF measurement

In the present study, the 4060-10-2000 force plate system from Bertec was used to measure GRF. The equipment specifications are shown in Table 2. To measure GRF, the participants preformed natural walking motions at a walking speed of 4.2 km/h. After 3 trials each, the mean value was used as data for statistical analysis.

Table 2. Specifications of the force plate system

Items	Standard
Plate size (inch)	15.75 × 23.62 × 3.94
Force range Fz (kN)	5~10
Shear force Fx, Fy (kN)	2.5~5
Natural frequency Fz (Hz)	340~750
Natural frequency Fz, Fy (Hz)	550~570
Weight (lb)	66

The force plate was fixed in the center of the control object to prevent shaking during walking. After which, a rubber mat for practice purposes was fixed on top of the force plate (Figure 3).

3. Data processing and statistical analysis

For statistical analysis of the raw data obtained in the present study by using SPSS Ver. 23.0 for Windows, the mean and SD were calculated by using a descriptive statistical analysis. Then, the measured values were reviewed for comparison of muscle fatigue and GRF among the outdoor walking shoes. One-way analysis of variance was performed on each variable value, while the Tukey test was used as a post hoc test for individual differences. The statistical significance level was set at α = .05.

RESULTS

1. Muscle fatigue

Analysis of the amount of change in muscle fatigue immediately after 60 min of treadmill walking at a speed of 4.2 km while wearing various types of outdoor walking shoes showed statistically significant differences in the tibialis anterior, gastrocnemius, vastus lateralis, and biceps femoris (p < .01; Table 3. In the tibialis anterior (F_3 = 4.818, p < .01), type C showed the lowest muscle fatigue, while types A, B, and D showed similar patterns. In the gastrocnemius (F_3 = 5.504, p < .01), the type C shoes showed the lowest muscle fatigue in the post hoc test, while the type B shoes showed the highest muscle fatigue, and the types A and D shows showed similar patterns. In the vastus lateralis (F_3 = 3.313, p < .05), muscle fatigue appeared in the lowest to highest order of types A, C, and B, with type D showing the highest fatigue level. In the biceps femoris (F_3 = 3.094, p < .05), muscle fatigue was the lowest in type C, while type A showed the highest muscle fatigue, and types B and D showed similar patterns to each other (Table 3).

Figure 4. GRF axis coordinates

Table 3. Comparison of muscle fatigue among the different outdoor walking shoes (unit: μV)

Item	Type	Mean ± SD	df	*F*	*p*	Tukey
Tibialis anterior	Type A (n = 30)	0.949 ± 0.14	3	4.818	.002	C > B, A, D
	Type B (n = 30)	0.953 ± 0.12				
	Type C (n = 30)	0.970 ± 0.14				
	Type D (n = 30)	0.940 ± 0.13				
Gastrocnemius	Type A (n = 30)	1.013 ± 0.15	3	5.504	.001	C > D, A, B
	Type B (n = 30)	0.995 ± 0.12				
	Type C (n = 30)	1.037 ± 0.23				
	Type D (n = 30)	1.030 ± 0.23				
Vastus lateralis	Type A (n = 30)	0.815 ± 0.60	3	3.313	.019	A, C, B > D
	Type B (n = 30)	0.810 ± 0.27				
	Type C (n = 30)	0.811 ± 0.35				
	Type D (n = 30)	0.749 ± 0.33				

Table 3. Comparison of muscle fatigue among the different outdoor walking shoes (Continued) (unit: μV)

Item	Type	Mean ± SD	df	*F*	*p*	Tukey
Biceps femoris	Type A (n =30)	0.960 ± 0.66	3	3.094	.026	C > D, B C > A
	Type B (n = 30)	0.971 ± 0.16				
	Type C (n = 30)	0.993 ± 0.19				
	Type D (n = 30)	0.977 ± 0.20				

2. GRF

The vertical GRF value during the landing and drive phases of the lower extremity joints during walking represented the value in the Fz (+) direction. The anteroposterior GRF Fy values represented values in the anterior (+) and posterior (-) directions, and the mediolateral GRF Fx values represented values in the medial (-) and lateral (+) directions.

1) Vertical GRF

The vertical GRF values measured during walking according to the type of outdoor walking shoes are shown in Table 4.

Table 4. Vertical ground reaction force values in each shoe type (unit: %BW)

Item	Type	M ± SD	df	*F*	*p*
1st Peak	A (n = 30)	1.215 ± 0.10	3	0.484	.694
	B (n = 30)	1.239 ± 0.07			
	C (n = 30)	1.225 ± 0.06			
	D (n = 30)	1.224 ± 0.07			
2nd Peak	A (n = 30)	1.210 ± 0.08	3	0.462	.667
	B (n = 30)	1.228 ± 0.06			
	C (n = 30)	1.221 ± 0.04			
	D (n = 30)	1.218 ± 0.07			

The first peak in the vertical GRF according to the type of outdoor walking shoes was highest in type B (1.239 ± 0.07 %BW) and lowest in type A (1.215 ± 0.10 %BW). However, differences were found only in the mean values but were not statistically significant ($p > .05$). Moreover, the second peak was also highest in type B (1.228 ± 0.06 %BW) and lowest in type A (1.210 ± 0.08 %BW). Again, differences were found only in the mean values, but were not statistically significant ($p > .05$).

2) Anteroposterior GRF

The anteroposterior GRF values during walking according to the type of outdoor walking shoes are shown in Table 5. During the landing phase, when the first peak that shows braking motion appeared, type B (0.213 ± 0.07 %BW) showed the highest GRF and type A (0.223 ± 0.06 %BW) showed the lowest GRF, but without statistically significant differences ($p > .05$).

Table 5. Anteroposterior ground reaction force values in each shoes type (unit: %BW)

Item	Type	Mean ± SD	df	*F*	*p*
Anterior (+)	A (n = 30)	0.208 ± 0.05	3	0.242	.867
	B (n = 30)	0.213 ± 0.07			
	C (n = 30)	0.212 ± 0.04			
	D (n = 30)	0.211 ± 0.06			
Posterior (-)	A (n = 30)	-0.223 ± 0.06	3	0.453	.716
	B (n = 30)	-0.235 ± 0.08			
	C (n = 30)	-0.232 ± 0.09			
	D (n = 30)	-0.234 ± 0.06			

Moreover, in the second peak, which showed propulsion, type A (-0.223 ± 0.06 %BW) showed the lowest GRF and type B (-0.235 ± 0.08 %BW) showed the highest GRF. However, differences were found only in the mean values but were not statistically significant ($p > .05$).

DISCUSSION

In the present study, a comparative analysis of muscle fatigue and GRF was conducted according to the type of outdoor walking shoes to provide basic data to allow users to choose the appropriate outdoor walking shoes.

Muscle fatigue refers to the acute decline in the ability to generate muscle force caused by exercise. The level of muscle fatigue can be quantified as the amount of decrease in maximum muscle force required for voluntary contraction or expressed as continued task failure time during contraction by maximum target force (Gandevia, 2001). When calculating muscle fatigue by using EMG, when the calculated results of muscle fatigue from which normalized MPF values were derived showed a MPF value of <1, the level of muscle fatigue increased, whereas when the value was >1 or that of the control group meant the level of fatigue decreased (Kong et al., 2009; Park et al., 2010). In the present study, the post hoc test results for the tibialis anterior

showed muscle fatigue in the highest to lowest order of type C < type B < type A < type D; for the gastrocnemius, type C < type D < type A < type B; for the vastus lateralis, type A < type C < type B < type D; and for the biceps femoris, type C < type D < type B < type A. Type A was designed as a multi-hardness outsole and midsole type with different hardness on the inner and outer sides to increase the efficiency of the midfoot, which absorbs GRF generated from the ground. Muscle fatigue appeared relatively higher in the tibialis anterior and biceps femoris, which are involved in tibial internal rotation and knee supination during loading response, and the gastrocnemius, which may be involved in the stability of the left and right feet in addition to propulsion in the toe-off phase. On the other hand, because the role of impact absorption decreased in the knees owing to the effects of efficient impact absorption, muscle fatigue in the vastus lateralis was relatively lower. Type B was designed to allow adjustment of the height of the arch support. Thus, muscle fatigue in the tibialis anterior tended to be low, owing to the effective arch support. However, the gastrocnemius, vastus lateralis, and biceps femoris showed relatively higher muscle activities. Thus, additional tests on the effects of arch support are deemed necessary. Type C used a fly-fit form for improved breathability, and its insole was designed to provide effective impact absorption. As a result, the role of the lower extremity muscles for absorbing impact during stance phase and movements for walking was reduced. Consequently, the tibialis anterior, gastrocnemius, vastus lateralis, and biceps femoris showed relatively lower muscle fatigue. Type D was used for rock climbing, having an outsole with high stiffness for improved traction. As a result, muscle fatigue increased from impact absorption and ankle plantar flexion by the tibialis anterior during the load response phase was controlled, which is believed to have also resulted in a tendency of muscle fatigue to increase in the vastus lateralis as a strategy for reducing the magnitude of impact to the knees. By contrast, owing to the effects of high stiffness, the muscle activities of the gastrocnemius recruited for propulsion during the terminal stance phase decreased. Consequently, muscle fatigue tended to appear slightly lower.

With respect to the results of the previous studies on vertical GRF, Byun (2010) reported that analysis of load factor from vertical GRF showed that the first peak played a type of braking role as the heel contacted the ground during landing. By contrast, the second peak plays a role of creating propulsion to move the body forward as a counterforce to the force of kicking the ground for forward movement during the toe-off phase (Lee & Sung, 2008). In the present study, none of the outdoor walking shoes showed statistically significant differences, but type A shoes showed the lowest vertical GRF at the first peak, where controlling motion was performed, and the second peak, where propulsive motion was performed. These results indicated that type A shoes are high-performance shoes that can most effectively absorb GRF. Moreover, with respect to previous studies on anteroposterior GRF, Perry and Burnfield (2012) stated that during normal gait, Fy1 (control phase) showed approximately 13% of the body weight, while Fy2 (drive phase) showed approximately 23%. In the present study, all 4 types of shoes showed higher GRF values during the control phase than during the drive phase, similar to the results of previous studies. All the shoes showed similar shapes during the braking and drive phases. Among them, the type A shoes, which had a different mediolateral hardness from that of the other shoes, showed the lowest anteroposterior GRF. Therefore, the type A shoes were determined to be high-performance shoes that can accommodate GRF most effectively. On the other hand, the type B shoes tended to show a high GRF in the first and second peaks of the vertical GRF, and the control and drive phases of the anteroposterior GRF. Based on these results, we assumed that the type B outdoor walking shoes are appropriate for fast and dynamic gait and can reduce impact load owing to its design with an adjustable arch height.

In summary, we believe that the data obtained from the analysis of outdoor walking shoes performed in the present study can be used for assessing and improving the functions of outdoor walking shoes, and that the findings can bear significance as basic data for the development of functional outdoor walking shoes. Future in-depth studies are needed on the effects of the muscle fatigue and GRF relationships examined in the present study on the lower extremity joints during actual walking.

CONCLUSION

In the present study, a comparative analysis was performed on the biomechanical variable of GRF and muscle fatigue according to the types of outdoor walking shoes. Based on the analysis results, the following conclusions were derived.

The outdoor walking shoes that were selected for the present study showed differences in muscle fatigue and GRF values according to the intended design goals for the development of outdoor walking shoes even though they belonged in the same category of outdoor walking shoes. Low muscle fatigue does not necessarily positively affect the ability to absorb impact generated on the ground. Even if the GRF was high, it could not be viewed as a poor GRF absorption capability. Therefore, even in the development of shoes belonging to the same product group, development efforts must consider the combination of materials, physical properties, stiffness, structural design, and support shape according to functional goals and characteristics.

Future studies should test the functions of outdoor walking shoes in actual outdoor environment and conduct in-depth examination into the effects of muscle fatigue and GRF relationships on lower extremity joints during actual walking according to the types of outdoor walking shoes.

ACKNOWLEDGEMENTS

This study was excerpted from the Young-Min Jang's PhD thesis in 2016.

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