

Kinematic and kinetic analyses of novice running in dress shoes and running shoes

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The purpose of the study was to investigate how novice runners adjust their lower extremities in heel-toe running while they wear dress shoes and running shoes. Ten novice male runners repeatedly ran across a force plate at 4 m/s in each type of shoes. Joint kinematics and kinetics, vertical ground reaction force, and utilized coefficient of friction during the stance phase were quantified. The results obtained showed no differences in impact peaks, stance time, stride length and joint kinematics. However, dorsiflexion moment was significantly greater with dress shoes (407 Nm) compared to that with running shoes (304 Nm; $p < 0.05$). Compared to the runners in running shoes (0.23), the runners in dress shoes (0.20) achieved a significantly lower utilized coefficient of friction ($p < 0.05$). When running in dress shoes, novice runners tended to use better a dorsiflexion moment than when running in running shoes. This adaptation appears to minimize the chances of slipping at the moment of heel strike.

Key words: running, dress shoe, running shoe, kinetics, friction coefficient, slip

Nomenclature

The number of subscript is used for a segment ($i = 1$: foot, 2: shank, and 3: thigh).

X, Y, Z – global reference frame

m_i – mass of the i -th segment

L_i – vector pointing from the distal joint to proximal joint of a segment

L_{gi} – vector pointing from the center of mass to the proximal joint of a segment

L_{GRF} – vector pointing from the center of mass of the foot to the point of ground reaction force

a_{gi} – translational acceleration vector of the center of mass of a segment

g – acceleration due to gravity

ω_i – angular velocity vector of a segment relative to the global reference frame

$\dot{\omega}_i$ – angular acceleration vector of a segment relative to the global reference frame

JM_i – resultant joint moment vector of the i -th segment applied at proximal joint

F_i – resultant joint force vector of the i -th segment applied at proximal joint

GRF – the ground reaction force applied to the foot

I_i – moment of inertia tensor defined at the center of mass of a segment

1. Introduction

Footwear has been frequently studied in the field of biomechanics because it is closely associated with human performance, health, and injury [1], [2]. Bare-foot running is significantly characterized by flat placement at touchdown and external higher loading rates than shod running, which elicits higher leg stiffness of lower extremity during the stance phase [3]. Thus wearing footwear is considered to reduce contact stress on foot during the stand phase. However, recent studies suggested negative effects of shoe walking on

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knee osteoarthritis due to higher knee adduction moment of shod walking [4], [5]. Therefore, it is very important to understand biomechanical characteristics of footwear and its effect on human activities.

Running, further higher loading activity than walking, is one of the most common activities that result in acute and overuse injuries [6], [7]. In particular, excessive and repetitive impact during heel-toe running has been associated with causing severe injuries to legs [8], [9]. In order to reduce running injuries related to the force of impact, many studies have attempted to associate impact force with midsole hardness; however, extant findings are contradictory. Some studies have found higher initial peak values for hard-soled shoes compared to those of athletic shoes [10], while others have not found any difference [11]–[13], and still others have reported smaller impact peak values for hard-soled shoes [14], [15] due to individual differences in adaptation strategies [16], [17]. Thus, additional investigations are necessary to understand the effect of different shoes on kinematics and kinetics of running.

Running in different shoes induces kinematic adaptations in runners. Hard-soled shoes have been shown to produce an increase in the rate of knee flexion [16], ankle pronation [15], and ankle dorsiflexion at touchdown [18]. Furthermore, hard-soled shoes are known to have less available friction than soft-soled shoes [19]. Recently TSAI and POWERS [20] found that walking in dress shoes with increased midsole hardness produced compensatory kinematic adaptations, such as a decrease in walking velocity, stride length, and ankle dorsiflexion angle in response to a smaller utilized coefficient of friction (COFu) for hard-soled shoes. However, the effect of dress shoes (DS) on running has not been well reported.

Although DS are designed for normal walking and typically have harder soles than do running shoes (RS), people sometimes have to run while wearing DS. For unconditioned people (e.g., sedentary people), running in DS might increase the risk of injury not only because hard-soled shoes increase the magnitude of impact, but also because running increases the frequency of impact. Not surprisingly novice runners adjust their lower extremities to minimize injury risks and the chances of slipping.

The purpose of this study was to analyze kinematic and kinetic adaptations in heel-toe running in novice runners wearing DS and RS. Specifically, we hypothesized that running in DS would elicit different kinematics and kinetics in comparison with running in RS. This study aimed to provide a better understanding of kinematic and kinetic adaptations of novice

runners in hard-soled shoes, which may be used in the development of methods for reducing running-related injuries.

2. Materials and methods

2.1. Subjects

Ten male college students (mean (M) \pm standard deviation (SD) age: 20.9 ± 1.9 years; body mass: 69.8 ± 3.7 kg, height: 1.76 ± 0.03 m) participated in this study. All participants were novice runners who reported regular jogging once per week or none. They signed consent forms approved by the ethics committee of the Kyung Hee University.

2.2. Experimental protocol and instrumentation

All testing was conducted in one session. Two types of shoes, dress shoes (leather, mass of 360 ± 13 g; DétenteTM, Lesmore Co., Korea) and running shoes (fabric, mass of 316 ± 5 g; Gel-Kanbarra 3TM, Asics Co., Japan), were tested (figure 1). Participants selected the best fitting shoe of each type among three available sizes (0.260, 0.265, and 0.270 m). The shoes were tested in a randomized sequence.

Participants were instructed to run across a force plate at 4 m/s after practising for several trials, which are speeds common to recreational runners [21], [22]. Running speed was monitored using two photocells (ST-50TM, Seed Technology Co., Korea) positioned 2 m apart, before and after a force platform (OR6-7, AMTI Inc., USA). There was a one-minute break between trials and a four-minute resting interval between conditions in order to prevent fatigue effect. When running speed did not stay within the limits (i.e., 0.02 m/s from 4 m/s), the trial was excluded and participants were instructed to repeat the run until the speed fell within the designated range. Three trials were collected for the analysis [22], [23]. A six-camera, high-speed video system (T40, Vicon Co., UK) was used to capture three-dimensional motion data from reflective markers at a sampling rate of 200 Hz. The lower body marker set corresponded to the standard VICON[®] plug-in gait model, which is widely used in motion analysis [23], [24]. Sixteen retro-reflective markers were placed on anterior superior iliac spines, posterior superior iliac spines, thighs, lateral

condyles, shanks, lateral malleoli, heads of second metatarsal bone (2), heel (2) (figure 1).



Fig. 1. Testing shoes and marker locations: dress shoe (top-left) and running shoe (top-right) with retro-reflective markers (toe and heel), and locations of sixteen body markers from sagittal view (bottom-left) and back view (bottom-right)

2.3. Data reduction and analysis

The ground reaction force (GRF) was collected at 2,000 Hz and was filtered at 100 Hz using a fourth-order Butterworth low-pass filter. From the normalized vertical GRF (vGRF) graph relative to body weight (BW), the normalized impact peak (the first peak within 50 ms after heel strike) and the normalized active peak (the second peak) were extracted [11], [25]. The utilized coefficient of friction (COFu) was calculated as the ratio of the shear (algebraic resultant of the anterior–posterior force F_{AP} and medial–lateral force F_{ML}) to vertical ground reaction force (F_{VER}) as follows [20], [26]:

$$\text{COFu} = \frac{\text{resultant shear GRF}}{\text{vertical GRF}} = \frac{\sqrt{F_{AP}^2 + F_{ML}^2}}{F_{VER}}. \quad (1)$$

During weight-bearing movement, the COFu peak immediately after impact indicates shear resistance to foot sliding. A small COFu peak implies that the shoe is susceptible to slippage due to insufficient shear

resistance relative to the vertical resistance from the ground [20].

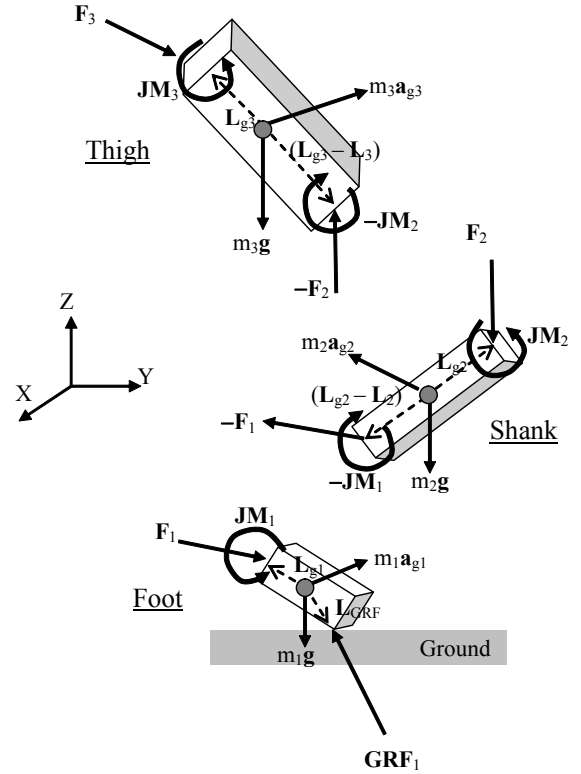


Fig. 2. Free-body diagram for each segment, including unknown joint forces and joint moments

Initial contact was defined as the point at which the vertical ground force exceeded 5 N, and the stance time was defined as the time between the right heel-strike and the right toe-off. Stride length was calculated as the displacement between the heel marker positions of the right heel-strike and the next right heel-strike.

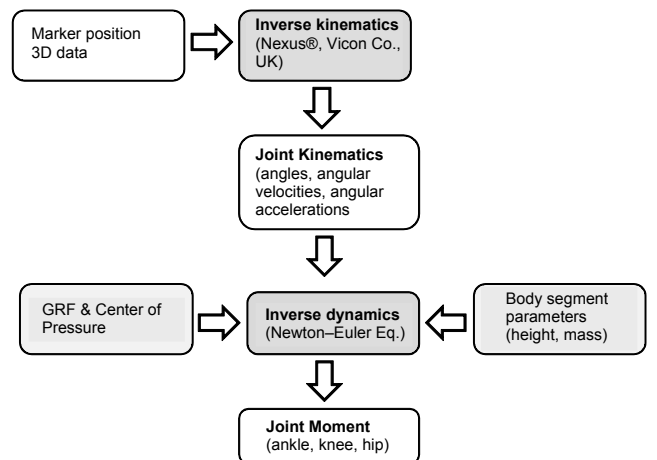


Fig. 3. Flowchart of calculation procedures of joint kinematics and kinetics

Joint angles, angular velocities, angular accelerations of the ankle, knee, and hip were calculated using Nexus® (Vicon Co., UK) after a filtering process was applied (Woltring quintic spline filter with the predicted mean square error of 15 Hz). With these kinematic data, GRF including center of pressure, and body segment parameters (height and mass) [27], the joint moment of each joint were calculated by the Newton–Euler equations at each segment according to free-body diagram (figures 2 and 3). Then at the foot segment, the equations of motion were as follows:

$$\begin{aligned} F_1 + m_1 g + \text{GRF} &= m_1 a_{g1}, \\ JM_1 + L_{g1} \times F_1 + L_{\text{GRF}} \times \text{GRF} &= I_1 \dot{\omega}_1 + \omega_1 \times (I_1 \omega_1). \end{aligned} \quad (2)$$

The equations of motion at the shank segment were

$$\begin{aligned} F_2 - F_1 + m_2 g &= m_2 a_{g2}, \\ JM_2 - JM_1 + (L_{g2} \times F_2) + [(L_{g2} - L_2) \times (-F_1)] \\ &= I_2 \dot{\omega}_2 + \omega_2 \times (I_2 \omega_2). \end{aligned} \quad (3)$$

Similarly, at the thigh segment, they were

$$\begin{aligned} F_3 - F_2 + m_3 g &= m_3 a_{g3}, \\ JM_3 - JM_2 + (L_{g3} \times F_3) + [(L_{g3} - L_3) \times (-F_2)] \\ &= I_3 \dot{\omega}_3 + \omega_3 \times (I_3 \omega_3). \end{aligned} \quad (4)$$

All kinematic and kinetic variables were normalized to stance time (i.e., right heel-strike to right toe-off) for multiple comparisons between subjects and trials.

2.4. Statistics

The mean value of three trials on dependent measures was used for statistical analysis. In statistical analysis, the paired *t*-tests were used to determine the influences of DS usage on the kinematic and kinetic variables. Analyses were performed using SPSS 15.0 statistical software (SPSS, USA), in which a significance threshold of 0.05 was used for all statistical comparisons.

3. Results

Running in DS and RS is represented by different vGRF curves in the early stance phase (figure 4a). Five out of ten participants in DS showed non-distinctive impact peaks at heel strike, while all par-

ticipants in RS showed clear, active impact peaks. Accordingly, the mean data of vGRF across ten participants in DS showed no impact peak (figure 4a). When comparing the mean of the participants in DS with that of ten participant in RS, impact peak for DS (1.71 BW) tended to be lower than that of RS (2.18 BW); however, this difference was not statistically significant (the table; $p = 0.06$). There was no difference in the mean active peaks between the two conditions either (2.63 BW and 2.66 BW for DS and RS, respectively). Figure 4b shows the qualitative changes in COFu across normalized stance time, where the peak for DS at heel strike was significantly lower than that for RS ($p < 0.05$, the table).

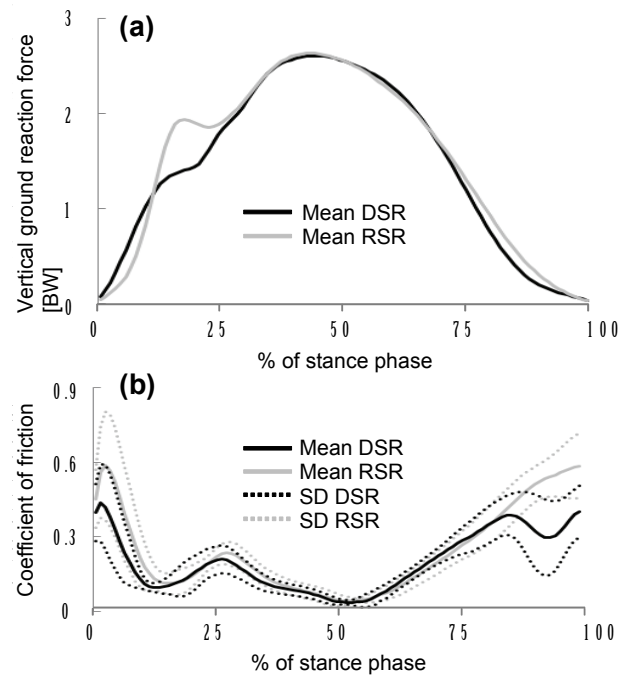


Fig. 4. (a) Mean vertical ground forces during dress-shoe running (DSR) and running-shoe running (RSR). There was indistinctive impact peak in DSR, while a clear impact peak was found in RSR (around 12–25% of stance phase). (b) Comparison of coefficients of friction (COF) between DSR and RSR. The solid line shows the mean values and the hidden lines indicate upper and lower bounds of standard deviation (SD). The peak COF in RSR (around 25–30% of stance phase) was higher than that in DSR.

Regarding qualitative or quantitative joint kinematics across the ankle, knee, and hip, no significant effect of shoe type was detected in the sagittal, frontal, and horizontal planes (figure 5a and the table). However, a significant effect of shoe type was found in the peak dorsiflexion moment, even though the qualitative shapes of joint moments across all three joints seemed similar between DS and RS (figure 5b). The runners in DS (407 ± 107 Nm) showed a higher peak dorsi-

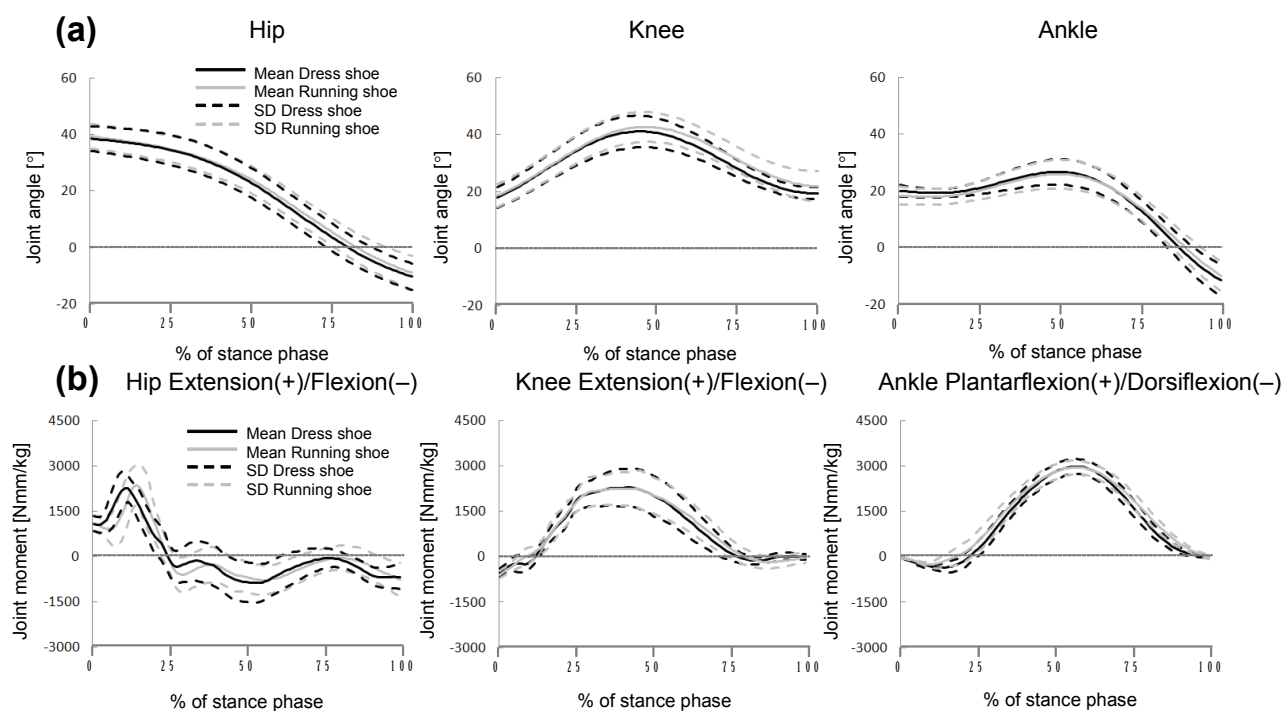


Fig. 5. (a) Joint angles and (b) joint moments of the hip, knee, and ankle in the sagittal plane during DSR and RSR. Only peak ankle dorsiflexion moments between DSR and RSR were statistically different (around 0–25% of stance phase) ($p < 0.05$)

Table. Means (standard deviations) of kinematic and kinetic parameters during running in dress shoes and running shoes (mean (*SD*))

		Dress shoe	Running shoe	<i>p</i>
vGRF (BW)	impact peak	1.71 (0.16)	2.18 (0.43)	0.06
	active peak	2.63 (0.13)	2.66 (0.23)	0.51
Peak COFu		0.20 (0.04)	0.23 (0.04)	0.04*
Stance time (s)		0.24 (0.01)	0.23 (0.01)	0.15
Stride length (m)		2.93 (0.18)	3.03 (0.22)	0.09
ROM (°)	hip	48.8 (3.9)	48.4 (5.7)	0.76
	knee	24.1 (3.6)	25.3 (3.9)	0.14
	ankle	38.6 (6.3)	36.4 (4.7)	0.17
Max. joint moment in sagittal plane (Nmm/kg)	hip extension	2529 (493)	2735 (643)	0.11
	hip flexion	1228 (511)	1249 (453)	0.82
	knee extension	2413 (544)	2368 (563)	0.59
	knee flexion	578 (162)	589 (128)	0.80
	ankle plantarflexion	2997 (257)	2966 (242)	0.52
	ankle dorsiflexion	407 (107)	304 (109)	<0.01*

* Shows significant difference in mean values between two conditions.

flexion moment than the runners in RS (304 ± 109 Nm) ($p < 0.01$, the table).

4. Discussion

This study investigated the kinematic and kinetic effect of running in DS on young novice runners. We

did not find any statistical differences between two different shoes in kinematic variables including stance time, stride length, and range of motion (ROM). However, for kinetic variables the maximum ankle dorsiflexion moment was greater during running in DS than during running in RS, which is consistent with one computer simulation study that demonstrates that the tibialis anterior muscle exerts a greater force for a hard-soled shoe compared to that for a softer-

soled shoe [28]. This greater dorsiflexion movement might be mainly generated by excessive contraction of the tibialis anterior muscle to resist plantar flexion and pronation at the moment of heel contact for hard-soled shoes [15], [29]. Surprisingly, some of our results are inconsistent with findings from previous studies. We found that DS did not influence joint kinematics significantly during running, in contrast to the results of the previous studies [11], [15], [18] and in a partial accordance with the results of KURZ and STERGIU [30]. They showed no significant difference in ankle coordination strategies during running between hard shoes and soft shoes.

The different patterns of vGRF at heel contact for hard-soled shoes might be attributed to extrinsic and intrinsic factors. Extrinsic factors such as no or few high-frequency components of impact signal (more than 12 Hz) at the shoe–surface interface (mechanical properties of DS) might have resulted in a smaller vGRF peak [19]. Intrinsic factors such as incomplete heel–toe running by primarily using forefoot contact may have also contributed to a smaller vGRF peak [31]. In this case, we speculate that participants may have adapted to running in a hard-soled shoe with altering muscle activities, including that of the tibialis anterior muscle [32].

In push-off phase (after active peak in GRF), there was no difference in active peak in GRF and peak plantar flexion moment between DS running and RS running. This might occur because the controlled running speed (4.0 ± 0.02 m/s) for both DR running and RS running, respectively, induced statistically similar propulsive joint moment and ground reaction force regardless of shoes.

Collectively, the results of the present study demonstrate that running in DS does not increase the risk of injury compared to running in RS in terms of the magnitudes of impact peak, which is at variance with the results from prior studies [6], [9] and our expectations. However, the finding that running in DS results in a smaller COFu peak and an indistinctive impact peak suggests an alternative interpretation of adaptation for running in DS. It may be that DS generate less friction than RS, implying that participants wearing DS could be at the greater risk of initiating a slip at the moment of heel contact compared to those wearing RS. Or it may be due to transient sensory-motor adaptation resulting from continuous stimuli of DS to prevent a slip. Therefore, those running in hard-soled shoes might try to adjust their lower extremities to exert an excessive dorsiflexion moment to land more smoothly. These changes might produce a less intense COFu at the

shoe–floor interface to increase the safety margin from available friction [33], [34]. It may be that we do not see the differences in joint kinematics between the two shoe types because adaptations in dorsiflexion moment are not sufficient to elicit changes in joint kinematics.

A couple of limitations should be considered in this study. First, we did not measure electric currents (electromyography) in leg muscles, so we were unable to infer whether or not the intrinsic factors discussed influenced our results. Alternatively, kinetic parameter and dorsiflexion moment may adequately explain the adaptation. Second, the test surface condition was the laboratory floor. People may run on outdoor asphalts when they encounter running in DS. Therefore, the shoe–surface interface might differ from those of the present testing conditions and may have impacted our results. Third, the small sample size of ten subjects may influence the results because the results of many variables between two shoes' running were not distinctively different. Another major shortcoming of this study was the lack of plug-in-gait model adjustment to the gait measurement in shoes. Even though this study followed the same protocol of KERRIGAN et al. [5] in using Vicon® plug-in-gait model, the results of joint angles and joint moments based on standard plug-in-gait protocol without any adjustment to the shoed gait should be interpreted with caution.

5. Conclusion

In summary, the results of this study demonstrate that novice runners show different higher ankle dorsiflexion moment during DS running than during RS running at the instance of heel strike. At the shoe–surface interface, an indistinctive impact peak and smaller utilized coefficient of friction were detected during running in DS compared to running in RS. However, the differences in the detected kinetic parameters could not induce the differences in joint kinematics of lower extremities shod with two different shoes. The modifications of kinetic parameters in running in DS may be associated with slip prevention due to the less available friction of DS. Practically the prolonged DS running in daily activities might induce a quicker muscular fatigue of dorsiflexor muscles as a result of producing higher dorsiflexion at the heel-strike. Therefore, RS running is recommended as effective for a prolonged running situation.

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