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Inclination angles during cross-slope roof walking

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Abstract

Residential roofers have the highest rate of falls in the construction sector with injuries and fatalities costing billions of dollars annually. The sloped roof surface is the most predominant component within the residential roof work environment. Postural stability on a sloped work environment is not well studied. Calculating inclination angles (IAs) using the lateral ankle marker could be a quality measure to determine how cross-slope roof walking will influence stability.

Will cross-slope roof-walking effect anterior-posterior (AP) and medial–lateral (ML) IAs in adult males?

Eleven adult males participated in two testing sessions—level and cross-slope roof gait session on a 6/12 pitched roof segment. Changes in AP and ML IAs between conditions were compared at: heel strike (HS) and toe off (TO). Legs were analyzed separately due to the cross-slope walking. The left foot was ‘higher’ on the sloped roof and the right was ‘lower.’

Significant increases ($p \leq 0.006$) in IAs were observed due to the sloped roof in all conditions except the AP ‘lower’ leg ($p = 0.136$).

Increases in IA suggest a decrease in postural stability as the body will result in greater sway compared to a natural posture. Increases in AP IAs may cause slipping in the anterior or posterior direction as the normal force will decrease during HS and TO. In the ML direction, fall risk is increased and more stress is placed on the hip abductors in order to reduce falling. Thus traversing a sloped roof surface reduces stability of healthy workers and escalates injury/fall risk factors.

Keywords

Gait; Center of mass-lateral ankle inclination angle; Sloped roof surface; Residential roofing; Construction

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6.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.

1. Introduction

Residential roofers not only encounter uneven or sloped roof surfaces, but need to traverse across the sloped roof surface. Due to the uniqueness of this environment and the amount of time on it, roofers in the United States experienced 874 out of the 2013 (43%) fatal falls in the construction sector between 2011 and 2017 (CPWR, 2019). Furthermore, United States roof workers had the highest risk of fatal falls with 35.9 deaths per 100,000 full time employees (FTEs), which was ten times greater than the rate of all construction United States occupations combined (CPWR, 2019). In addition to traumatic injuries, residential roofers also experience the second highest rate of musculoskeletal injuries within the construction sector. Given that roofers have such large repeated and traumatic injury risk, and it has been shown that changes in lower extremity dynamics, posture and gait variability have all been linked to increased risk for falling (Perry and Burnfield, 2010), the association of cross-slope roof walking and its influence on musculoskeletal function in gait and posture merits further study.

Two categories of general slope walking have been studied in the past—upslope/downslope is better documented and to a lesser extent cross-slope walking. Upslope and downslope walking involves the individuals walking up and down an inclined surface. Cross-slope roof gait is defined as walking perpendicular to the slope—i.e. parallel to the ridge of the roof—with one foot higher and one foot lower on the sloped roof (Breloff et al., 2019; Andres et al., 2005). Both classifications of sloped gait induce biomechanical changes in gait as compared to level walking (Breloff et al., 2019; Damavandi et al., 2010, 2012; Dixon and Pearsall, 2010; Dixon, 2011; McVay and Redfern, 1994; Redfern and DiPasquale, 1997). Walking either on an upslope or downslope surface will induce changes in gait characteristics (Sun, 1996), kinematics (Redfern and DiPasquale, 1997; Lay et al., 2006; Leroux et al., 2002; Lange, 1996; Kuster et al., 1995), kinetics (Redfern and DiPasquale, 1997; Kuster et al., 1995; Gazlay, 2005; Alexander and Schwameder, 2016), muscle function (Lange, 1996; Pickle, 2016; Lay, 2007), and mechanical work (Kuster et al., 1995; Alexander, 2017), while traversing cross-slope will change walking gait kinematics (Dixon and Pearsall, 2010; Wannop, 2014; Breloff et al., 2019; Andres et al., 2005; Damavandi et al., 2010), kinetics, (Dixon and Pearsall, 2010; Wannop, 2014) and running dynamics (Damavandi et al., 2012; Dixon, 2011; Willwacher, 2013). Additionally, upslope/downslope walking provokes a greater risk for falling than walking on stairs of similar angles (Sheehan and Gottschall, 2012).

As it has been shown that the introduction of a sloped surface changes many biomechanical measures and sloped walking prompts greater fall risks, it is important to further investigate in what way walking across a sloped roof surface influences dynamic walking stability. One particular measure to quantify stability would be the center of mass (CoM), as the CoM during locomotion has been described as the result of all forces and motion acting on the body segments (Saunders et al., 1953). A common measure of sway and instability during gait—which uses the CoM—is an inclination angle (IA). Traditionally, an IA is the angle formed by two vectors: the first vector is formed from the center of pressure (CoP) or lateral ankle marker to the CoM, while the second vector is formed from a vertical line through the CoP or lateral ankle marker (Chen and Chou, 2010; Lee and Chou, 2006). Though IAs have primarily been used as a clinical measure of instability during various gait conditions such as aging (Chen and Chou, 2010; Lee and Chou, 2006; Hsu, 2010; Hong, 2015; Silsupadol, 2009; Huang, 2008), obstacle crossing (Lee and Chou, 2006; Huang, 2008; Chou, 2001, 2004; Chou and Draganich, 1997), high heels (Chien et al., 2013), and uphill walking (Hong, 2015), this metric can provide useful stability information regarding gait related changes induced in individuals who are exposed to a sloped roofing surface. However, the traditional approach to IAs is not useful in an active residential roofing environment. It is impossible to record force plate data, which is necessary to record the CoP during gait. However, a new method for IA calculation does away with the need for force plate data (Chen and Chou, 2010) and therefore could be used to measure stability of actual construction workers in a sloped roofing environment. IAs will allow for a more in-depth investigation into dynamic walking stability during cross-slope roof walking.

The focus of the study will explore how two probable injury risks are potentially exacerbated when individuals traverse across a sloped roof surface. The first—and maybe most obvious—is that of instability and fall risk, the second—and less obvious—is that of musculoskeletal injury risk. Fall risk in healthy adults has been linked to increase sway of the CoM, in non-level gait conditions (Chou, 2001, 2004, 2007; Chou and Draganich, 1997; Hahn and Chou, 2003, 2004). While it is difficult to definitively link changes in biomechanics to musculoskeletal disorder (MSD) risk, there are several broadly accepted factors that are associated with MSD risk (CCOHS, 2014). Walking on a sloped surface presents extreme postures that are not commonly encountered in level surface gait (Breloff et al., 2019). Increase in sway is an extreme posture and has shown higher forces in lower extremity gait parameters (Lee and Chou, 2006; Hahn and Chou, 2004; Mandeville et al., 2007). Therefore utilizing the IA measure onto a sloped roof surface will not only uncover new and interesting information during cross-slope roof walking, but potentially offer a reliable and precise method which can be combined with validated clinical measures and deployed in an active residential roof work environment.

The current study reports on the extent which IAs—using a new validated method not requiring force plates—in the anterior/posterior (AP) and medial/lateral (ML) directions—are altered when individuals are first on and traverse across a sloped roof surface. The purpose of this study is to determine in what way navigating across a sloped roof surface alters AP and ML IAs compared to level walking. It is hypothesized that the introduction of a sloped roof surface will provoke an increase in the AP and ML IAs compared to level walking in young male subjects.

2. Methods

Healthy male subjects were recruited between the ages of 18 and 24 years. Eleven male subjects (19.1 ± 1.49 yrs, 81.15 ± 15.14 kg, and 180.73 ± 5.89 cm) who were considered inexperienced walking on sloped roof surfaces participated in the study. Inexperienced subjects were recruited to measure the change in IA 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 the roofer work population are male as reported by the Bureau of Labor Statistics (BLS, 2018). Subjects did not report any history or clinical evidence of neurological, musculoskeletal or other medical conditions affecting 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. All subjects reviewed and signed the University of Mississippi Institutional Review Board approved informed subject consent forms.

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 ten-meter vinyl covered walk-way. The sloped condition used a 2.43 m wide × 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 roof was covered with asphalt shingles and this roof covering system was used in 47% of new construction and 59% of reroofing in 2015–2016 (NRC Association, 2016). The difference between surface coverings (i.e. flat vinyl and slope shingles) is not expected to alter the results (Svensson, et al., 2018). Kinematic data were collected as the subjects traversed across (or cross-slope gait) the sloped roof surface. A residential roof is considered walkable until an angle of 33°; 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 10 trials of both conditions at a comfortable self-selected walking pace. Self-selected speeds were different between the level and slope conditions ($P < 0.05$). However, it has been reported that gait speed only effect AP HS IA's and that individuals with pathologies still exhibited larger IA's when gait speed was controlled between healthy controls and patients (Lee and Chou, 2006). The level condition required the subjects to walk across the ten-meter walkway; while the sloped condition asked the subjects to traverse across the 2.43 m wide × 7.32 m long sloped roof section. By traversing the roof section, one foot was higher on the slope (upslope) and one foot was lower on the slope (downslope), as seen in Fig. 1. Due to this distinction, gait symmetry was not assumed in the cross-slope conditions, and in the current testing procedure, the left leg was always higher on the slope with the right leg always lower on the slope. Therefore during the level walking condition, the left leg was named *upslope level* and while the subjects were on the sloped condition, the left leg was called *upslope*. The right leg was labeled *downslope level* while the subjects walked on the level condition and during the sloped roof condition, the right leg was named *downslope*. Comparisons in IA were then constrained to identifying differences in IAs in the same side of the body (e.g. upslope level compared to upslope). Furthermore, the IAs for each leg were calculated at heel strike (HS) and toe off (TO). These points within the gait cycle were chosen as they are easily identifiable between and within subjects to ensure the IA comparisons were at the same time point.

Kinematics were recorded for ten trials from each condition using a Vicon 612 system at 120 Hz. Subjects were allowed no acclimation time on the sloped surface, and kinematic data were collected immediately after the subjects stepped onto the roof surface. This was done to capture the kinematic change that occurs when individuals are first introduced to a sloped surface, akin to the situation when an individual first ascends a roof. A check of the data revealed there were no differences between the IA in the first trial and the IA in the tenth trial in both conditions. Marker trajectories—referenced to the same global coordinate system for both conditions—were filtered with a 4th order Butterworth filter with an 8 Hz cutoff frequency. Three-dimensional full body CoM positions were calculated in the Nexus software (Vicon Inc., Oxford, UK) using a 13 segment weighted average method (Winter, 2009).

After the ten trials, HS and TO were identified from the kinematic data within the capture volume. HS and TO were determined using the vertical foot velocity (Lugade et al., 2011). Using this method and coupled with the size of the roof segment, on average three bilateral HS and TO were recorded for each trial. The outcome measures were compared at these definable gait events. Outcome measures for this study were AP and ML IAs. Commonly, IAs were defined by Lee and Chou (Lee and Chou, 2006) for level gait as an angle formed by the intersection of the line connecting the CoP and CoM with a vertical line through the CoP (Lee and Chou, 2006). However, Chen and Chou (Chen and Chou, 2010) showed the use of the lateral ankle marker in lieu of the CoP can provide useable IA information (Chen and Chou, 2010) (Fig. 2). The lateral ankle marker approach is more advantageous in a work environment where embedding force plates into the waking surface is not practical. A custom MATLAB program (Mathworks, Natick, MA, USA) imported the CoM and lateral ankle marker data from Nexus and calculated the IAs for both the level and sloped conditions.

Differences between the level and sloped roof walking IAs were compared using repeated measures analysis of variance (ANOVA). Mauchly's Test of Sphericity was used to determine the sphericity of the data. If Mauchly's Test showed the data were spherical, then no correction was needed. If Mauchly's Test indicated sphericity was violated, the Greenhouse-Geisser correction was used if epsilon was less than 0.75 and if epsilon was greater than 0.75 the Huyhn-Feldt correction was used to determine significance. Data analysis was completed using SPSS v24 and p-values < 0.05 were considered significant.

3. Results

As hypothesized, walking cross-slope on a roof surface altered AP and ML IAs during heel strike and toe off compared to level surface walking. Of the eight outcome variables analyzed in the current study, seven—or approximately 88%—of these variables were significantly changed with the introduction of the sloped surface. The results comparing cross-slope (upslope and downslope) walking IAs with level walking IAs are summarized in Table 1 and Fig. 3.

3.1. Anterior-Posterior inclination angles

Level surface downslope leg IA at heel strike (18.34° ± 1.47°) was not significantly different than slope surface downslope leg IA at HS (19.21° ± 2.86°), p = 0.136; 95% confidence interval of the difference (CI) [−2.01, 0.28]. Level surface downslope leg inclination angle at toe off (−29.02° ± 2.02°) was significantly smaller than slope surface downslope leg IA at TO (−32.11° ± 1.80°), $p < 0.001$; 95% CI [2.22, 3.96]. Level surface upslope leg inclination angle at heel strike (18.01° ± 0.84°) was significantly smaller than slope surface upslope leg IA at HS (18.88° ± 1.77°), $p = 0.002$; 95% CI [−1.41, −0.33]. Level surface upslope leg IA at TO (−28.83° ± 1.14°) was significantly smaller than slope surface upslope leg IA at TO (−31.56° ± 1.77°), $p < 0.001$; 95% CI [2.12, 3.34].

3.2. Medial-lateral inclination angles

Level surface downslope leg IA at heel strike (9.38° ± 0.71°) was significantly smaller than slope surface downslope leg IA at HS (30.11° ± 1.59°), $p < 0.001$; 95% CI [−21.35, −20.08]. Level surface downslope leg IA at toe off (11.00° ± 0.83°) was significantly smaller than slope surface downslope leg IA at TO (34.26° ± 1.55°), $p < 0.001$; 95% CI [−23.86, −22.68]. Level surface upslope leg IA at heel strike (−9.25° ± 0.71°) was significantly different than slope surface upslope leg IA at HS (17.22° ± 1.49°), $p < 0.001$; 95% CI [−26.72, −26.04]. Level surface upslope leg IA at TO (−11.28° ± 1.64°) was significantly different than slope surface upslope leg IA at TO (17.97° ± 1.97°), $p < 0.001$; 95% CI [−30.01, −28.49].

4. Discussion

In the current study, it was determined by what extent cross-slope roof walking alters both AP and ML CoM-lateral ankle IAs at HS and TO compared to level walking. Overall, cross-slope walking on a 26° roof significantly altered 88% (or 7 out of 8) of the calculated IAs compared to a level self-selected pace walking. This study was the first to quantify the changes in CoM-lateral ankle IAs induced by a steep cross-slope roof walking on a roof which is commonly encountered by residential roofers.

Originally the IA method used in this paper was developed as a clinical tool to alleviate the burden of requiring pathologic and elderly subjects to consistently strike the force plate to allow for CoP calculation (Chen and Chou, 2010). Our level surface calculated IAs closely agreed with three (AP HS, ML HS and ML TO) of the four IAs reported originally by Chen and Chou (Chen and Chou, 2010) and with the ML IAs reported by Xu, Wang (Xu, 2017). The difference in the AP TO IAs may be associated with the difference in age of the subjects reported by Chen and Chou (2010) as the average age of the subjects was 77 years compared to 19 years in the current study. It is well known that healthy young adults walk faster with longer strides compared to elderly individuals (Perry and Burnfield, 2010; Houglum and Bertoti, 2011; Mbourou et al., 2003; Prince, 1997). Due to this, the CoM will be further away from the ankle marker at TO, thus providing the observed difference in AP IA at TO compared to the older subjects as was also mentioned by Lee and Chou (2006).

Three of the four (downslope TO, upslope HS, and upslope TO) AP IAs all significantly increased while traversing across a sloped surface. The fourth calculated AP IA (downslope HS) displayed an evident trend toward a significant change while traversing across a sloped surface. The increases in AP IAs from a level surface to a slope surface suggest that while traversing across a sloped surface, individuals are more likely to slip. Just after heel strike is considered to be the most dangerous stage for slipping as the weight of the body is transferred to the foot and if the forward slide of the foot cannot be controlled, the result will be a fall (You, 2001; Grönqvist, 1989; Redfern, 2001). Furthermore, forward direction shear force during HS is considered to be highly co-dependent with slipping (Redfern, 2001). The increased AP IA at HS will make recovery from a slide all the more difficult as it is necessary for the CoM to move ahead of the base of support in order to accomplish and preserve dynamic stability (Perry and Burnfield, 2010). Redfern, Cham (Redfern, 2001) suggest that a slip would be more likely to occur in the posterior direction during late stance as the body is being elevated due to the posterior shear force and the changes in the required coefficient of friction (Redfern, 2001). An increase in AP IA during the TO phase might well exacerbate this chance of a posterior slip. Though younger individuals tend to recover from slips (Moyer, 2006; Chambers and Cham, 2007), slips on ramps are a potential problem due to the higher shear forces (McVay and Redfern, 1994; Redfern and DiPasquale, 1997) thus making it even more difficult to recover from an otherwise recoverable slip. Additionally, should a slip lead to a fall on a sloped roof surface, the potential for sliding off the roof and suffering a fall from height is large.

In all instances of HS and TO, the IAs in the ML direction changed significantly compared to level surface walking and excessive ML IAs during gait may lead to the loss of balance (Lee and Chou, 2006). The ML IA has been used in the past as an important parameter to distinguish elderly and knee replacement patients with imbalance and elderly persons who are more likely to fall have larger ML IAs (Lee and Chou, 2006; Chou, 2001; Hahn and Chou, 2003; Mandeville et al., 2007). The young healthy participants in the current study all exceeded what would be considered healthy ranges of ML IAs while traversing the sloped surfaces (Lee and Chou, 2006; Chou, 2001; Hahn and Chou, 2004). This suggests that the musculature surrounding the hip joint that is responsible for controlling stability in the frontal plane must exert much more force to prevent the body from falling. In addition to an increased risk of falling, this increase in frontal plane muscle activity can potentiality lead to other issues such as faster fatigue or muscle strain and increased MSD risk, however future testing needs to be conducted to substantiate these speculations. Thus the results from this study suggest that individuals are at a much higher likelihood to fall while traversing across a 26° sloped surface before any other external factors (environment and material handling) are considered. Unlike in elderly, where a fall may only lead to a fractured hip, roofers are at a risk for much more serious injury due to a fall from a large height while on a roof (Wei et al., 2001; BLS, 2016, 2017).

A limitation of the current study was all subjects walked the same direction on the slope. Therefore, the left 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. Another limitation might have been the high boots the participants wore in the study. The high boots, though more common in a work environment—as we tried to mimic a work situation—covered the malleoli which could reduce the accuracy of the lower extremity ankle kinematics. Additionally, though in theory boots are generally accepted as the best option for roofing work, in practice roofing workers choose many different types of footwear to complete their tasks. Future studies will need to investigate what effect footwear choice has on the health and safety of the roofing worker.

Furthermore, one of the most difficult aspects to workplace safety research is testing in an active work environment during authentic work. Many factors contribute to this difficulty, such as; slowing down productivity, willing participants, and technology that does not interfere with the work. While the first two are difficult to overcome, advancement in technology is allowing for within environment testing to be more possible. Retro-reflective motion capture systems now have the capability to record data outside which will increase the chances of recording human motion in active construction environments. Though the current study is laboratory based, it can provide a proof of concept that validated clinical measures combined with new technology can provide a real-world look into construction health and safety concerns. Additionally, roofing takes place outdoors, future studies will need to include environmental factors such as, heat, cold, wet and frozen conditions. Finally, the roof segment was located on the ground, rather than at an elevation typical of a roof. This change might have negated any possible psychological effects associated with the height which could have influenced the kinematics.

5. Conclusion

The purpose of this study was to determine if dynamic stability during walking is altered while an individual traverses across a 26° sloped roof surface as compared to a level surface. The data in the current study suggest that this is the case, and slip and fall risk is amplified given the increased instability while traversing across a sloped roof surface, given the increase of IAs in both the sagittal and frontal plane during heel-strike and toe-off. While this research was conducted in the United States and focused on a 26° sloped roof surface, the results can be generalized to any country in the world where workers need to traverse a sloped roof surface. Individuals who work in this type of environment must be vigilant to the changes in gait that are experienced prior to any other external factors such as the weather and/or material handling. In addition to the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration’s (OSHA) recommendations to use fall protection while working on a sloped roof surface, educational and training materials can be created from the current study results which can inform an individual who works in this environment the changes to walking that occurs and teach them how to reduce the injury risk. Furthermore, this study shows the potential for health and safety researchers to consider recording highly accurate data in an active outdoor construction site using validated clinical measures for balance in order to better understand human movement during residential roof work.

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Fig. 1.
(A) Sagittal view of subject traversing the roof segment. (B) Frontal plane anterior view of subject traversing the roof segment. (C) A posterior frontal plane rendering of a subject traversing across the 26° roof surface. The left foot was the upslope foot and right was downslope.

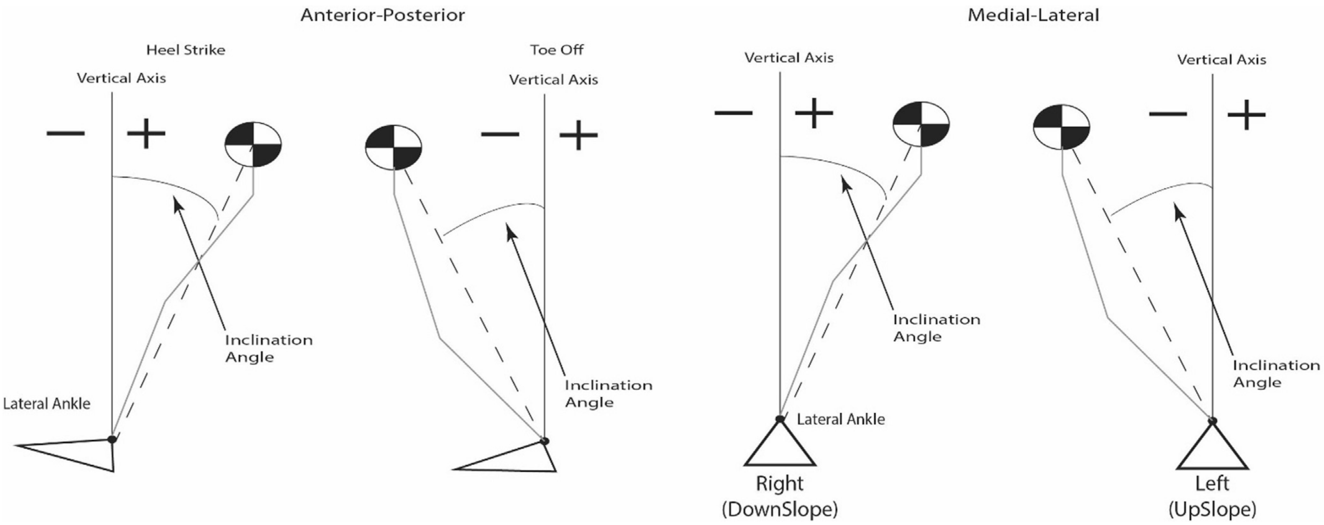

Fig. 2.

Center of mass – lateral ankle inclination angles in the sagittal and frontal plane. Solid black vertical line is vector created from the lateral ankle marker. The gray dotted line is the vector connecting the lateral ankle marker to the CoM. The IA is represented by a solid back curved line. Positive and negative values for IAs are indicated.

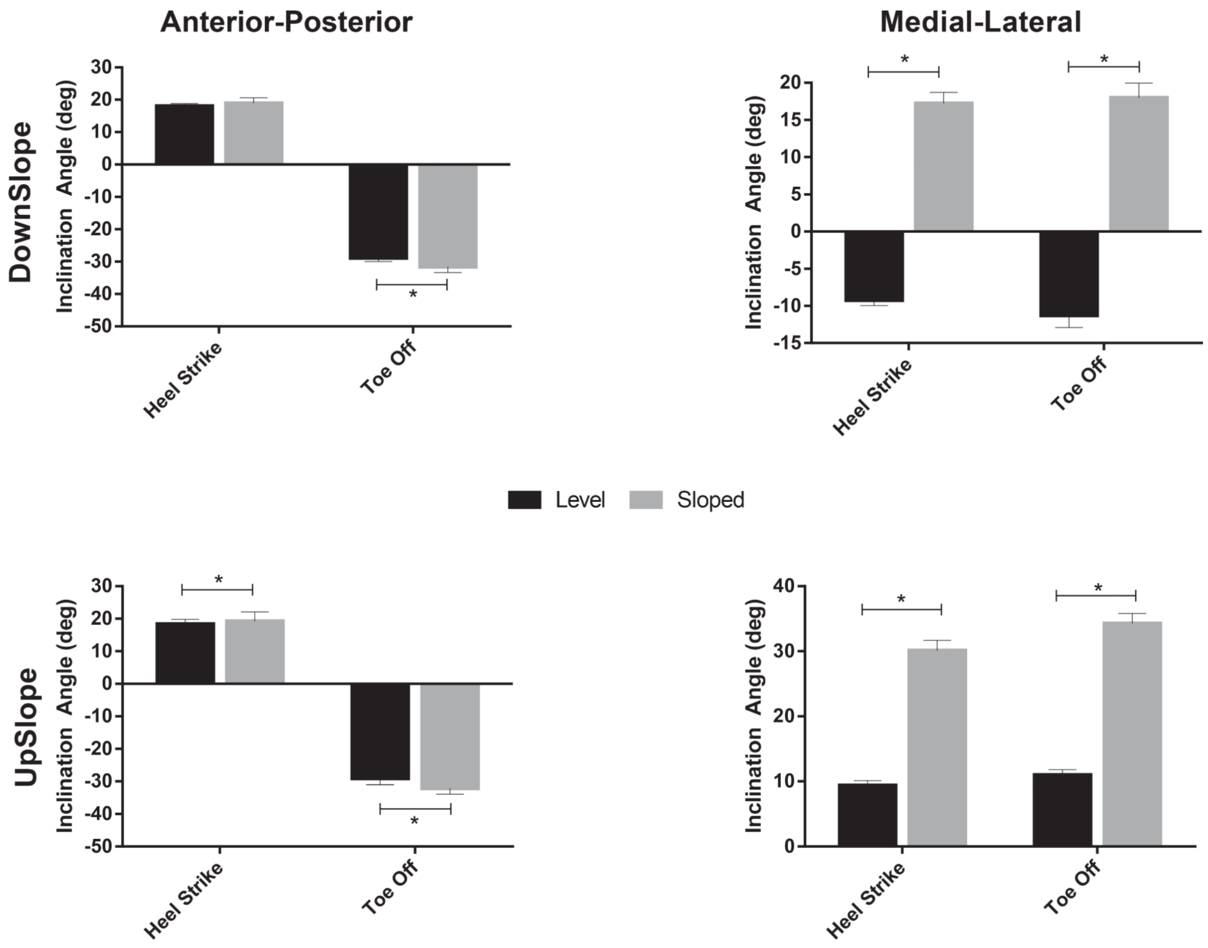

Fig. 3.

Anterior-posterior and medial-lateral inclination angle results at heel-strike and toe-off.

Table 1

Changes in inclination angles at heel strike and toe off between level and sloped surfaces. Bold font indicates statistically significant changes between conditions.

		DownSlope						UpSlope					
Inclination Angle (deg)		**Level**	**Sloped**	**Mean Difference**	**95% Confidence Interval of the Difference**		**p-value**	**Level**	**Sloped**	**Mean Difference**	**95% Confidence Interval of the Difference**		**p-value**
					Lower	**Upper**					**Lower**	**Upper**	
AP	Heel Stike	18.34 ± 1.47	19.21 ± 2.86	−0.862	−2.01	0.28	0.136	18.01 ± 0.84	18.88 ± 1.77	−0.871	−1.41	−0.33	**0.002**
	Toe Off	−29.02 ± 2.02	−32.11 ± 1.80	3.09	2.22	3.96	**<0.001**	−28.83 ± 1.14	−31.56 ± 1.77	2.73	2.12	3.34	**<0.001**
ML	Heel Stike	9.38 ± 0.71	30.11 ± 1.59	−20.72	−21.35	−20.08	**<0.001**	−9.25 ± 0.71	17.22 ± 1.49	−26.47	−26.90	−26.04	**<0.001**
	Toe Off	11.00 ± 0.83	34.26 ± 1.55	−23.27	−23.86	−22.68	**<0.001**	−11.28 ± 1.64	17.97 ± 1.97	−29.25	−30.01	−28.49	**<0.001**