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Ground reaction force adaptation during cross-slope walking on railroad ballast

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ABSTRACT

Background: : Walking on railroad ballast is a unique challenge for railroad workers and contributes to a large number of falls and slips. However, the characteristics of ground reaction force (GRF) when walking on ballast combined with a cross-slope condition are poorly understood.
Research question: : How does the magnitude and temporal distribution of GRF change during walking on railroad ballast combined with a cross-slope condition?
Methods: : Eight experienced railroad workers walked with their self-selected speed on three surfaces (mainline ballast, walking ballast and no ballast) in both a level and cross-slope (7°) condition. The magnitude and time of occurrence of selected key features of the GRF were extracted from the force plate. A two-factor repeated measures ANOVA was used to determine the effect of surface and cross-slope condition.
Results: : The minimum anteroposterior GRF and the first peak of the normal GRF occurred earlier on mainline ballast and walking ballast than no ballast. The maximum anteroposterior GRF was smaller, but the first peak of the normal GRF was larger on walking ballast compared with no ballast. Additionally, the asymmetrically mediolateral GRFs were observed between upslope limb and downslope limb in the cross-slope condition, which were also significantly different from the level condition.
Significance: : Ballast combined with a cross-slope condition posed a higher requirement for dynamic control to prevent downslope slippage and body instability, which could increase the fall risk for railroad workers. Future studies should investigate interventions to improve dynamic balance and reduce foot slippage on ballast.

1. Introduction

The walking conditions found in the railroad industry have some unique challenges, such as crushed rock aggregate (ballast) and cross slopes. There are two major types of ballast, which are defined as mainline ballast (MB) and walking ballast (WB). The larger MB is 63.5 mm and usually placed along the main track between stations to provide stability and drainage. The smaller WB is 31.75 mm and used in rail yards and generally in conditions where workers walk while performing inspection and maintenance activities [1,2]. According to the US Federal Railroad Administration (FRA) between 2005 and 2013, approximately 16% of railroad worker injuries were related to walking on ballast, including slipping, stumbling and falling and accounted for about 19% of all days absent from work [3].

Some previous studies have already focused on ballast walking [4–7]. Andres et al. (2005) investigated rear foot motion when walking on ballast without force plates and found that walking on MB significantly increased rear foot range of motion than either WB or no ballast (NB) [4]. A study performed by Wade and Redfern (2007) presented a method to measure ground reaction force (GRF) on MB by putting a 3-mm-thick carpet between a force plate and ballast. They reported that the magnitudes and time histories of GRF were similar between smooth surface and ballast conditions [5]. Then, in a follow-up study using the same experimental setup, they examined the effect of ballast on gait biomechanics in a level condition and found the joint moment ranges of lower limb were smaller for MB and WB compared with NB [6]. Merryweather focused on lower limb biomechanics on a cross-slope condition when walking on ballast. The main findings were walking on MB and WB significantly increased foot clearance and knee adduction moment was larger for downslope limb than upslope limb on

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the cross-slope condition [7].

Since GRF has been used widely to evaluate and understand the mechanics of human gait in varied walking conditions and is considered as a critical biomechanical factor in slips and falls, biomechanical analysis of gait on ballast using GRF evaluation could be a valuable tool to understand how to reduce falls. The purpose of this study was to examine the adaptations of GRF during walking on ballast in both level and cross-slope conditions. We hypothesized that the magnitude and temporal distribution of GRFs will be significantly different between surfaces (MB, WB and NB) and cross-slope conditions (level, upslope and downslope)

2. Methods

2.1. Experimental set-up

Two custom walkways (7.3 m long, 0.76 m wide and 0.23 m deep) were constructed of engineering I-beam for this study to test multiple walking conditions including varying walking surfaces and cross-slopes. MB and WB were placed in each walkway to simulate the railroad walking conditions and five adjustable jacks were placed on each side of the walkway to achieve a 7-degree cross-slope condition, which has been specified to represent a common lateral slope along the rails in railroad yards [4]. Two force plates (OR6-7, AMTI, Watertown, MA) were embedded 20 cm beneath the ballast surface in each walkway with an isolation fixture, which reduces the dissipation of force and accurately identifies measured GRF on ballast [8] (Fig. 1). The hard surface made from structural plywood was placed over the WB track to be used for the NB condition.

2.2. Participants

Eight male railroad workers from a local railroad facility were recruited for the study (age 39.17 ± 8.80 years old, height 1.76 ± 0.09 m, body mass 82.71 ± 14.14 kg, years with railroad 9.79 ± 8.30 years). Participant inclusion criteria included at least three years as a railroad worker, normal gait, no history of leg or back injuries and no abnormal foot physical features, such as club feet and flat feet. All participants reviewed and signed an informed consent document prior to participation.

2.3. Data acquisition and process

Each participant received a new pair of work boots (Red Wing, model 2408), which was the same type of shoes as they wore at work for the railroad. Then, 10 min were given to the participants to acclimate to the level and cross-slope walkway before data collection. Six different gait conditions were tested which included the combination of three surface conditions (MB, WB and NB) and two surface configurations (level and 7 ° cross-slope). Five trials with clean force plate strikes were collected at a self-selected speed for each condition. The walking direction was the same for all trials to keep the left limb in the

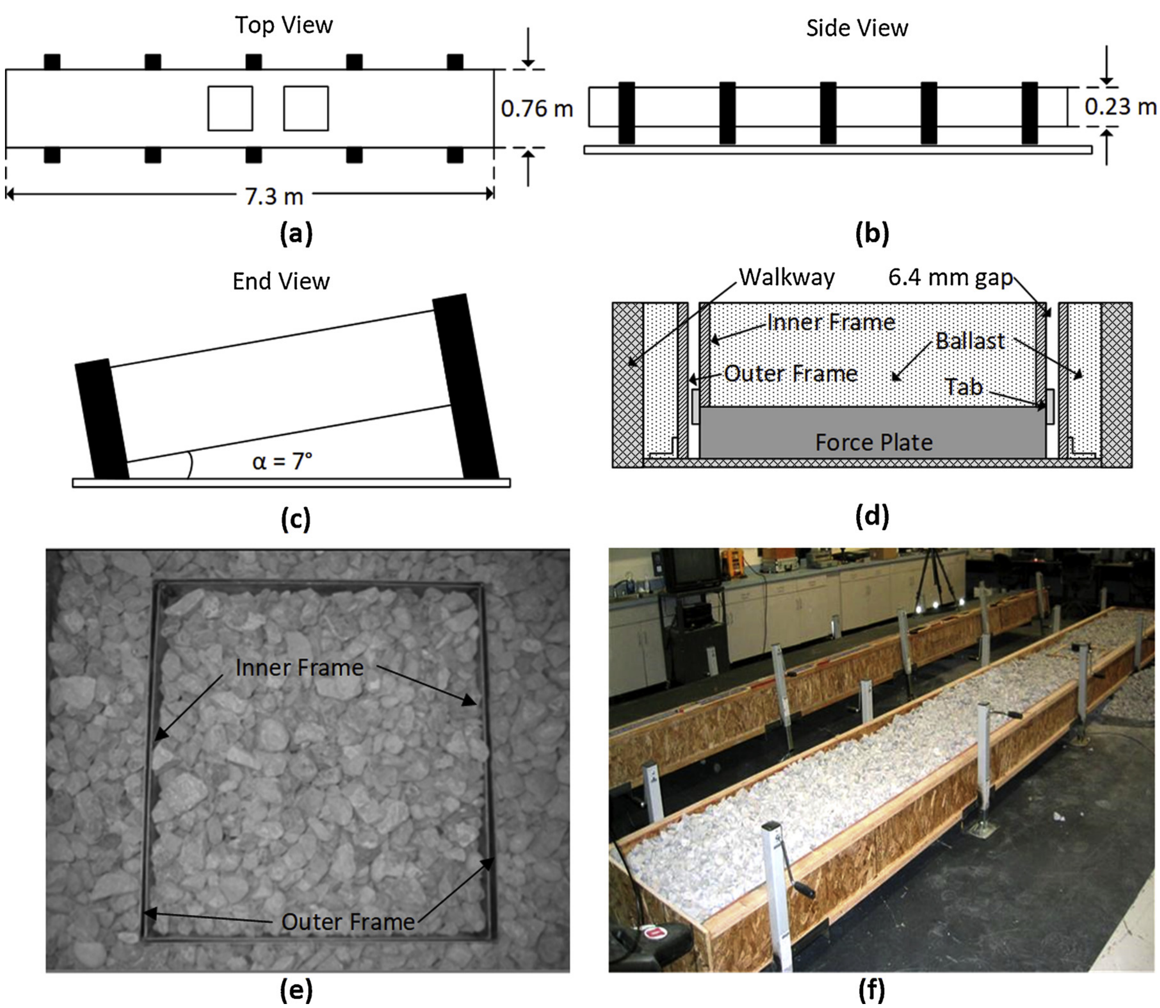

Fig. 1. The custom adjustable walkway and isolation fixture. (a) walkway-top view; (b) walkway-side view; (c) walkway-end view; (d) force plate isolation fixture diagram; (e) image of force plate isolation fixture; (f) image of walkway with ballast.

downslope and the right limb in the upslope for the cross-slope condition. The GRF data were collected at 600 Hz and then filtered using a fourth-order low-pass Butterworth filter at 20 Hz.

Major gait events (heel strike and toe off) were defined via force plate activation with a 20 N threshold to identify the stance phase of the gait cycle. The variables selected in this study were the magnitude of GRF and their time of occurrence along the anteroposterior (F_x), mediolateral (F_y) and normal (F_z) axes as done in a previous study [9]. More specifically, the first and second peaks of the normal GRF (MaxFz1 and MaxFz2) and the minimum value (MinFz) between these two peaks were evaluated. Similar peaks, MaxFy1, MaxFy2 and MinFy were analyzed for the mediolateral direction. Additionally, the minimum (MinFx) and maximum (MaxFx) values for the anteroposterior component were also included in this study. The GRF were normalized by body weight (BW) and the corresponding times were expressed as a percentage of stance phase to allow comparison between participants.

For the level condition, the data were first averaged across two limbs, then 5 trials and 8 participants. For the cross-slope condition, the variables were first averaged across 5 trials and then 8 participants to obtain the upslope and downslope variables separately. Standard deviation was calculated for average data across 8 participants.

2.4. Statistical analysis

The statistical analyses were performed using SPSS 20 (IBM Corporation, Armonk, NY). The two-factor repeated measures analysis of variance was used to determine the effect of surface (NB, WB and MB) and the cross-slope condition (level, upslope and downslope). The Greenhouse-Geisser correction was used when the assumption of sphericity was violated. Post-hoc tests were conducted using the Bonferroni adjustment to run the pairwise comparison. The alpha level was set at 0.05.

3. Results

The GRFs as well as the relative times plotted against stance cycle were similar during level and cross-slope conditions in normal and anteroposterior directions, but had substantially different patterns in the mediolateral direction (Fig. 2).

The surface effect significantly affected the MaxFx ($p = 0.001$), the timing of MaxFx and MinFx ($p = 0.011$ and $p = 0.001$) (Table 1 and Fig. 3). A smaller MaxFx was found for WB compared with NB ($p = 0.002$) and MB ($p = 0.005$). The timing of MinFx happened later for NB than MB ($p = 0.007$) and WB ($p = 0.004$). However, the timing of MaxFx occurred later for MB than NB ($p = 0.033$). In addition, a significant cross-slope effect was found for the timing of MinFx, which happened earlier for the downslope limb than upslope limb ($p = 0.045$). No significant surface × cross-slope interaction effect was found for anteroposterior GRF.

A significant cross-slope effect was found for MaxFy1, MinFy and MaxFy2 (all $p < 0.001$). The downslope limb showed a larger force than the level limb (all $p < 0.001$), but the upslope limb showed a smaller force than the level limb (all $p < 0.001$) (Table 2 and Fig. 3). Additionally, the timing of MaxFy1 was significantly affected by the cross-slope condition, which occurred later for the downslope limb than the upslope limb ($p = 0.005$). However, the surface effect and interaction effect between surface and cross-slope were not significant for any mediolateral GRF variables.

In the normal axis, significant surface effects were found for MaxFz1and MinFz in the magnitude ($p = 0.030$ and $p = 0.019$) and the timings of MaxFz1 and MaxFz2 ($p = 0.001$ and $p = 0.030$) (Table 3 and Fig. 3). Both MaxFz1 and MinFz were larger for WB compared with NB ($p = 0.018$ and $p = 0.027$). The timing of MaxFz1 was later for NB than MB ($p = 0.006$) and WB ($p = 0.006$). However, the timing of MaxFz2 occurred earlier for NB compared with WB ($p = 0.025$). Furthermore, a significant cross-slope effect was observed for MaxFz2 ($p = 0.009$), which showed a larger force for the level limb than the downslope limb ($p = 0.016$). No significant interaction effect was found for normal GRF variables.

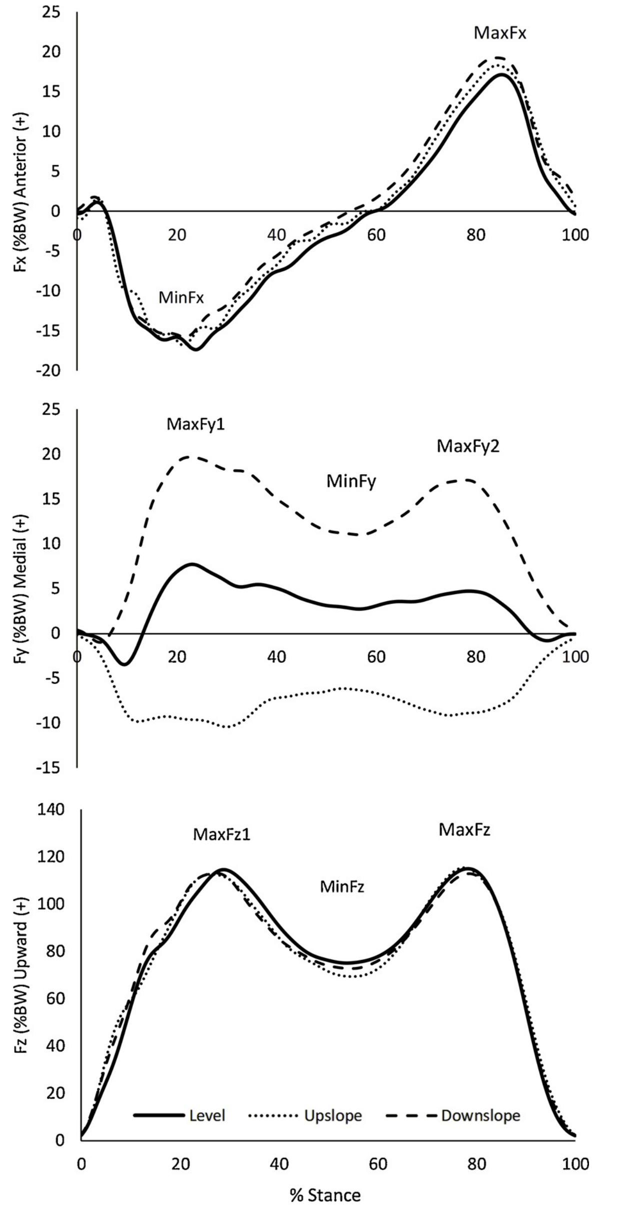

Fig. 2. The representative GRF during stance phase of level walking and cross-slope walking by averaging three surface conditions (MB, WB and NB) from one participant.

4. Discussion

The purpose of this study was to examine the magnitude and timing adaptation of GRF that occurs during cross-slope walking on two types of ballast. Overall, the GRF patterns were similar to the previous studies in level ballast walking [5] and cross-slope walking in NB [9–11].

The maximum propulsion (MaxFx) on WB was significantly lower than NB and MB, which was only about 65% and 68% of the value measured on NB and MB, respectively (Fig. 3c). This finding indicates that more compaction on small aggregate generates increased foot movement (i.e. slip) in the anteroposterior direction during terminal stance. The characteristics of WB make it prone to relative translation of individual ballast rock to each other. This movement may cause the foot to slide backward without propelling the body forward, which could

Table 1
Mean (SD) of the anteroposterior (Fx) components of ground reaction force.

Event	NB %Stance	NB %BW	MB %Stance	MB %BW	WB %Stance	WB %BW
Level						
MinFx	19.87(1.81)	−18.44(2.88)	16.37(2.28)	−20.16(4.73)	16.19(1.73)	−20.29(3.52)
MaxFx	83.37(0.99)	20.63(2.61)	85.37(0.95)	19.52(2.96)	84.94(2.06)	12.52(3.30)
Downslope						
MinFx	19.50(1.60)	−18.82(5.12)	15.75(3.20)	−20.12(4.28)	15.25(4.33)	−21.79(5.89)
MaxFx	83.50(1.93)	20.03(3.50)	83.87(0.99)	19.02(1.86)	84.88(1.64)	13.70(6.58)
Upslope						
MinFx	20.37(1.60)	−18.42(3.51)	17.88(3.27)	−20.83(4.34)	17.75(2.25)	−21.33(5.06)
MaxFx	84.12(2.59)	21.27(3.10)	84.50(1.07)	19.63(2.40)	85.50(2.14)	12.86(5.80)

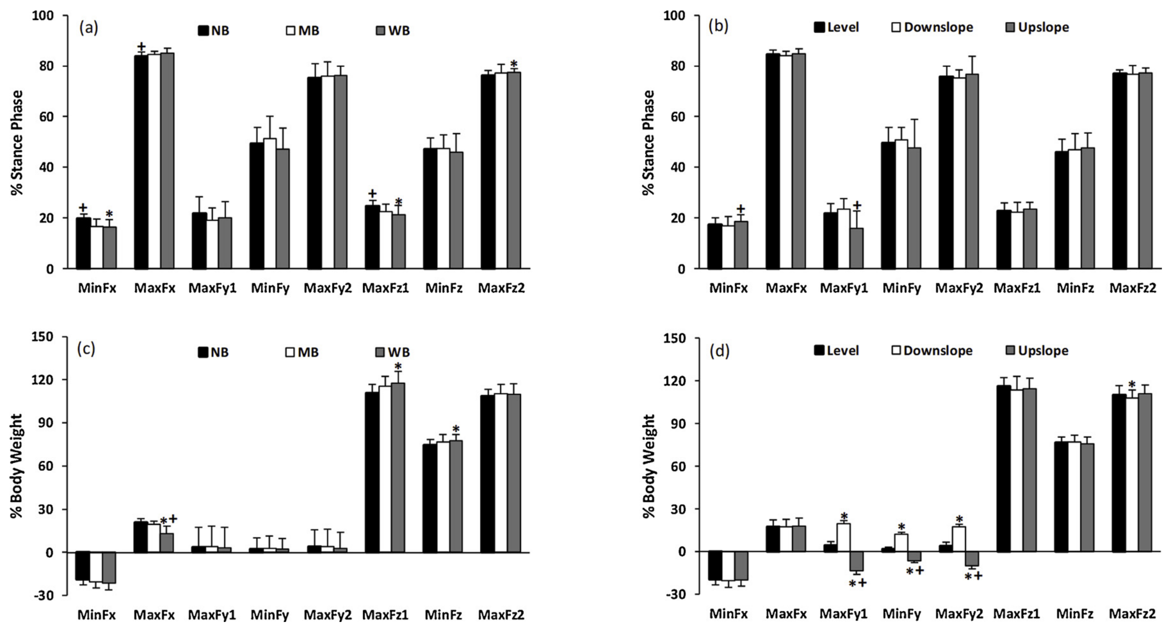

Fig. 3. The timing and magnitude of GRF. (a) the timing of GRF by surface; (b) the timing of GRF by cross-slope condition; (c) the magnitude of GRF by surface; (d) the magnitude of GRF by cross-slope condition. In (a) and (c), * indicates a significant difference with NB, + indicates a significant difference with MB. In (b) and (d), * indicates a significant difference with level limb, + indicates a significant difference with downslope limb.

Table 2
Mean (SD) of the mediolateral (Fy) components of ground reaction force.

Event	NB %Stance	NB %BW	MB %Stance	MB %BW	WB %Stance	WB %BW
Level						
MaxFy1	23.34(5.38)	4.79(2.57)	20.27(3.05)	5.14(3.03)	21.53(2.75)	3.56(2.43)
MinFy	49.70(4.32)	2.46(0.62)	50.48(6.05)	1.71(1.18)	48.78(7.90)	1.23(1.44)
MaxFy2	73.82(5.37)	5.23(1.31)	76.54(3.31)	4.18(2.62)	76.82(3.02)	2.09(2.99)
Downslope						
MaxFy1	24.60(4.78)	19.35(1.73)	22.59(3.20)	20.19(1.43)	22.95(5.07)	19.76(2.70)
MinFy	49.01(5.19)	11.77(0.84)	51.76(5.55)	13.21(1.72)	51.68(4.19)	11.81(1.01)
MaxFy2	74.89(2.46)	17.50(1.39)	75.41(4.04)	18.40(1.29)	75.19(3.76)	16.59(1.38)
Upslope						
MaxFy1	17.49(7.64)	−13.1(2.05)	14.59(4.60)	−13.36(3.44)	16.03(8.05)	−13.46(2.75)
MinFy	49.47(9.19)	−6.91(1.22)	51.96(13.43)	−6.91(1.54)	41.30(8.86)	−5.77(1.35)
MaxFy2	77.16(8.04)	−10.17(1.73)	76.15(8.76)	−10.35(1.77)	76.91(4.42)	−9.75(2.47)

increase the risk of losing footing when walking on WB [7]. This phenomenon, though not as extreme, is similar to gait performance reported on sand in the level and cross-slope conditions [12,13]. The timing of MinFx and MaxFx of one limb usually happened at the instances of the contralateral limb's toe off and heel strike. The timing of earlier MinFx during ballast walking indicates a shorter first phase of double support on ballast, which reduces the period of body weight shifting from one limb to the other and increases the gait instability [14].

Since the fluctuation in GRF is a result of the acceleration of the body's center of mass, the larger MaxFz1 in WB is partially explained by an increase in displacement of the foot because the WB is more compliant and the ballast compacts during these phases. This ballast surface deformation process seemed to continue until terminal stance since the timing of MaxFz2 occurred later on WB than NB. Additionally, the timing of MaxFz1 was earlier on ballast (MB and WB) than NB due to

Table 3
Mean (SD) of the normal (Fz) components of ground reaction force.

Event	NB %Stance	NB %BW	MB %Stance	MB %BW	WB %Stance	WB %BW
Level						
MaxFz1	25.06(2.21)	112.56(4.19)	22.19(3.16)	116.27(6.69)	20.94(2.86)	119.37(5.30)
MinFz	46.12(4.33)	75.20(2.93)	47.62(5.42)	77.11(5.31)	44.19(5.50)	76.83(4.60)
MaxFz2	76.06(1.37)	109.66(3.76)	77.69(1.49)	110.04(7.69)	77.06(1.35)	110.69(7.24)
Downslope						
MaxFz1	24.00(2.83)	110.82(8.63)	22.62(3.38)	113.46(6.20)	20.25(4.89)	116.31(12.54)
MinFz	46.87(4.70)	74.98(4.93)	47.87(5.38)	78.16(4.60)	46.00(8.96)	78.06(5.00)
MaxFz2	76.12(2.10)	105.72(5.37)	76.00(5.76)	108.31(6.22)	77.88(1.25)	108.97(6.73)
Upslope						
MaxFz1	25.25(1.75)	108.82(5.16)	22.87(2.48)	116.91(8.33)	22.63(2.67)	117.01(6.43)
MinFz	48.87(3.60)	74.08(4.08)	46.50(5.93)	75.07(5.48)	47.50(8.05)	77.58(4.84)
MaxFz2	76.50(2.73)	109.74(4.63)	77.75(1.28)	112.08(5.57)	77.63(1.69)	110.42(7.94)

the ballast shifts and compacts under initial heel strike. This finding indicates that a rapid foot plantarflexion is needed during the phase of loading response and an increased ankle plantar flexor torque is requested to maintain a constant gait speed, which aligns with the results of previous study [7].

Asymmetrical differences among level, upslope and downslope limbs were observed, especially in the mediolateral direction (Fig. 3d). A relatively small medial GRF occurred in most of the stance phase on the level condition. However, mediolateral GRFs (MaxFy1, MinFy and MaxFy2) increased laterally for the upslope limb and medially for the downslope limb in the cross-slope condition to oppose the additional shear force acting down the slope. This increased shear force is required to help preserve dynamic control and maintain upright posture to prevent a lateral fall [15]. The timings of the peak (MaxFy1) and valley (MinFx) were found approximately 30% and 10% different for the upslope limb than downslope limb in this study (Fig. 3b). This result implies that the altered timing of events may play an important role in transferring the body mass between the limbs in the frontal and coronal planes due to the cross-sloped condition.

Beside the mediolateral direction, the peak of normal GRF was also altered by the cross-slope condition, which showed a relatively smaller MaxFz2 for the downslope limb compared with the upslope limb and level limb (Fig. 3d). This asymmetric gait pattern is used to preserve lateral balance and sustain forward locomotion, which is similar to the performance of patients with leg length discrepancy, who also showed different vertical GRFs between limbs during gait [16,17].

Previous research confirmed that the utilized coefficient of friction (UCOF), which represents the friction needed to walk on a surface, can indicate walking strategy on slippery surfaces [18]. The UCOF was calculated by dividing the resultant shear GRF (anteroposterior and mediolateral forces) by the normal GRF [19,20]. In the present study, we found a larger MaxFz1 with a smaller MaxFx and a similar MaxFy1 on WB compared with NB, which indicated a decrease of UCOF and an increased fall risk when walking on WB. Additionally, the UCOF increased in the cross-slope condition compared to the level condition due to the larger medial and lateral GRFs observed in the downslope and upslope limbs separately while the anteroposterior and normal GRFs remained constant with the level condition (Fig. 2).

Limitations exist in this study, the major one is that gait speed was not controlled. A self-selected speed was chosen to show the normal walking status on different surface conditions and configurations. However, statistical analyses indicated that gait speed was not significantly different among NB, MB and WB either in the level condition or cross-slope condition. We believe the observed differences of magnitude and timing of GRF were mainly caused by surface conditions, and not gait speed in this study.

5. Conclusions

In summary, the present study evaluated the adaptations of GRF during cross-slope walking on two types of railroad ballast. It was found that (1) the timings (MinFx and MaxFz1) of GRF were significantly earlier on ballast (MB and WB) than NB, and (2) a smaller MaxFx, but a larger MaxFz1 were found when comparing WB to NB, respectively. Additionally, the asymmetrical GRFs (MaxFy1, MinFy and MaxFy2) among level, upslope and downslope limbs were observed in the mediolateral direction. These findings suggest that a ballast environment combined with a cross-slope condition increases the demand for dynamic control to prevent down slope slippage and vertical body instability. This additional requirement could increase the fall risk for railroad workers, especially on WB on a cross-slope. Future work is suggested to investigate the role of reducing walking speed to minimize dynamic control requirements on these irregular surfaces. Additionally, design modifications to footwear should be considered that reduce slippage and improve dynamic control on irregular, compliant terrain such as ballast.

Declaration of Competing Interest

The authors attest that there are no conflicts of interest to disclose.

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