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Spatiotemporal gait parameters while cross-slope residential roof walking

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Abstract

Falls from residential roofs account for 80% of roofing industry fatalities. Furthermore, roofing work represents 44.7% of work in residual construction specialty trades and residential roofers count for 2.1% of overall workers in construction, with an anticipated growth in roofers of 14.9% by 2024. The purpose of the study was to evaluate the alterations in spatiotemporal gait parameters while traversing along a 6/12 pitched residential roof segment. Eighteen of the nineteen calculated spatiotemporal variables were statistically, significantly changed by walking across a 6/12 pitched simulated residential roof. The study clearly demonstrates that spatiotemporal gait variables increase and decrease while traversing across a residential roof. The changes in spatiotemporal parameters might suggest alterations to a person's balance system resulting in an increased risk of falling. The knowledge generated in the current study will be relevant to the residential roofing industry when it can be used in educational materials to increase awareness of how a roofer's altered gait while working on a pitched roof may increase their falling risk.

Keywords

Spatiotemporal; Cross-slope; Gait; Level; Sloped; Roof

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Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

Credit author statement

Scott P. Breloff: Conceptualization, Methodology, Validation, Investigation, Visualization, Writing- Original draft preparation, Writing – review and editing. **Robert E. Carey:** Data curation, Investigation, Writing – review and editing, Visualization Software. **Chip Wade:** Investigation, Writing – review and editing, Conceptualization, Supervision. **Dwight E. Waddell:** Investigation, Conceptualization, Writing – review and editing, Supervision.

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.

1. Introduction

1.1 Burden

Roofing work constituted 39.1% of the work done in residual construction as a specialty trade and roofers were 2.7%, of all construction workers, with a projected 5% increase in roofers by 2030, with almost 3,400 individuals in active apprenticeships in 2016 (CPWR, 2018; Economic Census and Bureau, 2017; BLS and Labor, 2020).

Roofers are exposed to heights on the job daily, which is an environment where they must keep and/or regain their balance (CPWR, 2018). This environment has led residential roofing to be ranked as the second most dangerous occupation among all occupations for fatal injuries at 41.8 deaths per 100,000 full time employee (FTEs), and also resulting in nonfatal injuries with 130.3 days away from work 2011–2015 (CPWR, 2018).

In the residential roofing industry, 80% of fatalities are from falls (Dong et al., 2014) with the primary cause of fall fatalities in construction of falling from roofs. This accounts for one-third of all fatal falls to a lower level (CPWR, 2018). The rate of such deaths from falling to a lower level among roofers was 34.2 per 100,000 FTEs, for a total of 291 deaths, which on average was reported to be more than ten times that of all construction workers between 2011 and 2015 (CPWR, 2018).

1.2. Sloped gait

Sloped gaits are generally sub-categorized into two different actions depending on the relation of the movement to the sloped surface. One, up/down slope walking is defined as walking directly up or down a sloped surface (i.e. toward the roof ridge or eave), and two, cross-slope gait, is defined as walking along a sloped surface with one foot higher and one foot lower on the slope (i.e. progressing toward the roof hip) (Breloff et al., 2019a, 2019b, 2020; Andres et al., 2005). Even though up/down slope walking has been more thoroughly studied as compared to cross-slope walking, both categories of non-level walking incite biomechanical changes in gait when compared to level walking (Breloff et al., 2019a, 2019b, 2020; Damavandi et al., 2010, 2012; Dixon et al., 2011; McVay and Redfern, 1994; Redfern and DiPasquale, 1997). Up/down sloped surface walking will induce changes in kinematics (Redfern and DiPasquale, 1997; Lay et al., 2006; Leroux et al., 2002; Lange et al., 1996; Kuster et al., 1995), kinetics (Redfern and DiPasquale, 1997; Kuster et al., 1995; Alexander and Schwameder, 2016), gait characteristics (Sun et al., 1996), muscle function (Lay et al., 2006; Lange et al., 1996; Pickle et al., 2016), and mechanical work (Kuster et al., 1995; Alexander et al., 2017). Similarly, walking cross-slope will change gait kinematics (Breloff et al., 2019b, 2020; Andres et al., 2005; Damavandi et al., 2010; Dixon and Pearsall, 2010; Wannop et al., 2014), kinetics, (Dixon and Pearsall, 2010; Wannop et al., 2014), and running dynamics (Damavandi et al., 2012; Dixon et al., 2011; Willwacher et al., 2013). Furthermore, up/down slope walking provokes a greater risk for falling than walking on stairs of similar angles (Sheehan and Gottschall, 2012).

1.3. Spatiotemporal gait parameters

Spatiotemporal gait parameters are kinematic descriptors of distance (spatial – such as step/stride length and width) and time (temporal – such as cadence and step/stride time). These parameters have been abundantly studied in healthy, aging, and clinical populations during a variety of tasks (level, up/down slope, obstacle crossing, etc.) leading to normative databases and thereby changes in gait can be linked to aging effects such as health status, quality of life and physical function (Hollman et al., 2011; Perry and Burnfield, 2010; Stolze et al., 1998; Ferrucci et al., 2000; Cesari et al., 2005; Studenski et al., 2003). Additionally, changes in gait have been determined to assess risk of early mortality, dementia risk, and risk of falling (Studenski et al., 2011; Verghese et al., 2007, 2009; Maki, 1997).

External factors such as environment and divided attention have also been linked to changes in gait parameters (Brennan, 2019; Lamberg and Muratori, 2012; Marone et al., 2014; Plummer et al., 2015; Prupetkaew et al., 2019; Seymour et al., 2016; Ferraro et al., 2013; Park et al., 2020). Up slope walking has been shown to significantly decrease step length, cadence, and normalized velocity, while increasing the gait stability ratio (Ferraro et al., 2013). Down slope walking increased walking velocity and cadence but decreased step length (Scaglioni-Solano and Aragón-Vargas, 2015). Many spatiotemporal studies tend to use treadmills as a means to control speed and obtain a larger number of footfalls (Kimel-Naor et al., 2017; Castano, 2019; Hollman et al., 2016).

1.4. Purpose

Given the anticipated growth in residential roofer jobs over the next decade and the expected increase in medical and insurance costs, it is important to fully understand what risks a sloped residential roof work environment present. Though it has been established that cross-slope roof walking will change kinematics and increase inclination angles thereby decreasing stability (Breloff et al., 2019b, 2020), it is also important to comprehend how cross-slope roof walking changes foot placement. Further, the use of a simulated residential roof segment will have direct implications to worker safety and health, by providing relevant spatiotemporal gait data that closely mimics a real-world worksite. The current study assessed the differences in spatiotemporal gait parameters while walking along a twenty-six-degree sloped roof segment. It was hypothesized that the introduction of a sloped roof surface, compared to a level surface, induces extensive deviations in spatiotemporal gait parameters.

2. Methods

2.1. Participants

Eleven college-aged male subjects (19.1 ± 1.49 yrs, 81.15 ± 15.14 kg, and 180.73 ± 5.89 cm) who were considered inexperienced at walking on sloped roof surfaces participated in the study. Inexperienced subjects were recruited to measure the change in spatiotemporal gait parameters when individuals are first introduced to a sloped roof surface, akin to the situation when an individual first ascends a roof. All subjects were male as 97% of roofers are male (BLS, 2018). Subjects did not report any history or clinical evidence of neurological, musculoskeletal, or other medical conditions that affect gait performance such as stroke, head trauma, neurological disease (i.e., Parkinson's, diabetic neuropathy), or visual impairment uncorrectable by lenses and dementia. Subjects were not taking any medications for balance disorders. The current study was conducted under an approved University of Mississippi Institutional Review Board protocol and all subjects reviewed and signed the associated approved informed subject consent forms.

2.2. Gait trials

2.2.1. General procedure—Subjects completed two separate testing sessions on different days, at least a week apart: level surface (first visit) and sloped surface (second visit) walking in the biomechanics laboratory at the University of Mississippi. Due to the complexity and time requirements to install the sloped surface, the testing sessions were not randomized. The level condition consisted of a level 10-m vinyl covered walk-way. The sloped condition used a 2.43 m wide x 7.32 m long section of 15.24 cm/30.48 cm pitch (26°) shingled sloped surface—which was designed to simulate a walkable residential roof surface—and was attached to the laboratory floor (Fig. 1). The difference between surface coverings is not expected to alter the results (Svensson et al., 2018). Kinematic data were collected as the subjects walked through the capture volume in both of the two conditions. A residential roof is considered walkable at an angle of <33° and therefore the 26° angle was chosen as a more extreme but still walkable roof (Roofkey.com, 2017).

Subjects wore spandex clothes and work boots with a 15.24 cm high shaft for both testing conditions. The subjects were outfitted with thirty-nine 14 mm reflective markers according to the Plug-in-Gait marker set (Vicon Inc. Oxford, UK) and completed both conditions at a comfortable self-selected walking pace. Data were collected using a Vicon motion capture system sampling at 120 Hz. The level condition required the subjects to walk across the 10-m walkway, while the sloped condition asked the subjects to traverse across the sloped roof section. In the current study, data were collected as the subjects traversed the roof in only one direction. Therefore, the left foot was always higher (upslope) on the roof segment and the right foot was always lower (downslope), as seen in Fig. 1. Subjects completed both conditions at a comfortable pace.

2.2.2. Spatiotemporal variables—To measure the changes in gait parameters between level and sloped roof walking, eighteen spatiotemporal variables were calculated. Sixteen of the spatiotemporal were defined by and calculated using the operational definitions provided by Hollman, McDade (Hollman et al., 2011). These variables were subdivided into categories that focused on the distances of foot placement (spatial: step length, step width, and stride length), timing in foot placement in gait (temporal: cadence, step time, stride time, stance time, and swing time), a reflection of time-based percentages in reference to the gait cycle as a whole (temporophasic: stance time per gait cycle and swing time per gait cycle), and the distance and time of the foot placement (spatiotemporal: gait speed and stride speed).

2.3. Data analysis

Comparisons in spatiotemporal gait parameters between the level and sloped condition were made using paired samples T-tests using the SPSS v25 (IBM Corp. Armonk, NY) software package. Statistical significances was set at p-values ≤0.05.

3. Results

3.1. Spatiotemporal variables

As hypothesized, traversing across a sloped roofing surface statistically changed the spatiotemporal gait characteristics of healthy adult men. Of the nineteen spatiotemporal gait parameters, sixteen were significant at $p \leq 0.001$, two were significant at $p \leq 0.05$ and one was non-significant ($p > 0.05$). Data are summarized in Figs. 2–6.

3.1.1. Spatial parameters—All four spatial parameters were significantly ($p \leq 0.001$) different between the level walking and traversing a sloped roof condition (Table 1, Fig. 2). Level step length (0.77 ± 0.06m) was significantly larger than the sloped roof walking (0.71 ± 0.06m), and level step width (0.09 ± 0.04m) was significantly larger than the sloped roof walking (0.06 ± 0.04m). Left stride length (1.55 ± 0.10m) was significantly larger than the sloped roof walking (1.42 ± 0.09m), and right stride length (1.53 ± 0.08m) was significantly larger than the sloped roof walking (1.38 ± 0.09m).

3.1.2. Temporal parameters—All but one of the six temporal parameters were significantly ($p \leq 0.001$) different between the level walking and traversing a sloped roof condition (Table 1, Figs. 3 and 6). Cadence on the level surface (105.48 ± 7.25steps/min) was significantly larger than the observed cadence on the sloped roof walking (98.80 ± 6.00steps/min). Step time on the level surface (0.57 ± 0.05s) was significantly smaller than the observed step time on the sloped roof walking (0.61 ± 0.04s). Left stride time (1.15 ± 0.06s) was significantly smaller than the left stride time during cross-sloped roof walking (1.23 ± 0.10s). Right stride time (1.14 ± 0.05s) was significantly smaller than the right stride time during cross-sloped roof walking (1.22 ± 0.07s). Left stance time (0.69 ± 0.11s) was not significantly different ($p = 0.44$) than the left stance time during cross-sloped roof walking (0.70 ± 0.12s). Right stance time (0.65 ± 0.07s) was significantly smaller than the right stance time during cross-sloped roof walking (0.54 ± 0.13s). Left swing time (0.52 ± 0.20s) was significantly smaller than the left swing time during cross-sloped roof walking (0.69 ± 0.47s). Right swing time (0.51 ± 0.12s) was significantly smaller than the right swing time during cross-sloped roof walking (0.77 ± 0.28s).

3.1.3. Temporophasic parameters—All temporophasic parameters were significantly different at ($p \leq 0.001$)—unless otherwise noted—between the level walking condition and traversing across a sloped roof condition (Table 1, Fig. 4). Left stance time as a percent of the gait cycle on the level surface (60.52 ± 12.24%) was significantly larger ($p = 0.035$) than the observed left stance time as a percent of the gait cycle on the sloped roof walking (57.20 ± 9.28%). Right stance time as a percent of the gait cycle on the level surface (57.85 ± 5.51%) was significantly larger than the observed right stance time as a percent of the gait cycle on the sloped roof walking (45.87 ± 11.93%). Left swing time as a percent of the gait cycle on the level surface (44.84 ± 18.30%) was significantly smaller ($p = 0.013$) than the observed left swing time as a percent of the gait cycle on the cross-slope roof walking (56.41 ± 38.09%). Right swing time as a percent of the gait cycle on the level surface (43.07 ± 5.40%) was significantly smaller than the observed right swing time as a percent of the gait cycle on the cross-slope roof walking (62.03 ± 27.74%).

3.1.4. Spatiotemporal parameters—All three spatiotemporal parameters were significantly different ($p \le 0.001$) between the level walking condition and the cross-slope roof walking condition (Table 1, Fig. 5). Gait speed while on the level walking condition (1.35 ± 0.10 m/s) was significantly larger than gait speed during cross-slope roof walking (1.17 ± 0.09 m/s). Left stride speed during the level walking condition (1.35 ± 0.10 m/s) was significantly larger than left stride speed during cross slope-roof walking (1.16 ± 0.09 m/s). Right stride speed during the level walking condition (1.36 ± 0.11 m/s) was significantly larger than right stride speed during cross-slope roof walking (1.14 ± 0.09 m/s).

4. Discussion

The present study was able to quantify the extent at which spatiotemporal and other gait parameters are changed when young healthy males walk cross-slope on a 6/12 pitched roofing surface. Cross-slope roof walking changed 18 of the 19 (94.7%) measured gait parameters in the current study. This was the first study to measure the difference of spatiotemporal and other gait parameters while cross-slope residential roof walking, a task commonly encountered by residential roofing workers.

All the recorded spatial variables, statistically, significantly decreased during cross-slope walking on a residential sloped roofing surface (Table 1, Fig. 2). Though the magnitudes of the statistically significant decreases appear small, they represent physiological decreases of 7.79% for step length, 33.33% for step width, 8.38% for left stride length, and 9.80% for right stride length. It has been shown that a decreased step width indicates a smaller base of support which will decrease stability and increase fall risk (Perry and Burnfield, 2010; Marone et al., 2014; Lugade et al., 2011; You et al., 2001).

Seven of the eight recorded temporal variables, statistically, significantly changed because of cross-slope walking on a 6/12 pitch residential sloped roofing surface (Table 1, Figs. 3 and 6). Unlike the spatiotemporal measures, the temporal variables increased and decreased during the roof walking. Consistent to the spatiotemporal results, the magnitudes of the decreases appear small, however they represent physiological changes of 6.33% decrease for cadence, 5.26% increase for step time, 6.95% increase for left stride time, 7.02% increase for right stride time, 16.92% decrease for right stance time, 32.69% increase for left swing time, and 49.02% increase for right swing time. Left stance time was the only recorded variable that did not show a statistically significant change but did show a biological change of 1.45% increase due to walking across the sloped residential roof segment. An increase in both upslope and downslope swing times leads to an increased single stance time. During single stance, the base of support is largely reduced, and the control needed to maintain the center of mass within the base of support is much higher (Breloff et al., 2019a; Perry and Burnfield, 2010; Marone et al., 2014; Lugade et al., 2011; You et al., 2001; Chen and

Chou, 2010; Chien et al., 2013; Hong et al., 2015). These changes all suggest that stability decreases and fall risk increased when traversing cross-slope on a residential roof.

All four of the recorded temporophasic variables statistically significantly changed because of cross-slope walking on a 6/12 pitch residential sloped roofing surface (Table 1, Fig. 4). The temporophasic showed a mix of increased and decreased biological changes. Left stance time per gait cycle decreased by 5% during cross-slope residential walking, right stance time per gait cycle decreased by 21.05%, left swing time per gait cycle increased by 27.27%, and right swing time per gait cycle increase by 44.19% during cross-slope residential roof walking. The observed temporophasic changes suggest that with the decreased stance time and the increased swing time, cross-slope residential roof walking will decrease stability due to the fact more time is spent in single support compared to double support (Perry and Burnfield, 2010).

The three recorded spatiotemporal variables all statistically significantly decreased when walking on cross-slope on a 6/12 pitched residential roof segment; Table 1, Fig. 5. Physiological decreases were 13.33% (gait speed), 14.07% (left stride speed), and 16.18% (right stride speed). A decrease in gait speed has been repeatedly associated with an increase in falling, however this is also associated with aging (Cesari et al., 2005; Hong et al., 2016). In this instance, the decrease in gait speed alone is not indicative of an increased fall risk, but coupled with all the other indicators from this study it is apparent that cross-slope walking on a residential roof increases fall risk.

When considering the results of the current study several factors must be taken into account that may have an impact on the outcomes. The sloped residential roof segment was located on the ground, rather than at an elevation typical of a residential roof. This might have negated any possible psychological effects associated with the height which could have influenced the kinematics. The floor coverings were different in each condition—level vinyl & sloped asphalt shingles—but would not likely be the cause of the changes that were observed in the current study. In the current study all subjects traversed cross-slope in the same direction on the residential roofing segment. Due to this fact, the right leg was always the upslope leg. Furthermore, it was not determined which leg was the subjects' dominant leg. Future studies could compare how dominant vs nondominant legs respond as upslope compared to the downslope leg.

5. Conclusion

The purpose of the current study was to document how spatiotemporal gait variables are altered while cross-slope walking on a 6/12 pitched residential roof. The study was able to establish that spatiotemporal gait variables significantly increase and decrease during residential cross-slope walking.

The observed changes in the spatiotemporal gait variables could lead to an increased risk for falling in residential roofers, however further research is required to confirm this theory. Based on the current study's findings, residential roofers should consider walking with a wider stance, to increase their base of support, thereby increasing their stability and reduction fall risk. It is also recommended the workers take smaller steps to minimize single stance time, this will also increase stability. The current study findings will also allow for the development of educational and training procedures with the goal of providing workers with the information and expertise needed to work safely in a sloped environment. Such training is paramount to ensure individuals working on a sloped surface avoid hazards associated with this unique environment.

6. Practical applications

The information gathered in this study can be shared with residential roofing workers and their trade organizations. Residential roofing workers, seasoned or new, need to fully understand how walking across a sloped roof alters gait. This will allow this cohort of workers to remain cognizant of their work environment and thereby hopefully reducing falling while working.

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Fig. 1.

Set up for current study. A) the 6/12 pitched roof segment, B) close up of sagittal view of subject on roof segment, and C) frontal view of subject on the roof segment.

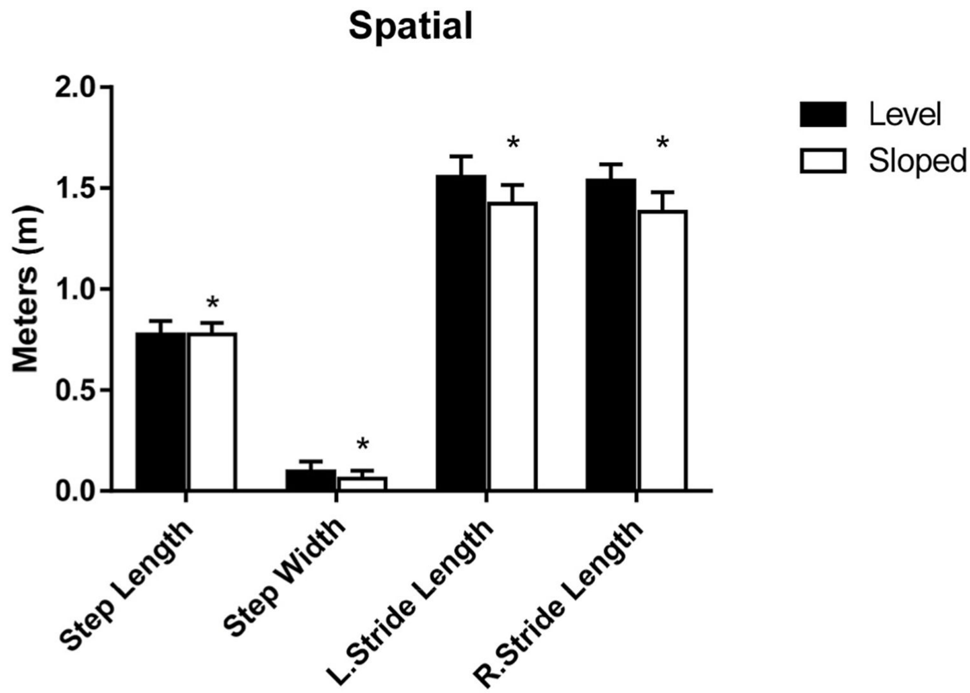

Fig. 2.

Changes in the spatial variables between level and cross-slope roof walking. * denotes statistically significant change.

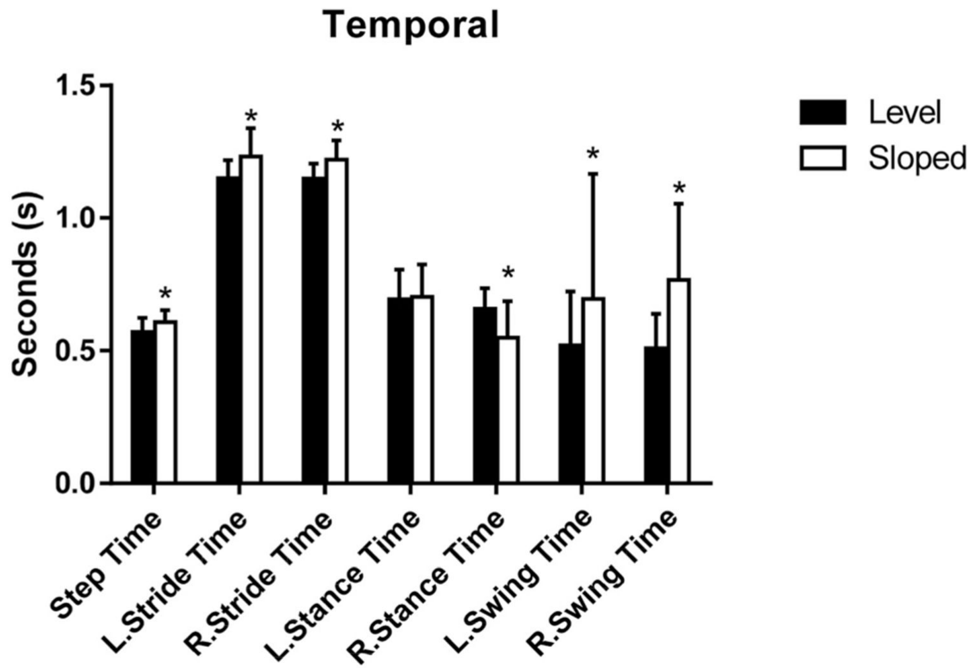

Fig. 3.
Changes in the temporal variables between level and cross-slope roof walking. * denotes statistically significant change.

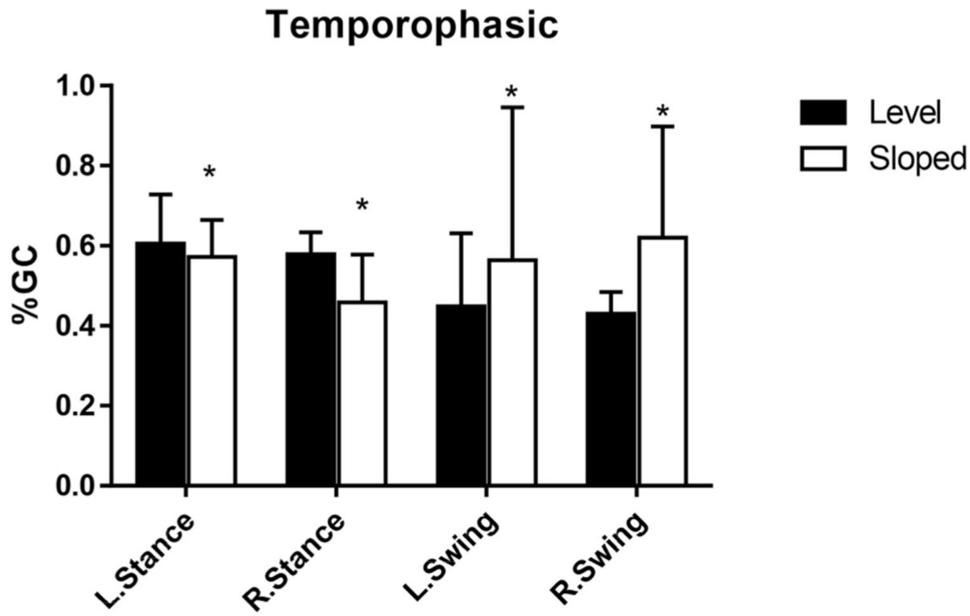

Fig. 4.
Changes in the temporophasic variables between level and cross-slope roof walking. The units of this figure are Time per Gait Cycle * denotes statistically significant change.

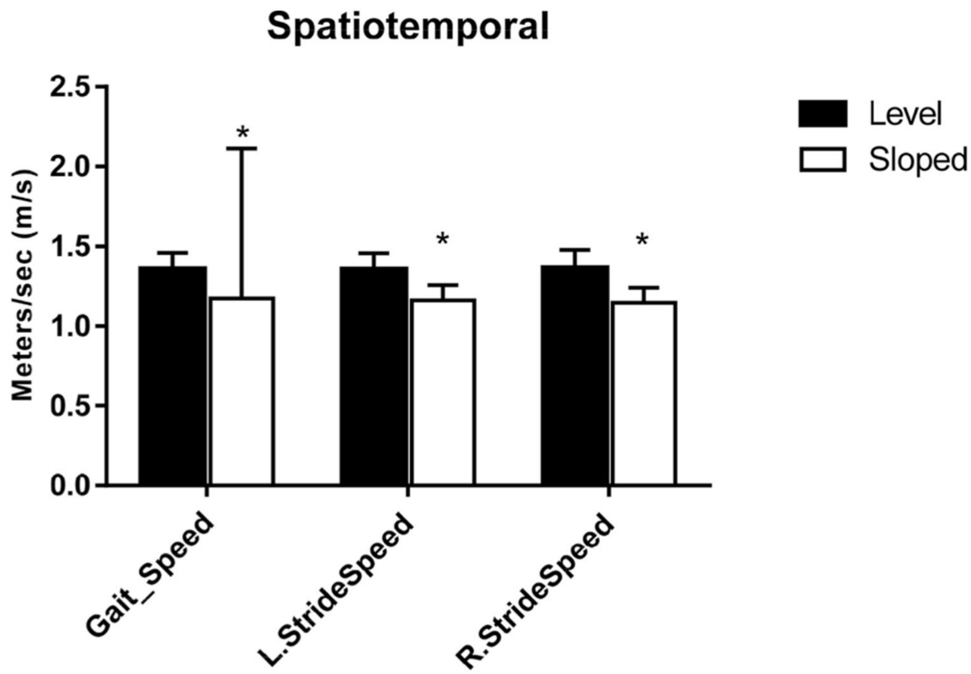

Fig. 5.

Changes in the spatiotemporal variables between level and cross-slope roof walking. * denotes statistically significant change.

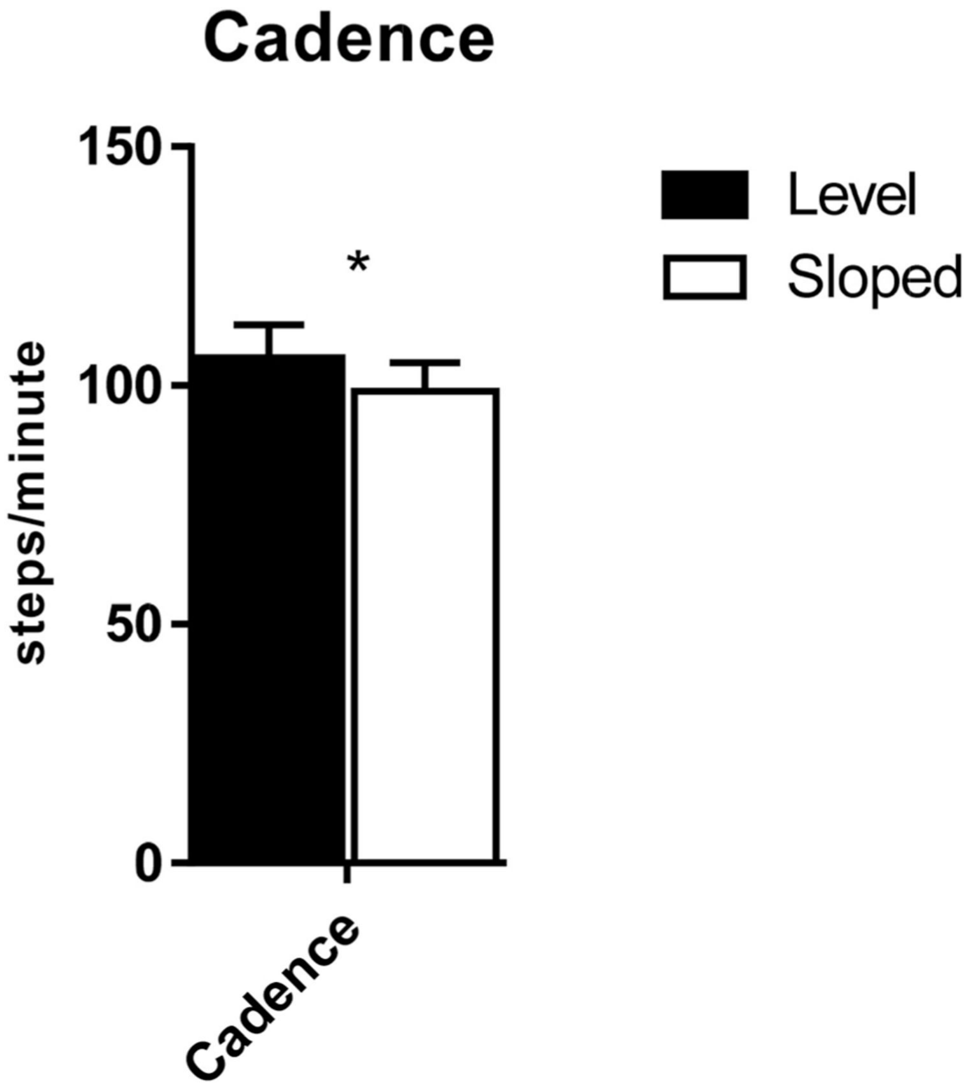

Fig. 6.

Changes in the cadence variables between level and cross-slope roof walking. * denotes statistically significant change.

Table 1

Changes in spatiotemporal variables between level surface and cross-slope roof walking.

	Level	Sloped	p-value
Spatial (m)			
Step Length	0.77 ± 0.06	0.71 ± 0.05	< **0.001**
Step Width	0.09 ± 0.04	0.06 ± 0.04	< **0.001**
L. Stride Length	1.55 ± 0.10	1.42 ± 0.09	< **0.001**
R. Stride Length	1.53 ± 0.07	1.38 ± 0.09	< **0.001**
Temporal (s)			
Cadence (steps/min)	105.48 ± 7.25	98.80 ± 6.00	< **0.001**
Step Time	0.57 ± 0.05	0.60 ± 0.04	< **0.001**
L. Stride Time	1.15 ± 0.06	1.23 ± 0.10	< **0.001**
R. Stride Time	1.14 ± 0.05	1.22 ± 0.07	< **0.001**
L. Stance Time	0.69 ± 0.11	0.70 ± 0.12	= 0.44
R. Stance Time	0.65 ± 0.078	0.54 ± 0.13	< **0.001**
L. Swing Time	0.52 ± 0.20	0.69 ± 0.47	< **0.001**
R. Swing Time	0.51 ± 0.12	0.76 ± 0.28	< **0.001**
Temporophasic (%GC)			
L. Stance Time Per Gait Cyclerowhead	60 ± 12	57 ± 9	= 0.035
R. Stance Time Per Gait Cycle	57 ± 5	45 ± 11	< **0.001**
L. Swing Time Per Gait Cycle	44 ± 18	56 ± 38	**= 0.013**
R. Swing Time Per Gait Cycle	43 ± 05	62 ± 27	< **0.001**
Spatiotemporal (m/s)			
Gait Speed	1.35 ± 0.10	1.17 ± 0.94	< **0.001**
L. Stride Speed	1.35 ± 0.10	1.16 ± 0.09	< **0.001**
R. Stride Speed	1.36 ± 0.11	1.14 ± 0.09	< **0.001**