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Walking biomechanics on a sloped residential roofing surface

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ABSTRACT

Residential roofing work is among the riskiest occupations in the construction sector, partially because walking on a sloped roof surface may result in substantial biomechanical changes that are associated with the potential of increased instability. The objective of this study is to find whether typical roof working variables such as roof slope, walking direction, and footwear, affect the patterns of the ground reaction forces (GRFs) that may be critical to worker stability. Ten healthy male subjects participated in the study. Data were collected while subjects walked across a roof simulator that was set at three different roof slopes (0°, ~14°, ~27°). The subjects walked in four different directions (i.e., cross-slope in opposite directions and up-/down-slope) wearing three different footwear (i.e., two types of roofing-specific boots, one type of general work boot). The normal and shear components, as well as the resultant of the GRFs, were analyzed for each foot separately. The results indicate that a linear relationship exists between roof slope and normal/shear ground reaction forces. Cross-slope walking resulted in larger shear forces for the foot that was lower on the slope. An increase in roof slope angle generally resulted in a longer stride time when walking up/down slope. The findings show that various roof-working factors collectively influence GRFs and stride times when traversing a sloped roof surface, indicating that worker stability may depend on multiple interacting aspects.

1. Introduction

In 2021, there were over 158,800 roofers in the United States, and the roofer population is expected to increase by 1.4% by 2031 (BLS 2023). Since 1992, roofing has ranked as the second most dangerous occupation in terms of fatal injuries, with 41.8 deaths per 100,000 full-time workers (CPWR 2018). During a period from 2011 to 2015, the rate of such deaths among roofers was 34.2 per 100,000 full-time workers, more than ten times that of all construction workers on average; the fatal falls from roofs accounted for one-third of all fatal falls (CPWR 2018). Since 1992, roofing has been ranked as the eleventh most dangerous job in terms of non-fatal injuries, with 130.3 injuries per 10, 000 full-time workers, of which 63.3 occurred from falls (CPWR 2018). Between 2005 and 2007, the incurred claims costs due to falls from elevation by the insured roofers was approximately $54,000,000 per year (OSHA, 2011).

Regional environmental factors cause residential roofs in the United States to vary in pitch, and the maximum pitch that is considered walkable is an 8:12 pitch (~33.7°) (Breloff et al., 2019a). While working on sloped surfaces, roofers are required to walk cross-slope, as well as up-/down-slope. As compared to walking on a level surface, walking cross-slope and up-/down-slope can result in large variations in biomechanical measures, such as kinematics, kinetics, and gait characteristics (Breloff et al., 2022). These changes can lead to an increase in inclination angle, indicating a decrease in the postural stability on a sloped surface (Breloff et al. 2019a, 2020; Svensson et al., 2018), increasing the likelihood of slip, trip, and fall events (Nadhim et al., 2016; Hu et al., 2011). Working on sloped roofing surfaces will potentially expose the roofers to a higher risk of both traumatic injuries (TI) and musculoskeletal disorders (MSD) (Santos et al., 2025; Nadhim et al., 2016).

To evaluate the risks of TI and MSD in roofing workers, it is important to analyze the mechanical effects induced by the sloped roof environment. Previous works have studied the effects of gait in a general

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sloped environment. Some studies have evaluated the kinetic effects of different sloped surface, such as down-slope gait (Kuster et al., 1995; Redfern and DiPasquale, 1997), cross-slope gait (Dixon and Pearsall, 2010), and up-/down-slope gait (Damavandi et al., 2012; Lay et al., 2006). Wannop et al. (2014) studied the effects of both up-/down-slope gait in a sloped environment on the traction coefficient; they only evaluated the kinetics of a single footstep. Some other works have observed the effects of gait in a roofing-specific environment, such as the effects of a sloped roof environment on spatiotemporal gait parameters (Breloff et al., 2022), lower extremity kinematics (Breloff et al., 2019a), and inclination angles (Breloff et al., 2020). Biomechanical analysis of gait through kinetic assessment remains a potentially invaluable tool in mitigating slips, trips, and falls, as it has the capacity to shed light on hazardous conditions that might arise (Damavandi et al., 2012). Despite the numerous studies analyzing gait on a sloped surface, the ground reaction forces (GRFs) of the human body while walking on a sloped roofing surface have not been comprehensively assessed.

The postural stability of roofing workers, which is related to safety, is associated with multiple, combined kinetic and kinematic factors (Svensson et al., 2018; Hsiao and Simeonov 2001). There are multiple factors that may induce changes in the mechanical response of roof workers; they include roof pitch, footwear, roof surface materials, and walking directions. The purpose of the current study was to assess the effects of the roofing pitch and footwear on the patterns of the GRFs and stride times while walking in different directions on a sloped roof simulator. It is hypothesized that changes in roof slope, walking

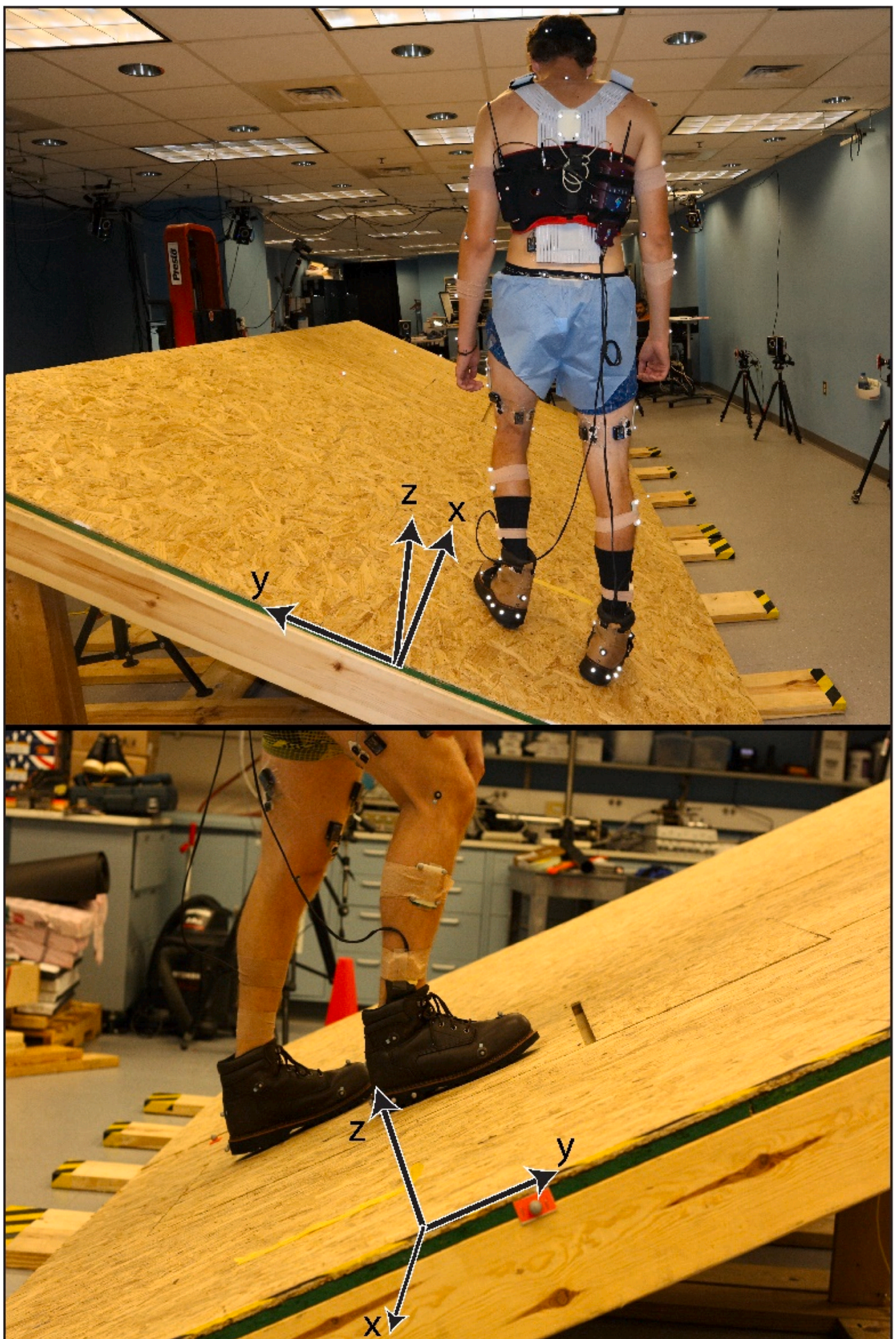

Fig. 1. Subject walking on the roof simulator. The x and y axis lie on the roof simulator's walking surface, while the z axis is normal to the roof simulator's surface.

directions, and footwear, will result in changes in GRFs and stride time.

2. Methods

2.1. Subjects

This study was reviewed and approved by the National Institute for Occupational Safety and Health (NIOSH) Institutional Review Board, and all participants provided written consent, before testing began. Ten healthy male subjects were recruited. The subjects were not roofing workers and had never worked in the industry. None of the participants had any diagnosed musculoskeletal or neurological disorders.

2.2. Data collection

All data were collected at a NIOSH laboratory (Morgantown, West Virginia), using a roof simulator with a surface of oriented strand board (Fig. 1) that could be angled at a flat (0° slope), a 3/12 (~14° slope), and a 6/12 pitch (~27° slope), which represent common residential housing roof pitches. Subjects changed into skin-tight clothing, and 82 retro-reflective motion capture markers (9 mm in diameter) were placed around the subject's body (Breloff et al., 2019b). Kinematic data were collected at 100 Hz using 14 Vicon Vantage cameras (Vicon Inc., Oxford, England). Embedded into the roof simulator were two force plates (Bertec, Columbus, Ohio, USA), which collected three-dimensional GRF data at 1000 Hz. At both the 14° and the 27° slopes, each subject was asked to walk up-slope (US) and down-slope (DS), as well as cross-slope in both directions (with the left-foot higher in one walking direction, CS_{left}, and the right-foot higher in the other walking direction, CS_{right}), and all walking tasks were at self-selected walking paces. For the 0° slope, the subject only walked in one direction since all directions were biomechanically identical. Each of these tasks was completed using three different representative footwear: a roofing boot with a hard sole (RB_{HS}), a roofing boot with a soft sole (RB_{SS}), and a general work boot (GWB). Each of the trials for a combination of roof slopes, walking directions, and footwear was replicated 4 times. The total trials were: 6 (subjects) x 3 (footwear) x [1 (0° slope) x 1 (walking direction) + 2 (14° and 27° slopes) x 4 (walking directions)] x 4 (replicates) = 648.

2.3. Data analysis

The coordinate system was fixed on the roofing surface, as illustrated in Fig. 1. The x axis was along the cross-slope direction, the y axis was along the up-/down-slope direction, and the z axis was perpendicular to both the x and y axes (i.e., normal to the roof simulator's surface). The GRFs in three directions (i.e., F_x, F_y, F_z) were collected. The normal force (F_N), the shear force in the up-/down-slope direction (F_{S_slope}), and shear force magnitude (F_{S_mag}) were defined as:

$$F_N^j = F_z^j;\ j = \text{left, right} \tag{1}$$

$$F_{S\_slope}^j = F_y^j;\ j = \text{left, right} \tag{2}$$

$$F_{S\_mag}^j = \sqrt{{F_x^j}^2 + {F_y^j}^2};\ j = \text{left, right} \tag{3}$$

Using Eqs. (1)–(3), the total normal force (F_N^{total}) was defined as the sum of the normal forces on the left and right foot, and the total shear force magnitude ($F_{S\_mag}^{total}$) was the magnitude of the vector sum of the shear force components on both feet:

$$F_N^{total} = F_z^{left} + F_z^{right} \tag{4}$$

$$F_{S\_mag}^{total} = \sqrt{\left(F_x^{left} + F_x^{right}\right)^2 + \left(F_y^{left} + F_y^{right}\right)^2} \tag{5}$$

Since the coordinate system was fixed on the roofing surface, the definition of the shear and normal forces were independent of the orientation or slope variations of the roofing surface. The collected kinematic and GRF data were loaded into Matlab (MathWorks, Natick, Massachusetts, USA) for analysis. For the GRF data, the occurrences of the events of the heel-strike and toe-off were determined when the reaction force exceeded 10 N and fell below 5 N, respectively (O'Connor et al., 2007). Due to the use of only two force plates in the roof simulator, an entire gait cycle for the GRFs of the feet could not be directly measured. To fix this issue, kinematic data were utilized to determine extra strides for each of the left and right feet. This was done using the midfoot vertical velocity, as described by O'Connor et al. (2007). Once the event of one additional heel-strike and toe-off for each foot were determined in the time histories using this method, the corresponding measured GRF profile was superimposed onto the end of the measured time histories of the GRF to create a full kinetic gait cycle. In the study, only trials of "reconstructed" full kinetic gait cycle, in which the subject took two subsequent strides with each left and right foot, were used for data analysis.

The average and maximum normal forces during stance phase, shear forces in the up-/down-slope direction during stance phase, total normal forces throughout the entire gait cycle, and total shear force magnitudes throughout the entire gait cycle, as well as the average stride times, were determined and analyzed for each trial. The average force was calculated by taking the integral of the force time-histories and dividing the integral value by the time duration (Δt):

$$\overline{F}_k^j = \frac{\int_0^{\Delta t} F_k^j \cdot dt}{\Delta t};$$

$$k = \text{N}, \text{S}_{\text{slope}}, \text{S}_{\text{mag}};\ j = \text{left, right, total} \tag{6}$$

To compare the results for subjects with different body sizes, the results of the average and maximum forces were normalized by each subject's body weight:

$$\widehat{F}_k^j = \frac{\overline{F}_k^j}{BW};$$

$$k = \text{N}, \text{S}_{\text{slope}}, \text{S}_{\text{mag}};\ j = \text{left, right, total} \tag{7}$$

where BW represents the body weight, which is the mass of the subject multiplied by the acceleration of gravity.

2.4. Statistical analysis

Outcome measures were: i) the average normalized normal force of the left foot, the right foot, and the total of both feet combined, ii) the average normalized shear force for the up-/down-slope direction of the left & right foot, iii) the total average normalized shear force magnitude, iv) the maximum normalized normal force of the left foot, the right foot, and the total of both feet combined, v) the maximum normalized shear force for the up-/down-slope direction of the left foot & right foot, vi) the total maximum normalized shear force magnitude, and vii) stride times. Differences for each outcome measure were compared using a multi-way repeated measures analysis of variance using SPSS v22 (IBM Corp., Armonk, New York, USA). To compensate for the increase in the family-wise error rate due to multiple comparisons, the Bonferroni adjustment was applied, which lowers the p-value used to determine significance, which in turn keeps the family-wise error rate low (all p-values were set to 0.05).

3. Results

For all the trials, GRFs (in newtons) were collected in the x, y, and z directions as a function of time for both the left and right feet. From these data, the shear force magnitude, the total normal force, and the total shear force magnitude (Eqs. (3)–(5)) were calculated (in newtons).

The analysis of representative subject data is illustrated in Fig. 2. Then using Eq. (6), the average values for each were calculated, and the maximum values were identified. All data were finally normalized according to Eq. (7) (resulting in unitless values i.e. newtons/newtons). Stride times (in seconds) were determined from the GRF data. Differences were seen in the normal and shear forces, as well as with the stride times, for different roof slopes, walking directions, and footwear, and are highlighted in Tables 1–4 and Figs. 3 and 4. Due to an equipment malfunction, data from four subjects were unusable, and therefore, only the data from six subjects are used for data analysis.

3.1. Effects of roof slope

The effects of the roof slope on the GRFs and stride time are shown in Tables 1 and 4A, respectively. The difference in the forces and stride time between the left and right foot was generally small (less than 0.02 N/N and 0 s). When the roof slope angle increased from 0° to 27°, the average of the left and right foot normalized average normal force ($\widehat{F}_N^j$) decreased from 0.77 to 0.65 ($p < 0.05$), the average of the left and right foot normalized average shear force in the up-/down-slope direction ($\widehat{F}_{S\_slope}^j$) increased from 0.004 to 0.32 ($p < 0.05$), and the average of the left and right foot stride time increased from 0.82 s to 0.96 s ($p < 0.05$). The corresponding average normalized total normal force ($\widehat{F}_N^{total}$) (which is the sum of the forces on the left and right foot) decreased from 1.00 to 0.88 ($p < 0.05$) and the average normalized total shear force ($\widehat{F}_{S\_mag}^{total}$) increased from 0.08 to 0.43 ($p < 0.05$).

3.2. Effects of walking direction

The effects of the walking direction on the GRFs and stride time are shown in Tables 2 and 4B, respectively. In the up-/down-slope direction, the difference in the forces and stride time between the left and right foot was generally small (less than 0.05 N/N and 0.02 s). The averages of the left and right foot normalized average normal force ($\widehat{F}_N^j$) were 0.66 and 0.72 in the up-slope and down-slope directions ($p < 0.05$), respectively, whereas the averages of the left and right foot normalized average shear force ($\widehat{F}_{S\_slope}^j$) were 0.26 and 0.28 in the up-slope and down-slope directions ($p < 0.05$), respectively. The average of the left and right foot stride times were 1.1 s and 0.86 s in the up-slope and down-slope directions ($p < 0.05$), respectively. The average normalized total normal force ($\widehat{F}_N^{total}$) and average normalized total shear force ($\widehat{F}_{S\_mag}^{total}$) were similar (less than 0.08 N/N and 0.04 N/N respectively) in both the up-slope and down-slope directions.

In the cross-slope directions, the difference in the average of the left and right foot normalized normal force and the stride time between the left and right foot was generally small. The average of the left and right foot normalized average normal forces ($\widehat{F}_N^j$) was 0.73 in both cross-slope directions ($p = 0.601$). The averages of the left and right foot normalized shear force ($\widehat{F}_{S\_slope}^{left}$ and $\widehat{F}_{S\_slope}^{right}$) for the foot that was lower and higher on the slope were 0.2 and 0.13 ($p < 0.05$), respectively. The averages of the left and right foot stride times were 0.86 s and 0.88 s for the cross-slope walking with the left foot higher and right foot higher ($p = 0.630$), respectively.

3.3. Effects of footwear

The effects of footwear on the GRFs and stride time are shown in Tables 3 and 4C, respectively. The difference in the forces and stride time between the left and right foot was generally small (less than 0.02 N/N and 0.01 s). For the tests wearing footwear RB_{HS}, RB_{SS}, and GWB, the averages of the left and right foot normalized average normal force ($\widehat{F}_N^j$) were 0.71, 0.72, and 0.71 ($p < 0.05$ RB_{HS}-RB_{SS}, $p = 0.525$ RB_{HS}- GWB, $p < 0.05$ RB_{SS}- GWB), respectively, the averages of the left and right foot normalized average shear force in the up-/down-slope direction ($\widehat{F}_{S\_slope}^j$) were 0.20, 0.19, and 0.19 ($p = 0.179$ RB_{HS}-RB_{SS}, $p < 0.05$ RB_{HS}- GWB, $p = 0.125$ RB_{SS}- GWB), respectively, and the averages of the left and right foot stride times were 0.9, 0.89, and 0.93 ($p = 0.169$ $RB_{H\ S}$-RB_{SS}, $p < 0.05$ RB_{HS}- GWB, $p < 0.05$ RB_{SS}- GWB), respectively. The corresponding average normalized total normal forces ($\widehat{F}_N^{total}$) (which is the sum of the forces on the left and right foot) for the footwear RB_{HS}, RB_{SS}, and GWB were 0.94, 0.93, and 0.94 ($p < 0.05$ RB_{HS}-RB_{SS}, $p = 1.000$ RB_{HS}- GWB, $p < 0.05$ RB_{SS}- GWB), respectively, and the average normalized total shear forces ($\widehat{F}_{S\_mag}^{total}$) were 0.29, 0.27, and 0.27, respectively ($p < 0.05$ RB_{HS}-RB_{SS}, $p = 0.062$ RB_{HS}- GWB, $p < 0.05$ RB_{SS}- GWB).

4. Discussion

A greater understanding of the kinetic changes induced by a sloped roof environment is imperative for roofers' safety. The current study investigated the interactions of the workers' GRFs walking on a sloped roof surface with the slope angle, walking directions, and footwear. Knowledge obtained in the study would help manufacturers improve their product design and help the safety management at construction sites to reduce the risks of both TI and MSD.

Slip is a threshold event that can occur whenever local shear demand momentarily exceeds available friction, and the timing of those peaks

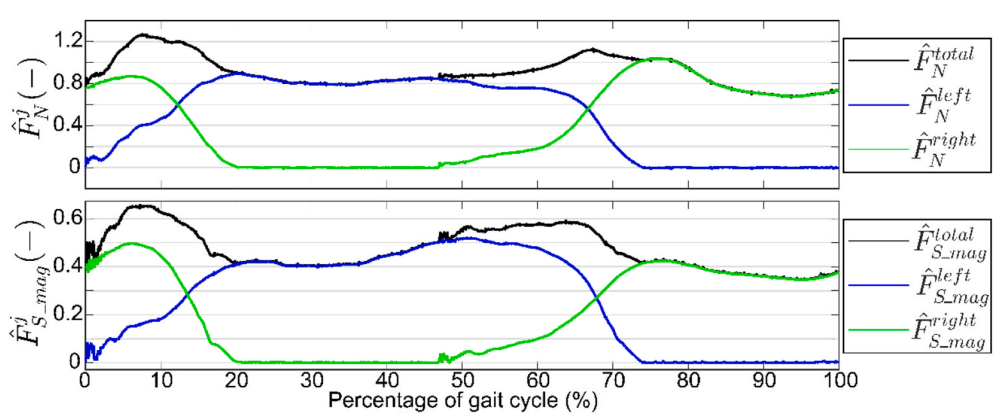

Fig. 2. Sample data of normalized normal force ($\widehat{F}_N^j$) and shear force magnitude ($\widehat{F}_{S\_mag}^j$) (top and bottom graphs respectively) for a single trial obtained from the testing of a representative subject, where j is either the left foot, right foot, or total (combination of left and right feet).

Table 1
Average normalized forces (and average maximum normalized forces) as a function of each roof slope angle. Forces for each roof slope includes all walking direction and footwear conditions. Normalized results are unitless. $\hat{F}_N^j$ is the average normalized normal force, and $\hat{F}_{S\_slope}^j$ is the average normalized shear force in the up-/down-slope direction, where j is either the left foot, the right foot, or the total value. (±SD).

Roof Slope (°)	$\hat{F}_N^{left}$ (−)	$\hat{F}_{S\_slope}^{left}$ (−)	$\hat{F}_N^{right}$ (−)	$\hat{F}_{S\_slope}^{right}$ (−)	$\hat{F}_N^{total}$ (−)	$\hat{F}_{S\_mag}^{total}$ (−)
0	0.76 ± 0.03 (1.07 ± 0.04)	0.003 ± 0.04 (0.07 ± 0.02)	0.78 ± 0.02 (1.10 ± 0.05)	0.006 ± 0.04 (0.07 ± 0.02)	1.0 ± 0.05 (1.38 ± 0.22)	0.08 ± 0.01 (0.21 ± 0.04)
14	0.73 ± 0.03 (1.07 ± 0.09)	0.17 ± 0.05 (0.29 ± 0.09)	0.75 ± 0.03 (1.09 ± 0.07)	0.17 ± 0.07 (0.28 ± 0.12)	0.96 ± 0.1 (1.36 ± 0.23)	0.24 ± 0.04 (0.4 ± 0.08)
27	0.65 ± 0.04 (0.97 ± 0.05)	0.31 ± 0.09 (0.49 ± 0.14)	0.66 ± 0.04 (0.98 ± 0.06)	0.33 ± 0.07 (0.52 ± 0.12)	0.88 ± 0.09 (1.26 ± 0.21)	0.43 ± 0.08 (0.65 ± 0.13)

Table 2
Average normalized forces (and average maximum normalized forces) as a function of each walking direction. Forces for each walking direction includes all slope and footwear conditions. Normalized results are unitless. $\hat{F}_N^j$ is the average normalized normal force, and $\hat{F}_{S\_slope}^j$ is the average normalized shear force in the up-/down-slope direction, where j is either the left foot, the right foot, or the total value. (±SD).

Walking Direction	$\hat{F}_N^{left}$ (−)	$\hat{F}_{S\_slope}^{left}$ (−)	$\hat{F}_N^{right}$ (−)	$\hat{F}_{S\_slope}^{right}$ (−)	$\hat{F}_N^{total}$ (−)	$\hat{F}_{S\_mag}^{total}$ (−)
US	0.66 ± 0.06 (1.01 ± 0.12)	0.23 ± 0.13 (0.37 ± 0.21)	0.66 ± 0.06 (0.99 ± 0.08)	0.28 ± 0.07 (0.45 ± 0.1)	0.88 ± 0.07 (1.34 ± 0.14)	0.34 ± 0.12 (0.57 ± 0.17)
DS	0.7 ± 0.05 (1.09 ± 0.11)	0.27 ± 0.07 (0.51 ± 0.11)	0.74 ± 0.04 (1.11 ± 0.07)	0.28 ± 0.08 (0.52 ± 0.13)	0.88 ± 0.28 (1.57 ± 0.4)	0.36 ± 0.15 (0.7 ± 0.24)
CS_{left}	0.72 ± 0.06 (1.03 ± 0.06)	0.13 ± 0.14 (0.24 ± 0.17)	0.74 ± 0.04 (1.07 ± 0.08)	0.2 ± 0.15 (0.31 ± 0.22)	0.94 ± 0.06 (1.28 ± 0.16)	0.25 ± 0.15 (0.4 ± 0.17)
CS_{right}	0.72 ± 0.04 (1.03 ± 0.07)	0.2 ± 0.13 (0.31 ± 0.19)	0.73 ± 0.06 (1.05 ± 0.07)	0.13 ± 0.14 (0.23 ± 0.18)	0.97 ± 0.06 (1.31 ± 0.24)	0.26 ± 0.16 (0.4 ± 0.18)

Table 3
Average normalized forces (and average maximum normalized forces) as a function of each footwear. Forces for each footwear includes all slope and walking direction conditions. Normalized results are unitless. $\hat{F}_N^j$ is the average normalized normal force, and $\hat{F}_{S\_slope}^j$ is the average normalized shear force in the up-/down-slope direction, where j is either the left foot, the right foot, or the total value. (±SD).

Footwear	$\hat{F}_N^{left}$ (−)	$\hat{F}_{S\_slope}^{left}$ (−)	$\hat{F}_N^{right}$ (−)	$\hat{F}_{S\_slope}^{right}$ (−)	$\hat{F}_N^{total}$ (−)	$\hat{F}_{S\_mag}^{total}$ (−)
RB_{HS}	0.7 ± 0.05 (1.03 ± 0.08)	0.19 ± 0.13 (0.32 ± 0.19)	0.72 ± 0.06 (1.05 ± 0.09)	0.20 ± 0.14 (0.33 ± 0.2)	0.94 ± 0.12 (1.36 ± 0.27)	0.29 ± 0.16 (0.46 ± 0.21)
RB_{SS}	0.71 ± 0.06 (1.03 ± 0.08)	0.18 ± 0.14 (0.30 ± 0.2)	0.73 ± 0.06 (1.04 ± 0.08)	0.19 ± 0.15 (0.31 ± 0.2)	0.93 ± 0.09 (1.3 ± 0.18)	0.27 ± 0.15 (0.45 ± 0.19)
GWB	0.7 ± 0.05 (1.03 ± 0.09)	0.18 ± 0.14 (0.30 ± 0.2)	0.72 ± 0.06 (1.06 ± 0.08)	0.19 ± 0.14 (0.32 ± 0.21)	0.94 ± 0.08 (1.31 ± 0.22)	0.27 ± 0.15 (0.44 ± 0.21)

Table 4
Stride time (in seconds) for each foot for different testing conditions. A: Effect of roof slope angle. B: Effect of walking direction. C: Effect of footwear. (±SD).

A		
Roof slope (°)	Left foot stride time avg (s)	Right foot stride time avg (s)
0	0.84 ± 0.1	0.84 ± 0.08
14	0.88 ± 0.09	0.88 ± 0.1
27	0.96 ± 0.15	0.96 ± 0.15
B		
Walking Direction	Left foot stride time avg (s)	Right foot stride time avg (s)
US	1.1 ± 0.16	1.1 ± 0.15
DS	0.85 ± 0.07	0.87 ± 0.11
CS_{left}	0.86 ± 0.08	0.86 ± 0.08
CS_{right}	0.89 ± 0.11	0.87 ± 0.08
C		
Footwear	Left foot stride time avg (s)	Right foot stride time avg (s)
RB_{HS}	0.9 ± 0.12	0.9 ± 0.14
RB_{SS}	0.89 ± 0.14	0.88 ± 0.12
GWB	0.93 ± 0.13	0.92 ± 0.12

can shift with slope, direction, and footwear. By computing stance-phase means and maxima for normal and shear components, our summary statistics capture the general trends of friction demand without presuming when the highest shear-to-normal ratios will occur. In practice, the maxima are dominated by transient peaks that typically arise near heel-strike or toe-off (Jiang et al., 2020; Revi et al., 2020, Pieper et al., 2020). These events were explicitly identified and used to reconstruct full kinetic gait cycles, ensuring that extremes at both ends of stance were included in the analysis. Consistent with this rationale, the wide variability we observed in the beta angles (direction of biodynamic shear) across slopes and tasks further indicates that risk-relevant shear peaks are not confined to a single sub-phase of stance.

Verification of the results was completed by comparing the average of the mean total normal force, and average maximum total normal force, to the expected static normal force (F_{N_static}), as well as the average of the mean total shear force, and average maximum total shear force, both in the up-/down-slope direction, to the expected static shear force in the up-/down-slope direction ($F_{S\_slope\_static}$). As seen in Fig. 3, the average of the mean total normal force, and the average of the mean total shear force in the up-/down-slope direction, quite closely match the expected static normal and shear forces, respectively, at each roof slope angle. A small discrepancy exists between the average of the mean total shear force and the expected shear force in the up-/down-slope direction at 0° because theoretically, there should be no shear forces, but

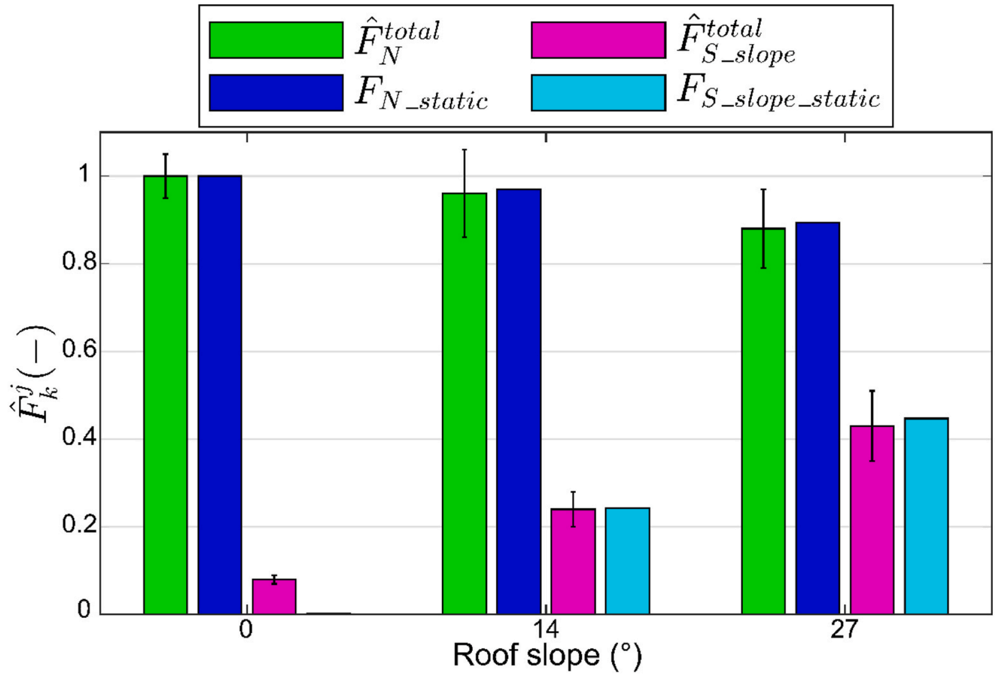

Fig. 3. Average of the mean total normal force ($\hat{F}_N^{total}$) and average shear force in the up-/down-slope direction ($\hat{F}_{S\_slope}^{total}$), normalized by body weight, as a function of roof slope angle. The expected static normal (F_{N_static}) and shear force in the up-/down-slope direction ($F_{S\_slope\_static}$) are presented for comparison.

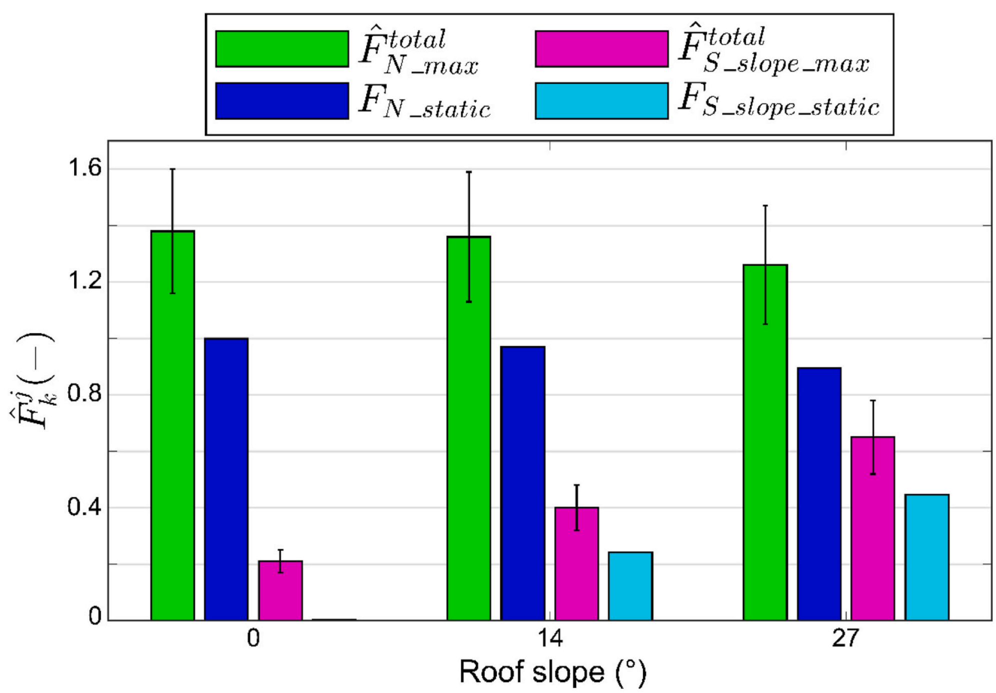

Fig. 4. Average maximum total normal force ($\hat{F}_{N\_max}^{total}$) and average maximum shear force in the up-/down-slope direction ($\hat{F}_{S\_slope\_max}^{total}$), normalized by body weight, as a function of roof slope angle. The expected static normal (F_{N_static}) and shear force in the up-/down-slope direction ($F_{S\_slope\_static}$) are presented for comparison.

variations in subjects' sway during static conditions will inevitability lead to a non-zero shear force. This measured shear force is very minimal and should not be considered to discredit the verification of the results. Similarly, in Fig. 4, the average maximum total normal force, and the average maximum total shear force in the up-/down-slope direction, were all measured to be greater than their respective static forces at each roof slope angle. This makes sense, as the maximum value is a result of the dynamic movement of each subject walking across the roof simulator surface. The dynamic movement will increase the acceleration of the subject at a point that will create a larger force than if measured statically. This verification provides additional confidence in the results of the study.

Changes in the slope of the simulated roof surface had a statistically significant effect on the resulting GRFs and stride time of the subjects (Tables 1 & 4A). As the roof slope increased from 0° to 14° to 27°, in the normal direction, the average of the mean normalized forces and average maximum normalized forces for both the left and the right foot decreased, as did the average normalized total normal and shear forces. Inversely, in the up-/down-slope direction, the average of the mean normalized forces and average maximum normalized forces for both the left and the right foot increased, as did the average normalized total normal and shear forces. These results are to be expected, as they follow basic physics principles in that an increased slope will increase the shear force in the up-/down-slope direction while decreasing the normal force (Redfern and DiPasquale, 1997). It can be seen from the data (Table 1) that there is a linear relationship between slope and the average normalized/average maximum normalized forces. This relationship is much stronger for the increase in shear force value with increasing roof slope (average R-squared value of 0.998/0.995) more so than the decrease in normal force value with increasing roof slope (average R-squared value of 0.931/0.794). Additional data points will allow for exploration of this relationship in more depth. It was also seen that an increase in roof slope caused an increase in stride time. This conclusion agrees with non-empirical observations as a roofer would want to take more time at a greater slope to ensure proper foot placement and stability to avoid events leading to TIs and/or MSDs.

Walking direction also had a statistically significant impact on the GRFs and stride time of the subjects (Tables 2 & 4B). Walking cross-slope produced a greater average of the mean normalized shear forces in the up-/down-slope direction for the foot that was lower on the slope compared to the foot that was higher on the slope, which agrees with findings in previous studies (Damavandi et al., 2012). This displays the subjects' need to compensate for the sloped surface by adjusting their center of mass towards the foot lower on the roof surface. In doing so, this adjustment increases inclination angle as compared to walking on a level surface, which has been shown to more likely cause slipping (Breloff et al., 2020). Walking cross-slope also yielded, in the up-down-slope direction, a smaller average of the mean normalized shear forces for both the left and right foot, average maximum normalized shear forces for both the left and right foot, average normalized total shear forces, and average maximum normalized total shear forces, compared to walking up-/down-slope. Walking cross-slope requires non-negligible shear force in both the cross-slope direction (for forward motion), as well as in the up-/down-slope direction (to keep from falling down the slope, while walking up-/down-slope only requires non-negligible shear force in the up-/down-slope direction (to keep from falling down the slope), with shear forces in the cross-slope direction being a fraction of those in the up-/down-slope direction. The subject's stride time was mostly consistent with the walking direction, except in the up-slope direction, which led to a longer stride time. This may be due to the physical effects of the roof slope, as walking up an increasing slope requires additional force and physical effort to counteract the increasing effects of gravity. Breloff et al. also found that as compared to a flat surface, walking on a sloped surface increased the stride time (Breloff et al., 2022). Walking cross-slope keeps the roofer on the same height of the roof and walking down-slope is aided by the effects of gravity, requiring the roofer to use less effort and physical force.

Footwear had a minimal impact on the data collected. No noteworthy differences were seen in the resulting GRFs (Table 3), and only small differences were seen in the stride time (Table 4C). Wearing designated roofing boots decreased the stride time by a small amount as compared to the general work boot. It is thought that this is due more to a psychological effect of wearing a shoe that is designed to better grip the roof's surface, rather than the physical effect of a possible increase in friction between the shoe's sole and the roof's surface. The subjects' knowledge of wearing footwear designed for roofers allowed them to walk with more pace and confidence. Previous studies have seen a change in walking strategies between different types of footwear while walking on an elevated surface (Simeonov et al., 2008), suggesting that gait patterns are altered based on physical and psychological effects of footwear choice.

Although not part of the original hypothesis, beta angle, defined by Dong et al. (2021) as the direction of the biodynamic shear force, was computed and then determined at the same time point as the maximum total shear force magnitude. These values are being presented as they reveal an interesting result of the study. For roof slopes of 0°, 14°, and 27°, the average and standard deviation of the beta angle was −4.38° ± 22.93°, −24.53° ± 32.46°, and −29.36° ± 34.41°, respectively. For walking directions of US, DS, CS_{left}, and CS_{right}, the average and standard deviation of the beta angle was −0.77° ± 2.73°, 1.2° ± 2.64°, −25.41° ± 36.48°, and −23.13° ± 33.56°, respectively. For different footwear of RB_{HS}, RB_{SS}, and GWB, the average and standard deviation of the beta angle was −14.73° ± 34.5°, −30.03° ± 34.81°, and −18.66° ± 35.37°, respectively. From these values, we can see that a different gait strategy is adopted for level versus sloped walking. Walking on the simulated roof surface at a slope produces a noticeably greater beta angle than when walking on the flat surface, regardless of walking direction or footwear. This may be explained by a few different causes, such as the increase in shear forces on a sloped surface, and the unfamiliarity of walking on a sloped surface. As suggested by Dong et al. (2021), a 'zigging' and 'zagging' walking strategy may be adopted on a sloped surface, which could produce a large beta angle at the maximum total shear force magnitude, as seen in this study. It is also interesting to see that the beta angle while walking upslope and downslope is much smaller than those while walking cross-slope. These results suggest that the study participants took a more straight-forward gait method while walking up and down the inclined surface, while taking a more side-to-side approach while walking parallel to the ridge of the roof, the latter a strategy which can produce greater beta angles. Another interesting finding is that there seems to be a distinction in beta angle between hard sole (RB_{HS} and GWB) and soft sole footwear (RB_{SS}). This finding may show that there is an adaptation period to different types of footwear. Most commercial footwear has a hard sole, and thus, there would be a large period of adjustment to a soft sole, which may cause an alteration in walking gait, especially on a sloped surface. No participants in this study were professional roof workers, which could produce different results due to previous use of soft sole roof boots.

These beta angle results suggest that the direction of the biodynamic shear force varies greatly amongst roofing activities, and this can be accounted for through both training and footwear design. There are expected to be differences between individuals who are walking on a sloped roof surface for the first time versus professionals who walk on a sloped roof surface daily. Training around an optimized sloped roof gait strategy can reduce the variability between individuals, streamlining the need for specialized footwear. Additionally, it cannot be expected for everyone who walks on a roof to undergo professional training, and thus, footwear development and design can help. The design of the sole of the footwear needs to take into account the possible biomechanical needs of both novice and professional roof workers, allowing for a safer experience on a sloped roof surface.

It can also be seen in Tables 2 and 4B that the measurements for the forces and stride times for symmetric roof gait (i.e., walking up-/down-slope) were similar, while asymmetric roof gait (i.e., walking cross-slope with one foot higher up the slope than the other) led to asymmetric shear forces in the up-/down-slope direction while stride times between feet remained symmetric. The results from the symmetric walking tasks suggest that the subjects have no predominant foot during gait. Previous studies have observed symmetric gait in healthy populations through the measurement of GRFs (Sadeghi et al., 2000). The results from the asymmetric roof gait are of greater concern, as each foot has a different friction requirement to avoid slipping (Dong et al., 2021).

This study was able to measure the GRFs and stride times of subjects while walking across a roof simulator, which can imitate an accurate real-life experience of walking on a roof surface. It is thought that some of the results found in this study may vary from data collected while walking on an actual roof surface due to the psychological effects of added height and danger of falling resulting in serious injury or death.

Lee and Lishman (1975) have suggested that being subjected to heights may contribute to instability, potentially affecting walking adaptations. Shimizu et al. (2025a) demonstrated that gait parameters were significantly different when measured in a laboratory versus real-world setting. Measurement of walking biomechanics on an elevated real-world roof surface necessitates further investigation.

Additionally, using only two force plates embedded in the roofing simulator caused a need for artificially added kinetic data as part of the analysis. Future roofing simulator builds can have more force plates included to negate that need. Subjects recruited to this study did not have professional roofing work experience, which may alter the results, so future studies may consider recruitment of professional roof workers. Due to an equipment malfunction, only six of the ten subjects' data was included as part of the data analysis. Future work may include data from more subjects to increase the statistical power of the results.

A recent study has shown that surface type does play a role on gait parameters on non-elevated surfaces (Shimizu et al., 2025b), therefore, one more future direction for this work is the inclusion of different roofing surfaces. For this study, only oriented strand board was considered, which is a common surface to be traversed during the roof installation process. Other surfaces to be considered in the future could be underlayment such as tar paper, and a top layer such as asphalt shingles.

Roofing remains a highly dangerous occupation as most of the time the worker must interact with a sloped surface, which can be difficult to navigate while also completing the required roofing tasks, such as shingle installation. The sloped surfaces can easily result in increased instability, possibly resulting in TI or MSD. This study looked at the forces created by walking cross-slope, as well as up-/down-slope, on a roof's surface, and the stride times involved, to create a better understanding of the effects that the sloped roof environment has on the workers. More research is needed to create a total grasp on roof safety. Future studies will look at the effects of different weather conditions on the safety of roofers.

5. Conclusion

Changes in roof working variables, such as roof slope, walking direction, and footwear, were shown to influence the measured GRFs and stride times. Analysis of these results show that different scenarios in roofing work are more likely to result in increased instability, possibly leading to TI and/or MSD. This work also emphasizes the need for additional study of roof worker safety to help avoid fatal and non-fatal injuries.

Disclaimer

The findings and conclusions in this research are those of the authors and do not necessarily represent the opinion of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH/CDC.

CRediT authorship contribution statement

Robert E. Carey: Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **John Z. Wu:** Conceptualization, Methodology, Writing – review & editing. **Scott P. Breloff:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Chris M. Warren:** Investigation. **Erik W. Sinsel:** Investigation, Writing – review & editing. **Ren G. Dong:** Conceptualization, Methodology, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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