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Lower extremity kinematics of cross-slope roof walking

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ABSTRACT

Working conditions of residential roofers expose them to a unique sloped environment. The purpose of this study is to determine in what way traversing across a sloped/roof surface alters lower extremity kinematics of the upslope and downslope legs compared to level walking. College aged males negotiated across a pitched (26 degrees) roof segment during which lower extremity three-dimensional kinematics were calculated. One foot was higher on the slope and one was lower for the duration of cross slope walking. Overall, cross-slope walking on a 26 degree roof significantly altered 77% of the measured lower extremity variables compared to level self-selected pace walking. The data suggest that roof pitch incite significant differences in crossslope walking of the kinematics in the lower extremity between the upslope and down slope limbs when compared to level surface walking. These alterations could temporarily alter proprioception which may in turn lead to increased falls and musculoskeletal injury, though further study is needed.

1. Introduction

Since 2011, 173 per 10,000 workers in the construction industry experienced non-fatal falls to a lower level (BLS, 2016a). Additionally, most fatal falls (81%) were falls to a lower level, and 40% of those fatal falls were from 15 feet or less. In the private construction industry, falls from height to a lower level were responsible for almost 40% of all deaths (BLS, 2016a). In addition to falls, roofers have the second highest incident rate of work—related musculoskeletal disorders (MSDs) in all construction sectors (BLS, 2013). Most of these MSDs are in the lower back and lower extremity (Holmström and Engholm, 2003). When roofers are burdened with MSDs they face work limitation, missed work, and/or reduced physical functioning, leading to premature departure from the workforce (Welch et al., 2008, 2009). Due to the fact roofers have such high injury risk and it has been shown that changes in lower extremity kinematics, posture and gait variability have all been linked to increased risk for falling (Perry and Burnfield, 2010), the association of cross-slope walking and its influence on gait merits further study.

Additionally, the demand for roofers is increasing, in 2015 there were roughly 140,000 roofers and in 2016 there were 146,000 (BLS, 2015, 2016b). The BLS also estimates that between 2016 and 2026 the job growth is at 11% suggesting that by 2026 there could be over 162,000 roofers (BLS, 2016a). Furthermore, over 90% of roofers work on residential projects, which usually have steeper roof surfaces which range as low as 10°, but can be as steep as 45° (BLS, 2015). According to Liberty Mutual 2018 Workplace Safety Index, direct costs for: repetitive motion injuries was $1.5 billion; falls on the same level was $11.2 billion; and falls from to a lower level was $5.9 billion. Together, these three classifications of occupation injuries accounted for 31.8% of all workplace injuries in 2018 (Mutual, 2018). As a result, the cost of injury and illness for roofers is extremely high (Leigh et al., 2004; Welch et al., 2010). For example, the insurance rates for roof work are nearly three times as high as the average rate of all construction trades in the Washington State (Industries, 2015) and more than three times of the average rate of all trades in the Ohio State (Compensation, 2015).

As it has been shown that individuals are less stable directly after working on a roof (Wade and Davis, 2009; Wade et al., 2014), and sloped working surfaces lead to an increased risk of slipping (OHSA, 2017) which, if on a roof, could lead to a fatal fall from height (BLS, 2016a; b). Furthermore, cross-slope walking induces an asymmetric gait, which might lead to increased risks for MSDs and falling; however much of the asymmetric gait research is focused on asymmetries caused by clinical disorders and aging (Hesse et al., 1997; LaRoche et al., 2012;

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Yogev et al., 2007). Thus with the immense costs associated with MSD and falling injuries and the increase in roofer employment opportunities in the future, it is important to determine if walking on a sloped surface alters gait characteristics in such a way to increase fall and MSD risk to the workers immediately upon getting on a pitched/sloped residential roof.

Sloped or inclined walking – defined as walking directly up or down a sloped surface (i.e. toward the roof ridge or eave)—has been studied in the laboratory in the past. With slopes as little as ± 10^0, there is an increase in hip and knee flexion as well as ankle dorsiflexion (McIntosh et al., 2006; Redfern and DiPasquale, 1997). Upslope walking induced kinematic postural changes that were needed for toe clearance at heel strike, and in addition, to regulate the body during downslope walking (Lay et al., 2006). Ankle, knee, and hip joint kinematics compensated for the gradient at push off and during swing (Kuster et al., 1995). While increasing the slope did decrease the step length and gait period during downslope walking, this did not alter gait speed (Leroux et al., 2002; Redfern and DiPasquale, 1997). Peak foot-floor angles during touchdown in the sagittal plane were smaller during uphill walking compared to level but larger in downhill walking in the frontal plane on a 19-degree laboratory sloped surface (Wannop et al., 2014). Toe-off foot-floor angles were smaller compared to level walking in the sagittal and transverse planes, but small than level walking in the frontal plane on a 19-degree laboratory sloped surface (Wannop et al., 2014).

When upslope walking was performed on a treadmill (up to 10% grade), an increased flexed posture of the hip, knee, and ankle at initial foot contact was observed. A downslope treadmill grade of 10% decreased flexion of the hip at initial foot contact as well as increased knee flexion during weight acceptance and late stance (Leroux et al., 2002). Toe clearance in young, healthy adults was significantly different between a positive 3% grade and negative 3% grade treadmill walking, but there was not a change from level to the graded walking (Khandoker et al., 2010).

Cross-slope gait, defined as walking along the slope with one foot higher on the slope and one foot lower on the slope (i.e. toward the roof hip), has been far less studied. Cross-slope gait evaluations have been made in low angle conditions ~6° in a clinical setting (Dixon and Pearsall, 2010) or railroad ballast in an occupational setting (Andres et al., 2005). Both conditions found significant changes from level conditions including ground reaction forces, joint moments, and sagittal kinematics (Dixon and Pearsall, 2010) as well as frontal kinematics (Andres et al., 2005). Wannop et al. (2014) studied cross-slope gait on a 19-degree slope and determined the foot-floor angles in the downhill foot do not change compared to level, but the uphill foot changed in all three planes. The sagittal plane angles decreased compared to level while the transverse and frontal plane angles increased (Wannop et al., 2014). While walking cross-slope—on a 19-degree surface—the foot-floor angles during toe-off in the downhill foot increased in the sagittal and transverse planes and increased in the frontal compared to level. In the uphill leg, only the transverse plane foot-floor toe-off angles increased compared to level walking (Wannop et al., 2014). Damavandi et al. (2010) investigated the effect on multi-segmented foot kinematics during 10° cross slope walking. Only the frontal plane kinematics were significantly changed from level to cross slope walking in a multi-segmented foot (Damavandi et al., 2010). While these findings are interesting, they do not come close to replicating the steep surfaces encountered by roofers. Although there is not a standard roof pitch—and pitch usually is dependent on geographical location—many modern roofs can have slopes greater than 30^0 (Myroof.com, 2017; Systems, 2017).

The current study reports on the extent which lower extremity kinematics are altered when individuals are first introduced and traverse across a sloped surface. The purpose of this study is to determine in what way traversing across a sloped/roof surface alters lower extremity kinematics of the upslope and downslope legs compared to level walking. It is hypothesized the introduction of a sloped surface will induce a substantial change in lower extremity kinematics when compared to level walking in healthy young male subjects.

2. Methods

Eleven college-aged male subjects (19.1 ± 1.49yrs, 81.15 ± 15.14 kg, and 180.73 ± 5.89 cm) who were considered inexperienced walking on sloped surfaces participated in the study. 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. All subjects reviewed and signed 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 and sloped surface walking in the biomechanics laboratory at the University of Mississippi. The first session was a level surface and the second session was the sloped surface. 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 contained a 2.43 m wide x 7.32 m long section of 15.24cm/30.48 cm pitch (26^0) shingled sloped surface—which was designed to simulate a walkable residential roof surface—was attached to the laboratory floor (Fig. 1). A residential roof is considered walkable until a pitch of 20.32cm/30.48 cm (33^0); therefore the 26^0 angle was chosen as a steeper walkable roof, but not to induce any greater risk than normal activities (Roofkey.com, 2017).

Subjects wore spandex clothes and 15.24 cm high work boots 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. The level condition required the subjects to walk across the ten meter walkway; while the sloped condition asked the subjects to traverse 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), Fig. 1.

Ten trials from each condition were recorded using a Vicon 612 system at 120 Hz. Subjects were allowed no acclamation 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 what occurs when individuals are first introduced to a sloped surface, akin to the situation when an individual first ascends a roof. Marker trajectories—referenced to the same global coordinate system for both conditions—were filtered with a Woltering filter and three-dimensional lower extremity kinematics (ankle, knee & hip) were calculated using the Plug-in-Gait pipeline in the Nexus software (Vicon Inc. Oxford, UK). After the ten trials, one gait cycle from each leg was collected. A gait cycle is defined by ipsilateral heel strikes and were

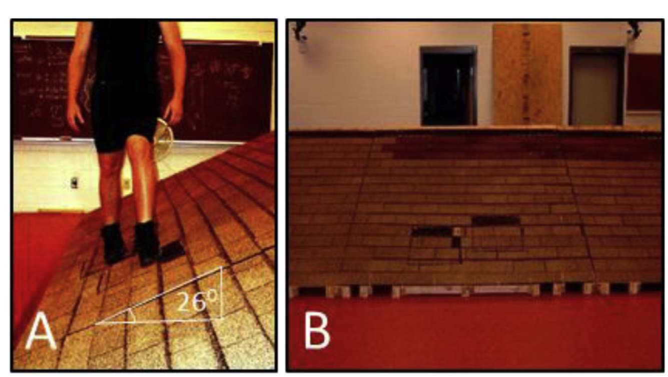

Fig. 1. A) Frontal view of subject on roof segment. B) Sagittal view of 15.24cm/30.48 cm pitch roof segment.