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Effects of treadmill cushion and running speed on plantar force and metabolic energy consumption in running

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ABSTRACT

Background: Repetitive loading with high impact forces are considered as a primary risk factor for overuse injuries. Cushion was proposed in running surface and shoe manufacturing to reduce impact forces and prevent injuries in running.

Research question: To investigate the effects of treadmill cushion and running speed on plantar force and metabolic energy consumption in treadmill running.

Methods: Plantar force data and metabolic data were collected for 20 men during running at 8 km/h and 10 km/h on the treadmill with and without cushion. Two-way ANOVAs with repeated measures were performed to determine the treadmill effects and the speed effects.

Results: Participants significantly decreased peak plantar force on the fore foot at both 10 km/h ($P = 0.001$) and 8 km/h ($P = 0.001$) and peak plantar force on the mid foot only at 10 km/h ($P = 0.011$) while running on the treadmill with cushion compared to the treadmill without cushion. The reduction of peak plantar force at 10 km/h was greater than that at 8 km/h while running on the treadmill with cushion. Participants significantly increased metabolic energy consumption while running on the treadmill with cushion compared to the treadmill without cushion ($P = 0.007$).

Significance: Running on the treadmill with cushion significantly decreased plantar force on the fore foot and mid foot, and increased metabolic energy consumption. Running on the treadmill with cushion may be a useful method in the prevention of fore foot injuries and increasing exercise effects.

1. Introduction

Running is one of the most popular sports and exercise activities in the world. It is easy to perform and has great accessibility. Over 40 million Americans participated in running or jogging as a form of exercise [1]. Studies have demonstrated that running could reduce the risk of cardiovascular mortalities [2] and many chronical diseases [3]. In addition, Chakravarty et al. found that running at middle and older ages not only prolong survival but also reduce disability [4].

Running, however, is also one of the sports and exercise activities with high injury rates, especially lower extremity musculoskeletal system injuries. Literature showed that the overall incidence of lower extremity injuries in running was between 19.4% and 79.3% [5]. A recent meta-analysis indicates that the incidence of running related injuries per 1000 h of running is 17.8% for novice runners and 7.7% for recreational runners [6]. Most commonly seen injuries include patellofemoral pain syndrome, iliotibial band friction syndrome, plantar fasciitis, meniscal injuries, and patellar tendinopathy [7,8].

Most injuries in running were overuse injuries associated with long running distance and repetitive loading with high impact forces [9–12]. The magnitude of impact force on a runner can be as high as 2–3 times body weight. This high impact force is considered as a primary risk factor for overuse injuries such as stress fracture, degenerative changes in cartilage and early knee osteoarthritis [13–16]. Female runners who had experienced stress fractures demonstrated greater vertical impact ground reaction force and greater vertical loading rates compared to those who had not experienced stress fractures [17–19]. The concept of cushion, therefore, was proposed in running surface and shoe manufacturing to reduce impact forces and prevent injuries in running.

Treadmills are commonly used in exercise, training, and rehabilitation [20,21]. Many treadmills have cushion systems designed to reduce impact forces. Our extensive review of literature, however,

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found only one study that reported no difference in the impact force of running between treadmills with and without cushion. A careful examination of the design revealed that the cushion effect in this study was created using an ethylene vinyl acetate surface on tread board, which is quite different from the cushion systems currently used in the treadmills. Current cushion systems on treadmills include not only the surface of tread board, but also shock-absorbing structures in the side frames and support plate. Previous study reported that running surface could affect plantar force [22–25] and metabolic energy expenditure [26–28]. However, the effects of cushion systems currently used in treadmills are still largely unknown.

The purpose of this study was to determine the effects of treadmill cushion on peak plantar force and metabolic energy consumption in treadmill running. We hypothesized that the peak plantar force would be decreased while running on a treadmill with cushion compared to running on a treadmill without cushion. We also hypothesized that the effect of treadmill cushion on peak plantar force would be affected by running speed. We further hypothesized that the metabolic energy consumption would be increased while running on a treadmill with cushion compared to running on a treadmill without cushion. We finally hypothesized that the effect of treadmill cushion on metabolic energy consumption would be affected by running speed.

2. Methods

2.1. Participants

Twenty males (age = 27.6 ± 4.3 years, height = 1.75 ± 0.04 m, body mass = 71.5 ± 6.9 kg) volunteered to participate in this study. All participants were self-described recreational runners who ran at least 30 min per week. The participants had no known history of neurological, cardiac, or pulmonary disease or disorders at the time to participate in the study, and no musculoskeletal system injuries in 6 months prior to the study. The use of human subjects in this study was approved by Internal Review Board of the University. Each participant read and signed a written consent before data collection.

2.2. Protocol

Two treadmills were tested in this study: a treadmill without cushion (Nordic Track, T17.5), and a treadmill with cushion (AOLRO, T50A10). Elastic arc strips, soft cushions, and soft silicone damping block were combined for cushion effects in the treadmill with cushion (Fig. 1). The entire experiment for each participant consisted of two Sessions with Session I for determining the effects of cushion on peak plantar force, and Session II for determining the effects of cushion on metabolic energy consumption. In each session, the participant was asked to run on two different treadmills and at two running speeds for each treadmill. The order of running on two treadmills in each session was randomized using Latin Square method. The participant was in black spandex shorts and given running shoes (Decathlon, Eliofeet man grey fluo) in each testing session.

Session I consisted of two tests completed in one day. Each test consisted of the following procedures: (1) the participant ran for 2 min on a given treadmill to familiarize the treadmill and warm up, (2) the participant ran on the given treadmill at a speed of 8 km/h for 2 min, (3) plantar force data were collected while the participant was running at 8 km/h, (4) the participant increased the running speed to 10 km/h, and ran for 2 min, (5) the plantar force data were collected while the participant was running at 10 km/h. The participant was then asked to run on the other treadmill and repeat the same procedures. 8 km/h and 10 km/h were chosen to investigate the cushioning effect at slow and medium running speed, respectively [28,29].

Session II consisted of four tests completed in a week and with a rest of at least 18 h between two consecutive tests. Each test consisted of the following procedures: (1) the participant wore breath mask and had a baseline resting state metabolic rate test, (2) the participant ran for 2–5 min on the given treadmill to warm up, (3) the participant ran at a given speed for 30 min on a given treadmill, since running for 30 min benefits health greatly [30] and 30 min moderate-intensity exercise was recommended by the American College of Sports Medicine [31], (4) metabolic data were collected during the entire 30 min of running at the given speed.

2.3. Data collection

Plantar force data were recorded using a Novel Pedar-X system (Novel, Munich, Germany) at a sampling rate of 100 Hz. A pair of pressure-sensing insoles in the same size as participant's shoes were placed in shoes and connected to an A/D converter with a Bluetooth communication system. The pressure-sensing insoles were calibrated following the manufacturer's guidelines before data collection. Plantar force data were collected for three trials with 10 consecutive running cycles in each trial at a given speed.

Metabolic data were collected via indirect calorimetry (Ultima CPX, Medgraphics, St. Paul, MN) using a neoprene mask and open pneumotach. The calorimeter was calibrated daily using a three liter syringe as well as prior to each test using certified gases [32].

2.4. Data reduction

Plantar forces on rear foot, mid foot, and fore foot, and the instant of peak force on different regions were calculated for the stance phases of 10 consecutive steps using a data reduction computer program package (Novel Automask, Novel Pedar System, Germany). The Novel automask computer program package automatically divided the entire foot plantar surface into rear foot, mid foot, and fore foot regions (Fig. 2). Peak plantar forces in each region were identified for each step. The instant of peak force was the time when peak force occurred in each region. The peak plantar forces of the left foot were used in data analysis because data on the left foot were complete for all participants.

The oxygen consumption (VO_2) and carbon dioxide production

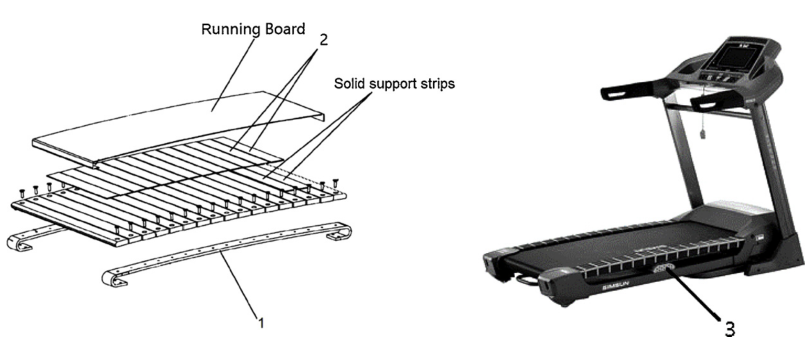

Fig. 1. The treadmill with cushion system. Three parts of devices are cooperated to form cushion effects: arc elastic strips (1), soft cushions (2), soft silicone damping block beneath the arc structural tread board (3).

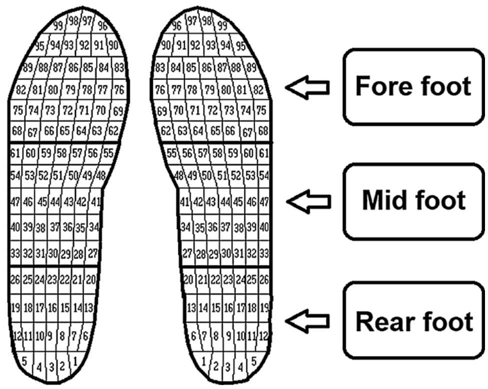

Fig. 2. The division of the plantar region.

(VCO_2) represent the mean volume of oxygen inhaled and carbon dioxide exhaled, respectively. The minute ventilation (V_E) was the volume of gas inhaled or exhaled per minute. The gross metabolic energy consumption (kcal) was calculated using

$$Metabolic \quad Energy \quad Consumption = 3.1{*}V_{oxygen} + 1.1{*}V_{carbon \quad dioxide}$$

Where V_{oxygen} was the volume of oxygen consumption, $V_{carbon\ dioxide}$ was the volume of carbon dioxide production [33].

The VO_2, VCO_2, and plantar forces were normalized to body weight of the participant. The instant of peak force on different regions were expressed as the percentage of stance phase. The net metabolic energy consumption was calculated by subtracting the resting state metabolic energy consumption from the running state metabolic energy consumption.

2.5. Data analysis

Two-way analyses of variance (ANOVA) with repeated measures were performed to compare peak plantar forces, VO_2, VCO_2, V_E, and metabolic energy consumption between treadmills (treadmill) and running speeds (speed). In case a significant interaction of treadmill and speed was detected, paired *t*-tests were performed to compare the dependent variable between treadmills at a given speed and between speeds on a given treadmill. All statistical analyses were performed using SPSS computer program package, version 16.0 (SPSS Inc., Chicago, IL, USA). A type I error rate less than or equal to 0.05 was considered as statistical significance.

3. Results

A significant interaction effect of treadmill and speed was detected for peak plantar force on the fore foot (P = 0.030) (Table 1). Post hoc tests showed that participants significantly decreased their peak plantar force on the fore foot while running at the two given speeds on the treadmill with cushion compared to the treadmill without cushion (P = 0.001, P = 0.001) (Table 1). Participants significantly increased their peak plantar force on the fore foot while running at the speed of 10 km/h compared to running at the speed of 8 km/h on the two given treadmills (P = 0.001, P = 0.002) (Table 1).

A significant interaction effect of treadmill and speed was detected for peak plantar force on the mid foot (P = 0.001) (Table 1). Post hoc tests showed that participants significantly decreased their peak plantar force on the mid foot while running at the speed of 10 km/h on the treadmill with cushion compared to the treadmill without cushion (P = 0.011) (Table 1). No difference in the peak plantar force on the mid foot was found between treadmills while running at the speed of 8 km/h (P = 0.758) (Table 1). Post hoc tests also showed that participants significantly increased their peak plantar force on the mid foot while running at the speed of 10 km/h compared to running at 8 km/h on the two given treadmills (P = 0.001, P = 0.001) (Table 1).

No significant interaction effect of treadmill and speed was detected for peak plantar force on the rear foot (P = 0.747) (Table 1). Cushion system of treadmill did not significantly affect the peak plantar force on the rear foot (P = 0.151) (Table 1). A significant main effect of speed showed that participants significantly increased their peak plantar force on the rear foot and entire foot while running at the speed of 10 km/h compared to running at the speed of 8 km/h (P = 0.001) (Table 1).

A significant interaction effect of treadmill and speed was detected for the time when peak plantar force on the rear foot occurred (P = 0.001) (Table 2). Post hoc tests showed that peak plantar force on the rear foot occurred later while running at the speed of 8 km/h on the treadmill with cushion compared to the treadmill without cushion (P = 0.001) (Table 2). No difference in the time when peak plantar force on the rear foot occurred was found between the two given treadmills while running at the speed of 10 km/h (P = 0.501) (Table 2). Post hoc tests also showed that peak plantar force on the rear foot occurred earlier while running at the speed of 10 km/h compared to running at 8 km/h on the treadmill with cushion (P = 0.001) (Table 2). No difference in the time when peak plantar force on the rear foot occurred was found between the two given speeds while running on the treadmill without cushion (P = 0.699) (Table 2).

No significant interaction effect of treadmill and speed was detected for the time when peak plantar force on the mid foot occurred (P = 0.124) (Table 2). A significant main effect of treadmill showed that peak plantar force on the mid foot occurred significantly later while running on the treadmill with cushion compared to running on the treadmill without cushion (P = 0.002) (Table 2). Running speed did not significantly affect the time when peak plantar force on the mid foot occurred (P = 0.293) (Table 2).

No significant interaction effect of treadmill and speed was detected for the time when peak plantar force on the fore foot occurred (P = 0.186) (Table 2). A significant main effect of treadmill showed that peak plantar force on the fore foot occurred significantly later while running on the treadmill with cushion compared to running on the treadmill without cushion (P = 0.001) (Table 2). A significant main effect of speed showed that peak plantar force on the fore foot occurred

Table 1
Mean ± standard deviations of peak plantar force (BW) on different treadmills at different running speed.

Location	Running Speed	Without Cushion	With Cushion	P-Value
Rear Foot	8 km/h	1.62 ± 0.25	1.64 ± 0.25	0.151
	10 km/h	1.74 ± 0.26	1.77 ± 0.26	
	P-Value	0.001		
Mid Foot	8 km/h	0.70 ± 0.13	0.69 ± 0.12	0.758
	10 km/h	0.78 ± 0.13	0.74 ± 0.12	0.011
	P-Value	0.001	0.001	
Fore Foot	8 km/h	0.79 ± 0.10	0.71 ± 0.12	0.001
	10 km/h	0.91 ± 0.16	0.77 ± 0.13	0.001
	P-Value	0.001	0.002	

Table 2
Time when peak forces occurs (% stance phase) in different foot regions (mean ± standard deviations).

Location	Running Speed	Without Cushion	With Cushion	P-Value
Rear Foot	8 km/h	10.86 ± 3.29	16.53 ± 6.60	0.001
	10 km/h	10.64 ± 1.93	11.17 ± 4.26	0.501
	P-Value	0.699	< 0.001	
Mid Foot	8 km/h	32.42 ± 4.52	35.73 ± 4.56	0.002
	10 km/h	34.02 ± 4.24	34.76 ± 4.36	
	P-Value	0.293		
Fore Foot	8 km/h	51.07 ± 5.30	53.92 ± 4.51	0.001
	10 km/h	53.86 ± 4.46	54.58 ± 3.62	
	P-Value	0.010		

Table 3
Mean ± standard deviations of metabolic parameters.

Variables	Running Speed	Without Cushion	With Cushion	P-Value
VCO_2 (ml/min/kg)	8 km/h	24.09 ± 2.54	25.39 ± 3.02	0.004
	10 km/h	30.11 ± 5.05	31.90 ± 4.25	
	P-Value	0.001		
VO_2 (ml/min/kg)	8 km/h	26.01 ± 2.35	27.34 ± 2.59	0.008
	10 km/h	31.41 ± 5.25	33.35 ± 4.41	
	P-Value	0.001		
V_E (L/min)	8 km/h	49.25 ± 9.05	51.78 ± 8.05	0.002
	10 km/h	61.40 ± 14.25	67.24 ± 16.33	
	P-Value	0.001		
Metabolic energy consumption (kcal)	8 km/h	211.1 ± 36.7	231.3 ± 28.8	0.007
	10 km/h	272.8 ± 60.8	290.8 ± 48.5	
	P-Value	0.001		

significantly later while running at the speed of 10 km/h compared to running at the speed of 8 km/h (P = 0.010) (Table 2).

No significant interaction effect of treadmill and speed was detected for VCO_2 (P = 0.699), VO_2 (P = 0.635), V_E (P = 0.188), and metabolic energy consumption (P = 0.898) (Table 3). A significant main effect of treadmill showed that participants significantly increased their VCO_2, VO_2, V_E, and metabolic energy consumption while running on the treadmill with cushion in comparison to the treadmill without cushion (P = 0.004, P = 0.008, P = 0.002, P = 0.007) (Table 3). A significant main effect of speed showed that participants significantly increased their VCO_2, VO_2, V_E, and metabolic energy consumption while running at the speed of 10 km/h in comparison to running at the speed of 8 km/h (P = 0.001, P = 0.001, P = 0.001, P = 0.001) (Table 3).

4. Discussion

The results of this study partially support our hypothesis that the peak plantar force would be decreased while running on the treadmill with cushion compared to running on the treadmill without cushion. The results demonstrated that peak plantar forces on the fore foot and mid foot were significantly decreased while running on the treadmill with cushion compared to running on the treadmill without cushion, but peak force on the rear foot was not significantly different between the treadmill with cushion and the treadmill without cushion. These results are consistent with the literatures. Fu et al. [25] studied the effects of running surfaces on plantar pressure, including concrete, synthetic, grass, the normal treadmill, and the treadmill equipped with an ethylene vinyl acetate (treadmill_EVA). They reported that no significant differences were found in peak plantar pressure at the heel among the concrete, synthetic, grass, and treadmill surfaces. Hong et al. [34] and Tessutti et al. [35] reported that running on natural grass significantly decreased the peak plantar pressure on the fore foot compared to running on the concrete or rigid surface. The results of this study indicated that peak force on the fore foot occurred during push-off phase, which is consistent with those reported by Adelaar et al. [36]. During running, elastic tissues conserve metabolic energy during early stance phase and release energy during push-off phase [37,38]. The decreased force on the fore foot may be associated with decreased running economy.

The results of this study support our hypothesis that the effect of treadmill cushion on peak plantar force would be affected by running speed. The results showed that a significant interaction effect of treadmill and speed was detected for peak plantar force on the fore foot and mid foot, which indicated that the effect of treadmill cushion on peak plantar force was affected by running speed. We found that the reduction of peak plantar force on the fore foot and mid foot while running at the speed of 10 km/h was greater than that running at the speed of 8 km/h on the treadmill with cushion. The findings suggested that the cushion effect was increased as running speed was increased. One possible explanation is that increasing running speed results in an increase in peak plantar force as shown in this study and literature [39,40]. As a result, the elastic deformation of tread board was increased, and this would result in an increased cushion effect when the runners land on the tread board.

The results of this study indicated that running on a treadmill with cushion system may assist in reducing the risk for fore foot injuries. The results of this study showed that peak plantar forces on the fore and mid foot while running on the treadmill with cushion were significantly decreased and that the studied treadmill with cushion had an increased cushion effect on peak plantar force on fore foot at higher running speed. Literature showed that runners who participated in high-impact sports involving running were at high risk for fore foot injuries, and that high and repetitive plantar loading may be a risk factor for fore foot injuries [41]. These results combined together indicated that running on the treadmill with cushion could reduce the risk of fore foot injuries, especially for high speed runners.

Although running on a treadmill with cushion may assist in reducing the risk of fore foot injuries, the results of this study suggested that it may not help reduce the risk of running injuries caused by high impact force on rear foot. Rear foot strike runners have the highest impact force on the rear foot, and most running injuries occur as results of high impact forces on the rear foot [12]. A previous study also reported that shoe cushioning did not significantly reduce the impact force on the rear foot [42]. As the results of this study and the study by Malone et al. [43] showed that high running speed increased impact force, which may increase the odds of lower extremity injury. One strategy for a runner to reduce impact forces is to reduce running speed. A study showed that weekly training volume was also an important risk factor for running injuries [44]. Therefore, factors that affect training volume such as training duration, frequency of running, running distance, and running speed, should also be considered for preventing running injuries.

The results of this study support our third hypothesis that the metabolic energy consumption would be increased while running on the treadmill with cushion compared to running on the treadmill without cushion, but do not support our last hypothesis that the effect of treadmill cushion on metabolic energy consumption would be affected by running speed. These results were consistent with the literatures. Hardin observed that metabolic energy consumption increased with the decreased stiffness of the treadmill board [45]. Similarly, Lejeune et al. reported that the energy expenditure for running on sand was 1.6 times of that on a hard surface [46]. The energy cost of running is affected by many factors including surface characteristics, muscle and tendon properties [47]. The increased metabolic energy consumption observed in running on the treadmill with cushion in this study is likely due to additional work the participants had to do to maintain running speed because treadmill with cushion absorbed more mechanical energy from the participants during support phase compared to treadmill without cushion [48]. The decreased bouncing effect may be another explanation of increased metabolic energy consumption. Running surface, leg stiffness, and compliance affect energy expenditure in running [49]. Running surface with cushion decreases surface stiffness while increasing surface compliance, which increases the mechanical energy absorbed by the running surface during support phase. As mechanical energy absorbed by the running surface increases, the runner has to increase work during support phase to maintain running speed, which decreases running economy [22].

Only male participants were included in this study, which simplified the study design but add a limitation to the study. Males and females may have different biomechanical and physiological reactions to running surface. Future studies may be needed to understand how female runners react to treadmill with and without cushion. Also, future studies may be needed to investigate the lower extremity kinematics and kinetics when running on treadmills with cushion systems to understand the interaction of running techniques and cushion effects and maximized the cushion effects to reduce the risk of running injuries and increase exercise intensity. Further, future studies may be needed to study the effects of foot strike patterns on treadmill cushion effects. As plantar force is affected by foot strike patterns [50,51], the treadmill cushion effects on plantar forces and energy consumption may be different for different foot strike patterns. The peak plant force on the rear foot was greater and occurred earlier than those on the mid foot and fore foot in this study, which means that most of the participants in this study were rear foot strikers. The results of this study, therefore, may be limited only for rear foot strikers. Finally, future studies are needed to determine the effects of shoe condition on treadmill cushion effects, as plantar force could be affected by different shoe conditions [24,52,53].

5. Conclusions

The results of this study appear to warrant the following conclusions for male runners who are rear foot strikers:

1 Running on the treadmill with cushion significantly decreased the peak plantar force compared to running on the treadmill without cushion but only on the fore foot and mid foot regions.
2 The effect of treadmill cushion on peak plantar force was affected by running speed with increased cushion effect at higher speed.
3 Running on the treadmill with cushion significantly increased the metabolic energy consumption compared to running on the treadmill without cushion.

Conflict of interest statement

The authors have no conflicts of interest to declare.

Declarations of interest

None.

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