

Assessing Lower Extremity Kinematics of Roofing Tasks

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ABSTRACT

Roofers spend considerable time in awkward postures due to steep-slope rooftops. The combination of these postures, the forces acting on them, and the time spent in such postures increases the chance of roofers developing musculoskeletal disorders (MSDs). Several studies have connected these awkward postures to potential risk factors for injuries and disorders; however, existing models are not appropriate in roof workplaces because they are designed to assess work-related risk factors for general tasks. This study examines the impacts of work-related factors, namely working posture and roof slope, on kinematics measurements of body segments in a laboratory setting. To achieve this objective, time-stamped motion data from inertial measurement unit (IMU) devices (i.e., accelerometer, gyroscope, and quaternion signals) were collected from a sample of six undergraduate students at George Mason University. Participants performed two common roofing activities, namely walking along the roof and squatting in different roof slopes (0°, 30°). Comparing IMU signals using statistical analysis demonstrated significant differences in body kinematics between roofing activities on the slope and level ground. Overall, sloped-surface activities on a 30° roof resulted in changes in about 26% of walking and 12% of squatting variables. Such information is useful for a logical understanding of roofing MSD development and may lead to better interventions and guidelines for reducing roofing injuries.

INTRODUCTION

Roofers have the second highest risk (after flooring) of work-related musculoskeletal disorders (WMSDs) in all construction sectors (BLS, 2017). Pitched rooftops force roofers to spend about 75% of their daily working time in crawling, squatting, stooping, and kneeling postures (CPWR, 2013). Assuming these awkward postures—especially for a long duration of time—has led to incidences of severe lower extremity pain among this population (Xu et al., 2017). Additionally, when workers suffer from WMSDs, their physical capability is reduced, resulting in significant loss of productive time and long-term health impacts (Welch et al., 2009). It also has been shown that changes in lower extremity kinematics, posture, and gait variables increase the risk of falling (Breloff et al., 2019). Therefore, it is important to assess whether certain types of activity on a sloped surface change body kinematic characteristics in such a way that roofers face increased risk of fall and WMSDs.

The unique work environment of roofers (i.e., slanted rooftops) limits the direct application of biomechanical models and sensor technologies for assessing WMSDs. These models are unable to account for postural differences and their influence on safety performance when workers carry out tasks on slanted rooftops. Most roofing-related studies have focused on preventing fall-related fatal injuries (Hsiao, 2014; Hasanzadeh et al. 2020). However, non-ergonomic postures and their cumulative effects on roofers' injuries have been overlooked. Additionally, the capabilities of inertial measurement units (IMUs) to measure postures and body motions associated with daily activities (e.g., walking, running, sitting) or complex work-related tasks (e.g., climbing, hammering, lifting) have gained significant interest among researchers recently. Therefore, the aim of this study was to use IMU devices to determine how walking or squatting on a sloped surface alters lower extremity kinematics of the legs and lower back compared to the impact caused by level activities.

LITURATURE REVIEW

Ergonomic studies among Roofers. Surveillance and pathology are the main types of existing studies on nonfatal ergonomic injuries in roofing-related activities. Some surveys and observation studies have evaluated the nature, severity, and causes of WMSDs among construction roofers. For example, overextension and repetition due to awkward postures are common risk factors that may cause MSDs among roofers (Hunting et al., 2004; Fredericks et al., 2005; Jaffar et al., 2011). Most health issues and injuries to roofers are caused by WMSDs, which decrease roofers' working life (Welch et al., 2010). Similarly, some epidemiological studies have indicated that some workplace parameters, such as heavy work, lifting, bending, and twisting, are associated with low back disorders (Bernard, 1997). Additionally, posture, roof pitch, face direction, and working pace were studied as risk factors in roofing tasks (Wang et al., 2017), while Breloff et al. (2019) studied lower extremity kinematics during cross-slope walking. These studies concluded that to prevent the risk of roofers developing MSDs, safety and health researchers and regulators need to pay more attention to roofers' ergonomics (Dai et al., 2016). These findings advance the construction knowledge by providing insights of roof work-related conditions on WMSD development and thereby helping reducing risks of injuries among roofers through developing training and ergonomic solutions. However, a systematic evaluation of residential working conditions on roofers' musculoskeletal injury risks is lacking; specifically, the combined effect of lower extremity-straining posture of roofers, roof slopes and their association to MSDs is still unknown

Sloped surface activities analysis. Stability of roofers decreases while working on a roof (Wade et al., 2014). Furthermore, sloped surface walking may induce an asymmetric gait, which might lead to increased risks for MSDs and falling. Therefore, analysis gait characteristics and their effects on fall and MSD risk to workers need to be determined. Inclined movement up or down has been studied in the laboratory in the past. Such studies showed that hip and knee flexion, as well as ankle dorsiflexion, increase with a slope of $\pm 10^\circ$ (McIntosh et al., 2006). Upslope walking on a 10% grade treadmill increases hip, knee, and ankle flexion with initial foot contact, while downslope walking on the same grade decreases the flexion of the hip with initial foot contact, increasing knee flexion during late stance (Leroux et al., 2002). Cross-slope walking along a slope involves significant changes from walking on level ground in regard to such areas as ground reaction forces, joint moments, and sagittal kinematics (Dixon and Pearsall, 2010). However, all these studies have focused largely on walking along low-sloped surfaces

with less attention paid to other common activities among roofers, such as squatting, hammering, and twisting along a steep-sloped roof.

Application of IMU devices in construction. Several studies have attempted to apply IMU sensors to assess and prevent MSDs in the construction environment. For example, Valero et al. (2017) used IMUs to detect awkward postures of trunk inclination, knee flexion, and arm elevation. Another study used IMUs to examine differences of working postures between experienced and novice masonry workers (Alwasel et al., 2017). Jebelli et al. (2016) proposed using an IMU attached to the ankle to predict fall-related activities. Most of these MSD studies place IMUs on the worker's back (Yan et al., 2017) or multiple body segments (Valero et al., 2016, 2017) for full body analysis. Additionally, machine learning algorithms were developed to distinguish awkward postures from safe activities via IMUs (Alwasel et al., 2017; Nath et al., 2018). This literature shows how IMU sensors are facilitating body posture and motion measurement, improving measurement accuracy and precision, reducing intrusiveness, and enhancing wearability. Thus, this study has carried such research further by using IMU sensors to examine body motion changes during sloped-surface activities.

As the literature shows, to date no study has attempted a full comparison of motion-related information about roofers in the construction roofing field. This study covered all parts of the lower limbs of roofers and was able to register each segment's IMU properties instantly under conditions of both sloped surface and floor activities. Finding significant changes in kinematic features and their locations may be useful for systematic understanding of the development and cumulative effects of roofing MSD and may lead to development of interventions and guidelines to reduce roofing injuries.

RESEARCH METHODS

Experiment. Subjects completed two separate testing sessions, including level-surface and sloped-surface activities in a laboratory at George Mason University (GMU). The sloped condition was conducted on a 30° sloped surface designed to simulate a residential roof surface (see Figure 1).

Walking was continuously performed on a 7ft line; participants walked upslope and downslope for the sloped surface session. Squatting was defined as sitting down and up; face direction was upslope for the sloped surface session (Figure 1). We asked participants to repeat each activity twenty times between predesigned intervals. To help participants align their activities between intervals, we timed them with a stopwatch and made some warning sounds when the activity period drew to an end.

Sensor Set-up. Participants were outfitted with 10 Shimmer 3 IMU devices to measure acceleration, magnetic heading, and angular velocity, at a sampling rate up to 50 Hz. As Figure 2 shows, sensors numbered 1 and 4 were attached to the wrists, 2 and 3 on upper arms, 5 and 6 on the upper and lower back, 7 and 9 on thighs, and 8 and 10 on shanks (see Figure 2). This placement allowed us to fully examine upper and lower extremities in detail (Alwasel et al., 2017; Nath et al., 2018; Valero et al., 2016, 2017). To precisely measure body kinematics and prevent sensors from slipping, sensors were attached to the subject's body using elastic straps, as shown in Figure 2, and fitted tightly to the body segments. In addition to the data obtained from sensors, experiments for both sessions were video recorded to evaluate the quantity and quality of each task (Valero et al., 2017).

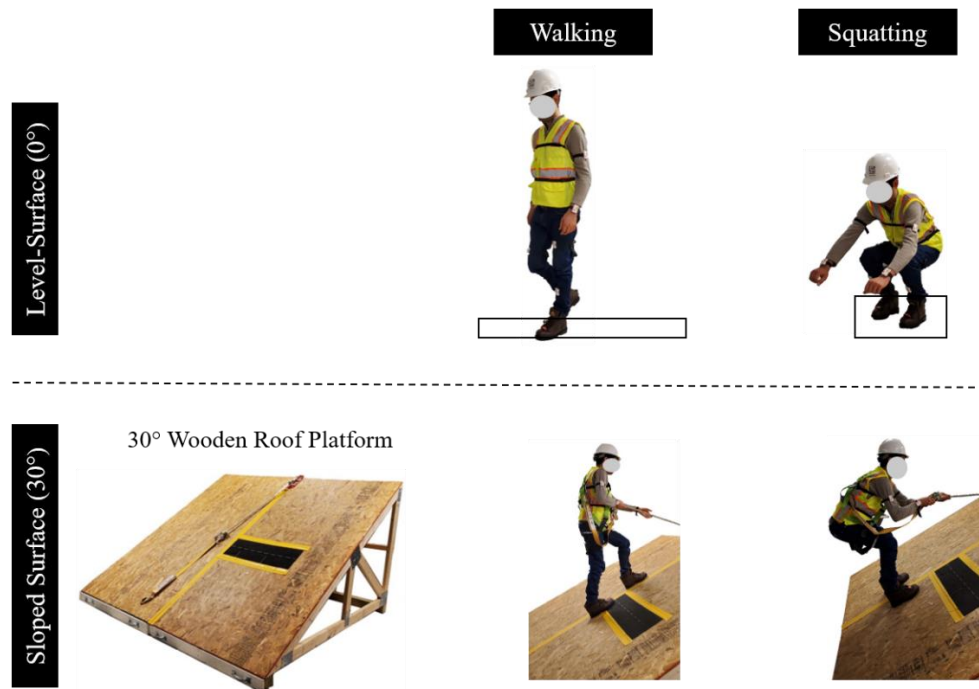


Figure 1. Testing sessions: walking and squatting on level-surface and sloped-surface.

Participants. Six undergraduate students from GMU participated in this experiment. Subjects did not report any history of musculoskeletal or other medical conditions affecting their performance on the roof and were compensated for participating in the experiments. All procedures were approved by the Institutional Review Board (IRB) at GMU. Before participating in the study, the subjects read and completed an informed consent form.

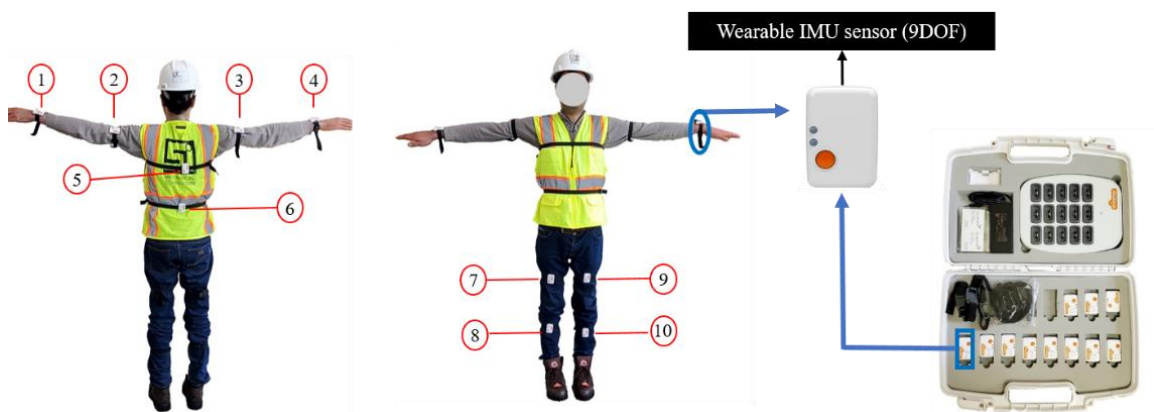


Figure 2. Sensors' placements.

Data Analysis. Outcome measures for this study were the statistical features derived from IMU signals (acceleration, angular velocity, quaternion) collected from the sensors placed on the lower back, thighs, shanks. The statistical features included minimum, maximum, standard deviation, and mean values of IMU signals, based on past studies that used these features for classification activities or statistical analysis (Nath et al., 2018; Jebelli et al., 2016).

We performed a two-sided permutation test to test the null hypothesis that two groups, "floor" and "sloped surface," came from the same distribution. We specified $\alpha=0.01$ as our significance level. Also, a partial significant level between 0.1 and 0.01 was defined to recognize any possible significant measures if the number of participants increased.

RESULTS

First, we computed statistical features of mean, maximum, minimum, and standard deviation for each IMU signal, based on the sensor location and different activities, for both the floor and slope groups. Statistical analysis was performed over acceleration-x, -y, and -z; gyroscope-x, -y, and -z; quaternion-w, -x, -y, and -z derived from the IMU devices. Therefore, the total number of outcome variables for both floor and slope groups was 400 altogether. Some of the permutation tests' results are summarized in Table 1. Lower extremity kinematics for the sloped-surface group were significantly changed compared to the floor activities group. 9 outcome variables, or 2.25%, and 68 variables, or 17%, among the 400 variables changed significantly or partially significantly when activities were performed on the sloped surface.

Table 1. Some of results of permutation tests for differences between floor and sloped groups.

Activities and sensor placement	IMU signal	Direction	P-value for statistical features			
			Mean	Maximum	Minimum	Standard deviation
Walk/ Left thigh	Acceleration	x	0.696	<0.01**	0.146	<0.1*
		y	<0.1*	<0.1*	0.127	0.672
		z	<0.1*	1.0	0.686	0.541
Walk/ Right shank	Acceleration	x	0.343	0.305	<0.1*	<0.1*
		y	<0.1*	0.696	0.573	0.663
		z	<0.1*	0.217	0.784	<0.1*
Walk/ Lower back	Acceleration	x	0.893	0.153	0.393	<0.1*
		y	<0.1*	0.760	<0.01**	<0.1*
		z	0.226	<0.1*	0.403	<0.1*
Walk/ Left thigh	Gyroscope	x	0.195	0.233	0.343	<0.01**
		y	0.179	<0.1*	0.157	0.404
		z	<0.1*	<0.1*	0.157	0.156
Walk/ Right shank	Gyroscope	x	0.874	<0.1*	<0.1*	<0.1*
		y	<0.1*	0.749	<0.1*	<0.1*
		z	0.157	0.931	<0.1*	<0.1*
Squat/Right thigh	Quaternion	w	0.650	0.383	0.873	0.134
		x	0.139	0.927	<0.1*	0.143
		y	0.788	0.636	<0.1*	0.269
		z	0.313	0.415	<0.1*	<0.1*
Squat/Left shank	Quaternion	w	<0.01**	<0.01**	<0.01**	0.453
		x	<0.01**	<0.01**	<0.01**	0.457
		y	1.0	0.991	1.0	0.756
		z	0.881	0.817	1.0	0.957
Walk/ Left shank	Quaternion	w	0.143	0.535	<0.1*	0.390
		x	0.160	0.426	<0.1*	0.126
		y	<0.1*	0.218	<0.1*	0.532
		z	<0.1*	0.272	<0.1*	0.785

*. Partially Sig. at the 0.1 level

**. Sig. at the 0.01 level

A summary of significant and partially significant changes based on activity type and sensor placement is presented in Table 2. The number of outcome variables with p-values lower than 0.01 and between 0.01 and 0.1, divided by the number of total variables for each activity (200) and multiplied by 100 yielded the percentage of significant and partially significant movement changes, respectively. We found that 26% of walking variables and 12% of squatting variables changed when activities were performed on the slope compared to the level surface. In addition, the sensor placed on the right thigh during squatting activities and the sensor placed on the right shank during walking activities exhibited greater differences than did sensors on other body parts.

Table 2. Percentage of significant and partially significant changes based on the activity type and sensor placement

Activity type	Sensor placement	Significant change	Partially significant change
Squat	Right thigh	—*	4.5%
	Left thigh	—*	3.5%
	Right shank	—*	1%
	Left shank	3%	—*
	Lower back	—*	—*
Walk	Right thigh	—*	4%
	Left thigh	1%	3.5%
	Right shank	—*	8%
	Left shank	—*	4%
	Lower back	0.5%	5%

*. There were no significant or partially significant changes among this group

Table 3 illustrates a comparison of IMU signals, and shows the percentage of significant (less than 0.01) and partially significant (between 0.01 and 0.1) movement changes for each activity between the two groups on level and sloped surfaces. For squatting, quaternion-w and -x show higher significant differences; acceleration-z, gyroscope-x, and quaternion-y had a higher percentage of partially significant changes than other signals. For the walking activities, higher percentages of significant changes were related to acceleration-x and -y and gyroscope-x, and a higher percentage of partially significant changes was noted for acceleration-y.

DISCUSSION

In this research, we studied changes of IMU signals as lower extremity kinematics during sloped-surface activities compared to level activities. Walking and squatting, the most common and most hazardous activities among construction roofers, were examined. Overall, sloped-surface activities on a 30° roof (compared to the same activities on a level surface) resulted in movement changes of about 26% for walking and 12% for squatting variables. This study was an introduction to quantify movement changes induced by a sloped surface, which is a common workplace condition for construction roofers.

Sloped surface walking involved significant changes in acceleration-x and -y and gyroscope-x, as well as for the sensor placed on the right shank. Squatting also was significantly changed in quaternion-w and -x for the sensor placed on the right thigh.

Table 3. Percentage of significant and partially significant changes based on the IMU signals

Activity type	IMU signals	Significant change	Partially significant change
Squat	Acceleration-x	_*	0.5%
	Acceleration-y	_*	_*
	Acceleration-z	_*	2%
	Gyroscope-x	_*	2%
	Gyroscope-y	_*	_*
	Gyroscope-z	_*	_*
	Quaternion-w	1.5%	_*
	Quaternion-x	1.5%	1.5%
	Quaternion-y	_*	2%
	Quaternion-z	_*	_*
Walk	Acceleration-x	0.5%	2%
	Acceleration-y	0.5%	4%
	Acceleration-z	_*	3%
	Gyroscope-x	0.5%	3%
	Gyroscope-y	_*	2.5%
	Gyroscope-z	_*	3%
	Quaternion-w	_*	2%
	Quaternion-x	_*	3%
	Quaternion-y	_*	1%
	Quaternion-z	_*	1%

*. There were no significant or partially significant changes among this group

Changes in acceleration-x and -y and gyroscope-x on the right shank during up- and down-slope walking is indicative of the stresses placed on lower extremity parts. In particular, the sensor placed on the right shank indicated differences in acceleration and velocity of body segments due to the nature of the slope. Also, placing the sensor closer to the ankle achieved greater accuracy in recognizing walking parameters than the accuracy of this measurement found in past literature (Jebeli et al., 2016, Yang et al., 2016). Greater changes in quaternion-w and -x for squatting on the slope showed that changes in segment angles in the lower extremity parts, especially the right thigh, are more likely compared to level squatting. This also can be suggestive of fatigue, especially for the thighs, and a decrease in the ability to produce the same flexion seen in level activities (Parijat et al., 2008). Significant changes of acceleration specially in x and y, gyroscope specially in x, quaternion specially in w and x might be related to the small number of participants. Repeating experiments with higher number of data will probably show the results over other directions.

A limitation of this study was that all participants performed walking and squatting in the same direction on the slope, which was not completely reflective of the combination of activities that roofers typically engage in on a roof: standing up and turning at the same time, or walking diagonally and sitting simultaneously. Further studies could analyze more complicated activities that occur in the construction roofing environment. Also, both level and sloped surfaces were located on the ground, while performing roofing activities at a high elevation may cause more significant kinematic changes. The other limitation is that all participants were graduate students

who may never had experience in roofing environment before. To get more accurate results, the experiments are needed to perform by actual roofers or people who had more experiences in roofing activities. Additionally, only six participants were involved in this experiment. Therefore, to increase significant results, these experiments could be repeated with a larger number of participants. And the final limitation of this study is that the comparison was done only for raw IMU signals of acceleration, gyroscope, and quaternion in all directions. More sensible kinematic data, like body angles or a combination of kinetic and kinematic data, would provide better understanding of activity changes.

CONCLUSIONS

This study concluded that sloped surface walking and squatting have a significant effect on lower extremity kinematics. Sloped surface walking resulted in significant changes in acceleration-x and -y and gyroscope-x, as well as in measures on the right shank. Squatting also was significantly changed in quaternion-w and -x, and for the sensor placed on the left thigh.

It is clear that sloped surface activities produce many challenges for the lower extremities, which can lead to musculoskeletal disorders and increased risk of fall among roofers. This study can be an introduction to better understanding of roofers' performance and can lead to better training procedures to improve safety and prevent unknown hazards for those working on sloped surfaces.

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