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Short communication

Optimal shear cushion stiffness at different gait speeds

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ABSTRACT

The present study quantified the effects of different shear cushion stiffness on the time to peak posterior shear force (TPPSF), peak posterior shear force (PPSF), average posterior loading rate (APLR), and maximum posterior loading rate (MPLR) at different locomotion speeds using a custom-made sliding platform, as well as to identify the optimal stiffness of shear cushion. Twelve male collegiate students (heel-strikers) performed walking at 1.5 m/s, jogging at 2.5 m/s, and running at 3.5 m/s. A custom-made sliding platform was used to provide the different shear cushion conditions. The shear cushion conditions were fixed (a fixed platform; control group), stiff (K = 2746 N/m), medium stiff (K = 2256 N/m), medium soft (K = 1667 N/m), and soft (K = 1079 N/m). The results showed that all cushion conditions produced sliding displacement and delayed the TPPSF during walking, jogging, and running compared with fixed condition. The APLR and MPLR were lowest under medium soft condition during walking, while the PPSF was similar between medium soft and soft conditions. For jogging and running, the PPSF as well as APLR and MPLR were the lowest under medium stiff condition except the maximum PLR was similar among stiff, medium stiff, and medium soft conditions during running. In conclusion, shear cushion produces appropriate sliding displacement and effectively delays the TPPSF to provide the musculoskeletal system additional time to absorb the impact and reduce loading. The present study demonstrates optimal stiffness of shear cushion at different traveling speeds and suggests that a shear cushion system can be applied in future designs of cushion structures.

1. Introduction

Repetitive vertical impact loading of ground reaction forces has been suggested to be one of the major kinetic factors that attributes to lower extremity overuse running injury in sports participations (Cavanagh and Lafortune, 1980; Hreljac, 2004; Hreljac et al., 2000; Milner et al., 2006). This repetitive vertical impact loading typically occurs at the initial contact (first 10% of the stance phase) of the gait cycle and the loading varies in magnitude from approximately 1.5 to 5 body weights (Blackmore et al., 2016; Hreljac, 2004). To reduce the vertical impact loading, footwear scientists have been focusing on innovating the cushion materials of the midsoles and outsole (Addison and Lieberman, 2015; Chang et al., 2014a; Lin et al., 2017; Trama et al., 2019; Wang et al., 2012; Wei et al., 2018). Although the vertical loading has been the focus, the posterior shear force (PSF) generated by the movement between the feet and ground may contribute to lower extremity injury among different sports events (Boyer and Nigg, 2006; Fietzer et al., 2012; Lorimer and Hume, 2014, 2016; Napier et al., 2018; Villwock et al., 2009; Yavuz et al., 2008).

While the PSF is only is equivalent to 20–25% of the magnitude of the vertical impact force (Divert et al., 2005; Gottschall and Kram, 2005; Helseth et al., 2008), its influence on lower extremities in sports could be substantial. During running, it has been shown that the peak PSF (PPSF) increased by 144% as the running speed increases from 4 m/s and 8.5 m/s, while the peak vertical force only increased by 18% (Kyröläinen et al., 2005). These disproportional changes were also observed in high-speed sprints at 7 m/s and 9.73 m/s. Peak vertical force does not change with speed; however, the PPSF significantly increases with velocity during both braking and push off phases (Kuitunen et al., 2002). In addition, while the magnitude of the PSF is a quarter of the magnitude of the vertical

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impact force, the external torque generated on the shank has been shown to be up to 3.8 times greater compared to vertical force in both walking and running (Helseth et al., 2008). It is suggested that the PSF possesses a relatively greater moment arm about the segments, in turn, has higher contribution to the external torque about shank compared to vertical force. Taken together, it is suggested that the PSF may play an important role in modulating lower extremity kinetics during locomotion. In fact, Napier et al. (2018) investigated the association of kinetic variables with running-related injury risk. The authors found that the PSF during braking phase was the only kinetic variable that was a significant predictor of running-related injury. The results showed that runners with high PPSF were injured at 5.08 times the rate of those with the middle and 7.98 times the rate of those in the low. Moreover, studies has confirmed high posterior force was associated with increased risk of Achilles tendon injuries (Lorimer and Hume, 2014, 2016).

American Society for Testing and Materials (ASTM) defined cushion as the ability to reduce the impact force peak by prolonging applied force duration (ASTM, 1994). Thus, it is conceivable that the PSF may be reduced by prolonging the posterior impact force peak using different cushion designs. One study implemented the concept of shear cushion into functional footwear outsoles aiming to reduce the PSF during locomotion. Chan et al. designed different outsole tread patterns at the heels (straight groove sole and 45°groove sole) providing different shear cushion effects and found that both types of shear cushion delayed the time to peak PSF (TPPSF) during walking; however, this delay TPPSF was not seen during jogging and running. In addition, there was no change in PPSF and maximum posterior loading rate (MPLR) among walking, jogging, and running (Chan et al., 2013). Considering the magnitudes in impact differ during locomotion, the stiffness of shear cushion may play a role in modulating PSF and loading rate. Nevertheless, to our knowledge, no study has quantified optimal shear cushion stiffness among different types of locomotion. Therefore, the present study aimed to quantify the optimal shear cushion stiffness under different locomotion speeds using a custom-made sliding platform. The shear cushion condition with the lowest PPSF, average posterior loading rate (APLR), and MPLR was defined as an optimal shear cushion stiffness.

2. Methods

Twelve male collegiate students (heel-strikers in walking and running) participated in this study (height: 173.3 ± 2.5 cm; weight: 67.1 ± 7.2 kg; age: 23.2 ± 1.3 year). The experiments were conducted on a 12-m long straight runway in the laboratory. A custom-made sliding platform (90 cm×60 cm) (Fig. 1) was used to provide different shear cushion stiffness: fixed (a fixed platform; control group), stiff (K = 2746 N/m), medium stiff (K = 2256 N/m), medium soft (K = 1667 N/m), and soft (K = 1079 N/m). The custom-made sliding platform was affixed on force plate (Kistler™, 90 cm×60 cm, sampled at 1000 Hz) (Chang et al., 2014b) located at 6-m behind the starting point on the runway (Fig. 2). The participants were instructed to walk barefoot at 1.5 m/s, jog at 2.5 m/s, and run at 3.5 m/s (Chen et al., 2014) under five shear cushion conditions. Tasks and conditions were assigned in a counter-balanced order. For each condition, three successful trials were collected and analyzed. A successful trial was determined if the speed was within ±0.2 m/s of the designated speed and the entire right foot landed using a rearfoot-strike on the sliding platform. The maximum sliding displacement, TPPSF (Fig. 3A), PPSF (Fig. 3A), APLR, and MPLR (Fig. 3B) were analyzed (Chang et al., 2001). The data of PPSF, APLR, and MPLR were normalized to body weight (Chang et al., 2015). One-way analysis of variance with repeated measures was performed to assess the differences on the variables of interest among five cushion conditions under of each task (IBM SPSS 23.0, Armonk, NY, USA). The partial eta squared (η^2) as a measure of effect size and observed power (OP) ware also calculated. Bonferroni's method was adopted for post hoc tests. The level of significance was set at $\alpha = 0.05$.

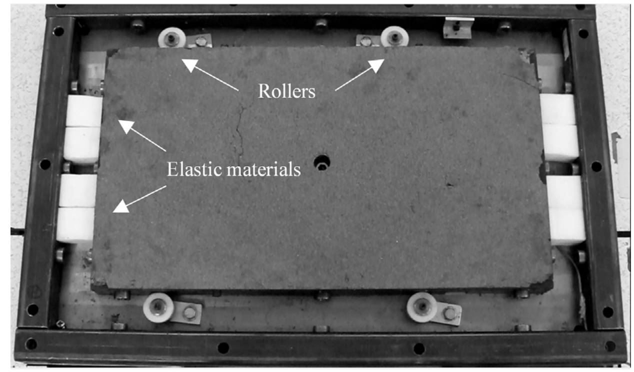

Fig. 1. The custom-made sliding platform. The sliding platform attached with rollers below allowing the sliding platform to move freely within the frame. To limit the side-to-side movement of the sliding platform within the frame, two one degree of freedom rollers were affixed on both lateral sides of the sliding platform. Both anterior and posterior ends of the platform were equipped with elastic materials to provide different shear cushioning stiffness by changing the number of elastic materials.

3. Results

Table 1 showed all outcome during walking, jogging, and running under different shear cushion conditions. Main effects of condition in maximum sliding displacement, TPPSF, PPSF, APLR and MPLR were observed in walking, jogging, and running ($p < 0.05$).

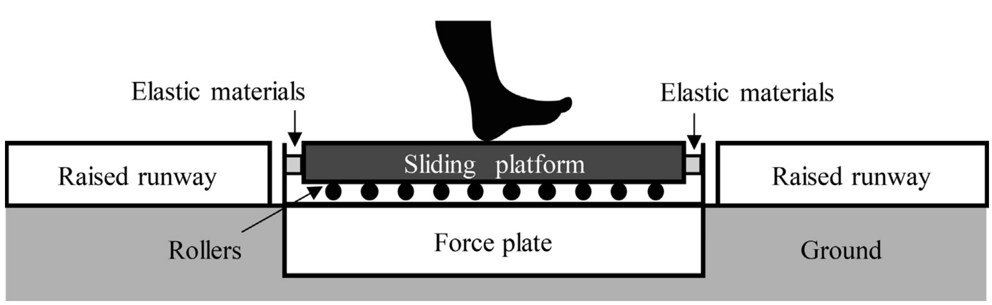

Fig. 2. Experimental setup. Participants were instructed to walk barefoot at 1.5 m/s, jog at 2.5 m/s, and run at 3.5 m/s on a 12-m long straight runway, and use a rearfoot-strike to land their right foot on the sliding platform affixed on force plate.

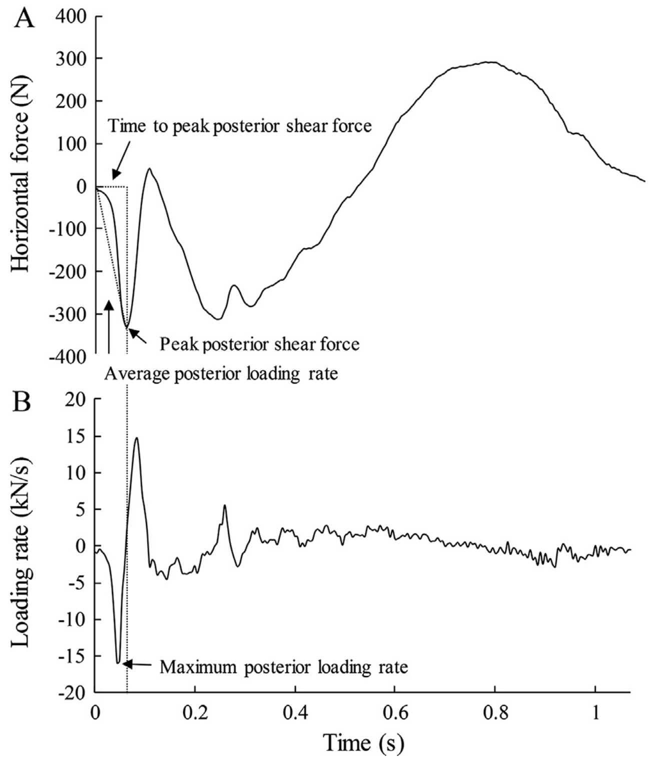

Fig. 3. Typical plots of the horizontal component of the ground reaction force (GRF) (A) and the loading rate of the horizontal GRF (B) for running. The maximal sliding displacement, time to peak posterior shear force (TPPSF), peak posterior shear force (PPSF), average posterior loading rate (APLR), and maximum posterior loading rate (MPLR) were analyzed.

The results of post hoc tests among five cushion conditions under of each task was also shown in Table 1.

4. Discussion

The present study demonstrated that all the shear cushions produced by the custom-made platform effectively delayed the TPPSF through sliding displacement of sliding platform, and certain shear cushion stiffness reduced PPSF, APLR, and MPLR during walking, jogging, and running. In general, these aforementioned benefits of shear cushion were more apparent with reduced stiffness; however, these benefits were not seen when stiffness was too much low. Moreover, the optimal cushion effect appears to be task dependent. Overall, the medium soft (K = 1667 N/m) demonstrated optimal shear cushion effect for walking with the lowest APLR and MPLR, while the medium stiff (K = 2256 N/m) demonstrated the optimal shear cushion effect with the lowest PPSF, APLR, and MPLR in jogging and PPSF, and APLR in running.

To clarify the effect of different shear cushion stiffness on PSF at different gait speed, we customized a sliding platform (Fig. 2) to produce effect of shear cushion. Elements producing the effect of shear cushion can be distinguished as: 1) foot allowed to move forward relative to ground after foot contact due to sliding platform and 2) the forward move resisted by different cushion stiffness (achieved by different number of elastic materials). In former element, the slide displacement between foot and ground contributed to delay the TPPSF and reduce PSF. However, because foot was moved forward relative to the body, the hip joint might be the major contributor to the motor adjustments (Pinnington et al., 2005) as opposed to the distal joints in regular running (Bazuelo-Ruiz et al., 2018; DeVita et al., 2016; Moore et al., 2012). In latter element, the magnitude of resistance to the forward moving of foot affected the moving speed, and this moving speed could be a major contributor to cause positive or negative cushion effects. When the moving speed too fast (shear cushion stiffness too soft), the maximum sliding displacement and TPPSF was not increased. This was possibly because lower limb causes a reactive recovery response to slipping consisted of a rapid onset of a flexor synergy, thereby resulting in a negative effect.

In this study, the maximum sliding displacement increases with reduced stiffness at different gait speeds. However, this phenomenon was not observed under least stiff condition (soft condition, K = 1079 N/m) except in jogging. The change in TPPSF was similar to maximum sliding displacement. The TPPSF was delayed with reduced stiffness. However, the advantage of delaying the TPPSF was reduced under the soft condition. The longest TPPSF were observed under the medium soft (K = 1667 N/m) during walking, jogging, and running. On average, the TPPSF was

Table 1
The posterior shear force during walking, jogging, and running under different shear cushioning conditions.

	Fixed	Stiff	Medium Stiff	Medium Soft	Soft	p	η^2	OP
Walking								
Maximum sliding displacement (mm)	–	8.54 ± 1.37[d,e]	7.92 ± 1.06[d,e]	9.58 ± 1.04[b]	9.20 ± 1.86[c]	0.016	2.266	0.788
Time to peak posterior shear force (ms)	102.8 ± 24.3[b,c,d,e]	175.9 ± 19.0[a]	174.8 ± 21.3[a,d]	185.7 ± 21.5[a,c]	164.9 ± 32.3[a]	0.000	0.832	1.000
Peak posterior shear force (BW)	0.29 ± 0.04[c,d,e]	0.27 ± 0.03[c,d,e]	0.25 ± 0.03[a,b,d,e]	0.24 ± 0.03[a,b,c]	0.22 ± 0.03[a,b,c]	0.000	0.970	1.000
Average posterior loading rate (BW/s)	2.27 ± 1.04	1.77 ± 0.27[d]	1.70 ± 0.29[d]	1.46 ± 0.22[b,c]	1.78 ± 0.45	0.050	0.275	0.544
Maximum posterior loading rate (BW/s)	8.47 ± 3.80[c,d]	4.96 ± 1.33	4.85 ± 1.44[a]	4.64 ± 1.49[a,e]	7.40 ± 2.98[d]	0.001	0.502	0.971
Jogging								
Maximum sliding displacement (mm)	–	4.06 ± 1.18[c,d,e]	5.14 ± 1.79[b,d,e]	6.14 ± 2.05[b,c,e]	7.16 ± 2.14[b,c,d]	0.000	0.892	1.000
Time to peak posterior shear force (ms)	73.8 ± 22.8[b,c,d,e]	125.7 ± 13.8[a,d]	131.0 ± 15.2[a]	137.0 ± 14.8[a,b]	125.5 ± 21.7[a]	0.000	0.782	1.000
Peak posterior shear force (BW)	0.28 ± 0.04	0.26 ± 0.04[e]	0.26 ± 0.05[e]	0.27 ± 0.06	0.30 ± 0.04[b,c]	0.013	0.330	0.786
Average posterior loading rate (BW/s)	4.48 ± 1.31[b,c,d]	2.30 ± 0.33[a,e]	2.18 ± 0.39[a,e]	2.21 ± 0.54[a,e]	3.06 ± 0.77[b,c,d]	0000	0.694	0.999
Maximum posterior loading rate (BW/s)	16.25 ± 7.36[b,c,d]	6.59 ± 1.56[a,e]	5.68 ± 1.68[a,e]	6.16 ± 2.02[a,e]	11.27 ± 4.76[b,c,d]	0.000	0.618	0.995
Running								
Maximum sliding displacement (mm)	–	3.83 ± 1.62[c,d,e]	4.94 ± 1.32[b,d,e]	6.37 ± 2.20[b,c]	6.19 ± 1.41[b,c]	0.000	0.752	1.000
Time to peak posterior shear force (ms)	68.4 ± 18.0[b,c,d,e]	109.3 ± 12.2[a]	112.6 ± 12.1[a]	114.7 ± 13.1[a]	110.2 ± 18.2[a]	0.000	0.758	1.000
Peak posterior shear force (BW)	0.35 ± 0.09	0.30 ± 0.05[e]	0.29 ± 0.05[e]	0.31 ± 0.09	0.36 ± 0.05[b,c]	0.019	0.294	0.741
Average posterior loading rate (BW/s)	5.90 ± 2.41[b,c,d]	3.05 ± 0.52[a]	2.92 ± 0.51[a]	3.20 ± 1.00[a]	3.89 ± 1.38	0.002	0.517	0.934
Maximum posterior loading rate (BW/s)	25.85 ± 14.12[b,c,d]	7.62 ± 2.30[a]	8.18 ± 2.66[a]	7.48 ± 2.35[a]	15.68 ± 10.01	0.001	0.546	0.965

[a] Significant differences were achieved with fixed.
[b] Significant differences were achieved with stiff.
[c] Significant differences were achieved with medium stiff.
[d] Significant differences were achieved with medium soft.
[e] Significant differences were achieved with soft.

78% longer in the medium soft condition compared to the fixed condition. However, the shorter TPPSF (8% reduced) was observed in the soft condition compared to the medium soft condition suggests that too much shear cushion during foot contact could not warrant a better shear cushion effect. As the foot contacts the ground, similar to the vertical ground reaction force, the PSF also increases the stress on the passive structure of lower extremity if the impact is not sufficiently absorbed (Hewett et al., 2010; Lorimer and Hume, 2014, 2016). In general, increasing the TPPSF allows the musculoskeletal system to more sufficiently absorb the impacts as the foot contact the ground. However, too soft cushion stiffness may cause a reactive recovery response to slipping consisted of a rapid onset of a flexor synergy of lower limb because the speed of foot moved forward relative to the ground was too fast. These muscle onset latencies range from 90 to 232 ms during the anterior slip in walking (Marigold and Patla, 2002; Tang and Woollacott, 1999), which was slightly earlier than the TPPSF range from 110 to 164 ms under soft condition in this study. This response could be a negative effect on the TPPSF, impact force, and loading rate during foot contact. As a result, too soft a cushion stiffness may not be ideal to reduce posterior impact force. It is suggested that the benefits of shear cushion are only warranted under appropriate cushion stiffness and are task dependent.

In consistent with the TPPSF, the PPSF as well as APLR and MPLR were reduced with decreased cushion stiffness and increased again as the cushion stiffness was too soft. The optimal cushion stiffness was observed in the medium soft condition (K = 1667 N/m) during walking, where the APLR and MPLR were the lowest and PPSF was the second lowest. However, the lowest PPSF as well as APLR and MPLR were observed in the medium stiffness condition (K = 2256 N/m) in jogging while the lowest PPSF and APLR were observed in running. On average, the PPSF in the medium stiff condition decreased 7% and 15% compared to the medium soft and soft conditions during jogging and, 16% and 18% during running, respectively. Surprisingly, the MPLR in medium stiffness condition was almost 3 times lower compared to the fixed condition and 2 times lower compared to the soft condition during jogging and running. These results suggest that the higher cushion stiffness was required during jogging and running to sufficiently reduce PPSF and loading rates. It is suggested that the optimal cushion stiffness is medium soft condition (K = 1667 N/m) during walking and medium stiffness condition (K = 2256 N/m) during jogging and running.

Shear force between the foot and ground has been shown to contribute to sports related injury among different sports events (Boyer and Nigg, 2006; Fietzer et al., 2012; Lorimer and Hume, 2014, 2016; Napier et al., 2018; Villwock et al., 2009; Yavuz et al., 2008). The present study showed that the optimal shear cushion appears to be task dependent which may be driven by different locomotion speeds. These results were in accordance with previous studies, indicating that different locomotion speeds require different stiffness of shear cushion. Movement patterns at different speed could cause different impacts (Kuitunen et al., 2002), therefore, cushion materials with varied stiffness are required. The sliding platform shear cushion system of the present study can be applied in future cushion designs to determine optimal stiffness of shear cushion at different gait speeds. Optimal shear cushion may reduce the incidence of sport-related lower extremity injuries.

In conclusion, the present study demonstrated that the shear cushion provided by the custom-made sliding platform effectively delayed the TPPSF during walking, jogging, and running. The sliding displacement produced by appropriate shear stiffness could be a major contributor to delay the TPPSF. The longer TPPSF allows the musculoskeletal system to be more sufficiently absorb the impacts on the human body than the shorter TPPSF. An optimal shear cushion reduced the magnitude of the PPSF and loading rate, suggesting the effectiveness of shear cushion to absorb impacts. The optimal shear cushion differs with different locomotion speeds. The cushion materials with a high coefficient of elasticity are required for high-speed movement. The present study suggests that the optimal stiffness of the shear cushion was medium soft condition with K = 1667 N/m during walking, and medium stiff condition with K = 2256 N/m during jogging and running. The shear cushion system provided by the present study can be applied in future designs of cushion structures.

Declaration of Competing Interest

The authors have no conflict of interests regarding the publication of this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.07.018.

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