

Lateral Ankle-Center of Mass Inclination Angles as a Measure of Dynamic Postural Instability while Cross-Slope Roof Walking

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Abstract: Roofers suffer from the highest incidence of falls in the construction sector with injuries and fatalities costing billions of dollars each year. While several factors (weather, work experience, material handling) could contribute to this high rate of injury in residential roofers, the sloped surface of the roof is the most prevalent and unique component within the residential roofer work environment. Therefore, it is imperative to investigate how walking on a sloped surface contributes to the high rate of falling observed in the residential roofer community. One common variable to explore is stability. Stability has been very well defined on level surfaces and with aging and pathologic populations, but to date, stability on a sloped work environment is not well studied. Inclination angles (IA) have been used previously to quantify stability of aging and individuals with gait related pathologies populations, and will be a quality measure to determine how the addition of a slope will influence walking stability. Eleven healthy adults participated in the study. Kinematic data were recorded during a level-walking and a cross-slope gait session on a 6/12 pitched roof segment. Anterior-posterior (AP) and medial-lateral (ML) IAs were calculated during the entire gait cycle, however changes between level and sloped conditions were compared at defined gait events (heel strike (HS) and toe off (TO)). Legs were also analyzed separately because of the cross-slope walking. The left foot was 'higher' on the slope and the right was 'lower.' Significant increases ($p \leq 0.00625$) in IAs were observed due to the slope in all conditions except the AP 'lower' leg ($p=0.136$). An increase in IA suggests a decrease in stability as the body will sway further away from a neutral posture. In the AP direction, an increase in IA may cause slipping in the anterior or posterior direction as the normal force will be decreased during HS and TO, thereby increasing the shear. In the ML direction, fall risk is increased and more stress is placed on the hip abductors to reduce falling. In conclusion, traversing a sloped surface greatly reduces stability of healthy workers and thus escalates injury risk factors.

Keywords: Inclination Angles, Sloped Roof, Stability, Falling

1. Introduction

Residential roofers not only encounter uneven or sloped surfaces, but need to traverse across the sloped surface. Due to the uniqueness of this environment and the amount of time engaged with it, residential roofers experienced 1,533 fatal falls between 2011 and 2015 and approximately 33% of those falls were from roofs [1]. 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 [2], the association of cross-slope walking and its influence on musculoskeletal function in gait and posture merits further study.

The current study used inclination angle (IA) as the instability measure. 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 [3,4]. Though IAs have primarily been used as a clinical measure of instability during various gait conditions [3-12], this metric can provide useful information regarding gait related changes induced in individuals who are exposed to a sloped/non-level surface.

The focus of the study explores how two probable injury risks are potentially exacerbated when individuals traverse a sloped surface. The first is instability and fall risk, and the second is that of musculoskeletal injury risk. Fall risk in healthy adults has been linked to increased sway of the CoM, particularly during obstacle crossing [9-11,13-15]. 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 [16].

The current study reports on the extent which IAs—in the anterior/posterior (AP) and medial/lateral (ML) directions—are altered when individuals are first on and traverse across a sloped 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 surface will induce an increase in the AP and ML IAs compared to level walking in young male subjects.

2. Methods

Eleven male subjects who were inexperienced walking on sloped surfaces participated in the study. All subjects were male as 97% of roofers are male [17]. Subjects completed two separate testing sessions on different days, at least a week apart: level surface (first visit) and sloped surface (second visit). Due to the complexity and time requirements to install the sloped surface, the testing sessions were not randomized. The sloped condition used a 2.43m wide x 7.32m long section of 15.24cm/30.48cm pitch (26°) shingled sloped surface, which was attached to the laboratory floor. Kinematic data were collected as the subjects traversed across the sloped surface (cross-slope). A residential roof is considered walkable until an angle of 33°; therefore the 26° angle was chosen as a steeper walkable roof, but not to induce any greater risk than normal activities [18]. The subjects completed both conditions at a comfortable self-selected walking pace. The level condition required the subjects to walk across a ten meter walkway; while the sloped condition asked the subjects to traverse across the 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).

Kinematics were recorded for ten trials from each condition using a Vicon 612 system at 120Hz. Subjects were allowed no acclimation time on the sloped surface, and data were collected immediately after the subjects stepped onto the roof surface. This was done to capture the changes that occurs when individuals are first introduced to a sloped surface, akin to the situation when an individual first ascends a roof.

After the ten trials, heel strikes (HS) and toe offs (TO) were identified from the kinematic data within the capture volume. HS and TO were determined using the vertical foot velocity [19]. 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, Chou⁴ as an angle formed by the intersection of the line connecting the CoP and CoM with a vertical line through the CoP [4]. However, Chen, Chou³ showed the use of the lateral ankle marker in lieu of the CoP can provide useable IA information [3]; Figure 1. The lateral ankle marker approach is more advantageous in a work environment where embedding force plates into the working surface is not practical. A MATLAB program imported the CoM and lateral ankle marker data calculated the IAs for both the level and sloped conditions.

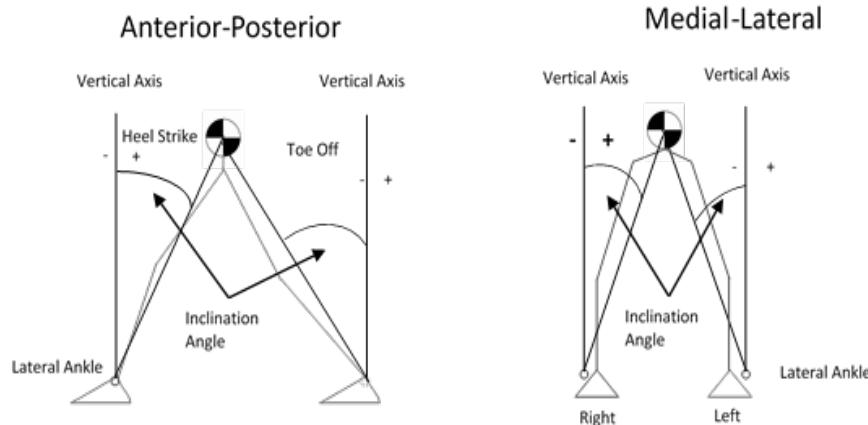


Figure 1. Center of mass – lateral ankle inclination angles in the sagittal and frontal plane.

3. Results

As hypothesized, walking cross-slope on a sloped roofing surface extensively 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. A summary of the data is presented in Figure 2.

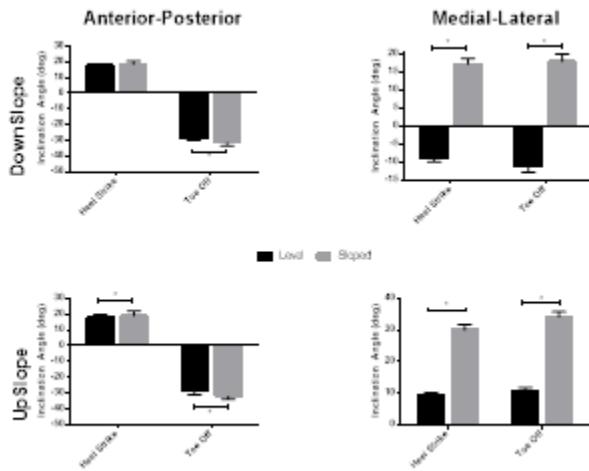


Figure 2. Anterior-posterior and medial-lateral inclination angle results at heel-strike and toe-off.

4. Discussion

This study was the first to quantify the changes in CoM-lateral ankle IAs induced by cross-slope walking on a roof which is commonly encountered by residential roofers. Overall, cross-slope walking on a 26^0 roof significantly altered 88% of the calculated IAs compared to a level self-selected pace walking.

The increases in AP IAs from a level surface to a sloped surface suggest that while traversing across a sloped surface, individuals are more likely to slip in the AP direction. 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 [20-22]. Furthermore, forward direction shear force during HS is considered to be highly co-dependent with slipping [22]. 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 [2]. It has been suggested 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 [22]. 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 more often than older individuals [23,24], slips on a sloped surface ramps are a potential problem due to the higher shear forces [25,26] 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 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 [4]. 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 [4,9,15,27]. The young healthy participants in the current study all exceeded what would be considered healthy ranges of ML IAs while traversing the sloped surfaces [4,9,14]. 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 potentially lead to other issues such as faster fatigue or muscle strain and increased MSD risk. 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 [28-30].

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. Another limitation might have been the high boots the participants wore in the study. The high boots, covered the malleoli which could reduce the accuracy of the lower extremity ankle kinematics, particularly in the transverse plane. 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 compromised while an individual traverses across a 26° sloped roofing surface. The data in the current study strongly suggest that this is the case, and slip and fall risk is much higher while traversing across a sloped surface, given the increase of IAs in both the sagittal and frontal plane during heel-strike and toe-off. 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. 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.

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.

6. References

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