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# SENSOR-BASED FACTORIAL EXPERIMENTAL STUDY ON LOW BACK DISORDER RISK FACTORS AMONG ROOFERS

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**Abstract:** Roofers have long suffered from low back disorders (LBDs), which is a primary non-fatal injury in construction. Until present, most of the research on roofing safety is mainly focused on fatal injury risks such as falls from height, leaving much to be desired in the risk assessment of non-fatal, cumulative musculoskeletal disorders among roofers. Ergonomics studies have identified several physical risk factors associated with LBDs in workplaces and applied selective ones to develop predictive models for general LBD risk assessments. However, these models cannot be used for roofing assessments in that they are designed for general tasks without considering different roofer working postures and the effect of working on uneven rooftops. To understand the relationship between the risk factors (i.e., slope angle, posture, facing direction, and working pace) and LBD incidence in roofing shingle installation, a factorial in-lab experiment is conducted with the aid of the Vicon camera system and Electromyography (EMG) sensors. The bending angles and muscle strengths in the low back, which are measured by the two sensor systems, are analyzed as facts that indicate the LBD risk. The proposed experiment finds out the risk factors with significant effect on the LBD injury and interaction between the studied factors. The findings may be used to study the detailed ergonomic safety guidelines for roofing contractors, which will be useful for eliminating LBD risk factors on the roofing sites.

## 1    INTRODUCTION

As a major construction workforce, roofers have long suffered from low back disorders (LBDs), which is a primary non-fatal injury in construction. For roofing workers, it was found that 30% (i.e., 3,300 of 10,815) cases of injuries and illnesses occurred in the trunk (Fredericks et al. 2005). In roofing, shingles are widely used as roof covering materials, and shingle installation is a most time-consuming activity where most injured cases take place (Wiki 2015; CPWR 2015). Without enough knowledge of the nature and disease formation of LBDs, roofers tend to adapt themselves to the harsh workplace environments (e.g., steep rooftops) and fast work pace. In addition, the roofers' working postures can vary due to their personal preference. It has not been revealed what factors are prone to cause LBDs and needs to be rectified. Till present, there are only general guidelines available, which are designed for general industrial tasks (e.g., manual material handling) (Wang et al. 2015), ignoring the differences in environment settings, working procedures, job rotations, and alternative postures. The research in roofing safety mainly focuses on fatal injuries, while existing efforts in non-fatal studies are focused on sample studies and disease diagnosis. In order to better understand the relationship between the LBD incidence among

roofers and the potential risk factors, in this study, the main risk factors in the roofing shingle installation are identified. Then, a factorial experiment is designed to study their effects and their interaction on LBDs. Advanced motion capture system Vicon and skeletal muscle signal recording system Electromyography (EMG) are utilized to conduct the LBD risk measurements. Through this experiment, it is expected to reveal the effects of the risk factors on the LBDs and to report the risk level at certain conditions, which may be helpful to the study of detailed ergonomics guidelines for roofing workers.

## 2    RESEARCH BACKGROUND

### 2.1    State of Practice

In the United States, there is a total of approximately 132,700 workers employed as roofers whose main jobs include repair and install the roofs using shingles, asphalt, metal, and solar panels, etc. (BLS 2015a). Roofing work can be categorized into commercial roofing on low-pitch roofs (below $10^{o}$) and residential roofing on a relatively steep roof ($10^{o}$~$45^{o}$) (National Contractors Inc. 2015). Roofing work can be hot and physically demanding. It involves heavy lifting, as well as climbing and bending. According to the survey (BLS 2015b; Fredericks et al. 2005), roofers spent over 60% of their working time on roofs. Shingle installation is a major repetitive task for roofers. The time roofing workers spent on crawling, squatting, stooping and kneeling is among top 7 of all industrial activities (O*NET 2013). The cumulative effects of stooping, kneeling or squatting may not only lead to low back pains, but also can increase forces in the knee (CPWR 2015).

Roofers have a higher incidence rate of injuries and illnesses than the national average. Among all construction sectors, roofing workers have the second largest WMSD (work-related musculoskeletal disorder) incidence rate (i.e., 50.7 per 10,000 full worker year) (BLS 2013). Roofing workers suffer from not only fatal injuries, but also non-fatal injuries. In terms of fatal injuries, workers may slip or fall from scaffolds, ladders, or roofs. Through proper safety protection, most accidents can be prevented (EU-OSHA 2015). In contrast, roofing installation contractors frequently conduct labor-demanding operations, including stooping, kneeling, lifting, twisting, bending, and drilling. Although such operations would not cause acute pain after a short period of work, high repetition could accumulate the burden on the musculoskeletal system in the back and pose roofers to a threat of LBDs (Wang et al. 2015).

Till present, there are very limited guidelines promoted to protect roofers from non-fatal injuries like LBDs. The documented guidelines simply list the causes of hazards, such as severe stooped postures, keeling, lifting and carrying (CPWR 2015). Comparing to fatal injuries, the non-fatal issues are not receiving enough attention. In industry, the sacrifice of safety for productivity is common (Lynch Ryan 2015). An agricultural study revealed that reduced productivity outweighs the benefits brought by knee support intervention which is designed for LBD injury prevention (Jin et al. 2009). However, non-fatal injuries can have a significantly negative impact on productivity by resulting in long days away from work. Besides, workers who had a history of WMSD injuries are reported to have a higher possibility of recurring and can decrease the productivity, in that the risky posture can cause pain in body parts and consequently affect productivity (Serranheira and Smith 2014).

### 2.2    State of Research

Plenty of roofing research has been conducted with a focus on fatal injuries (e.g., fall, slips). The implemented studies covered risk assessment, communication, and prevention (Hisao 2014). In contrast, the up-to-date studies in non-fatal injuries are still at the stage of performing sample studies and injury formation analysis. Hunting et al. (2004) have conducted a survey study of the nature and cause of injuries among 2916 injured construction workers by detailed occupation. It revealed that half of injuries among the roofers are in the back and most non-fatal cases are caused by overexertion and strenuous movement. Fredericks et al. (2005) has analyzed the U.S. Bureau of Labor Statistics (BLS) data in roofing and revealed the trends and causes of both fatal and non-fatal injury incidences among roofers. It was reported that roofers spend 61% of their time on roofs and typically spend 3-4 hours daily on manual lifting/carrying. In addition, they have conducted a self-report survey of injuries and risk factors, including

personal information, working environment, and lifting/carry strength to identify the most frequent roofing injury combination.

In epidemiological and ergonomic studies, a lot of efforts have been put in studies of injury nature and risk assessment methods for WMSDs and LBDs (Wang et al. 2015). However, these methods are mostly developed for general industrial tasks, for example, lifting, bending, and carrying (Pan et al. 1999). Up to date, observation tools and predictive models have been developed by summing up the detected risk factors multiplied by assigned weights to evaluate the LBD risk in the workplaces, such as NIOSH lifting equation (Waters et al. 1994) and 4D WATBAK (Neumann et al. 1999). However, for roofing construction activities, no specific studies have been conducted to identify and measure the risk factors on roofing sites.

## 3    RESEARCH PROBLEM STATEMENT

All the presented data brings forward the problem of LBDs among roofers, which requires actions taken to study and alleviate LBDs among this population. The existing observation tools are able to detect the LBD risk in the workplaces, but provide no clue on how to redesign the work procedures and the environment settings in order to reduce the LBD incidences (CPWR 2015). Epidemiological studies have identified certain physical risk factors for LBDs in workplaces and predictive models are developed based on those selected factors. However, the models cannot be used for roofing activities due to dissimilarity in the survey sample that determines the coefficients and the raised risk factors need modification before applying to roofing tasks. These models do not take into account a diversity of roofer working postures (e.g., stooping, kneeling) and effects of working on slanted rooftops. In addition, in roofing, the effect of gender can be ignored as the majority (over 90%) of workers on construction sites are male (BLS 2015a). Through abundant literature review and site observation, the main risk factors in roofing tasks are detected and summarized as follows for the examination of the experiment.

### 3.1    Postures: Stooping and Kneeling (or Crawling)

Through on-line search and site observation, two main postures in shingle installation were found: stooping and kneeling. Roofers can use different working postures due to personal preference. Stooping posture, which requires the roofers to bend forward while holding their legs upright, is illustrated in Figure 1. In contrast, kneeling typically requires the workers to kneel on the roof and make the trunk parallel to the roof (Figure 2). However, the existing risk assessment methods do not examine the relationship of an injury to stooping or/and kneeling. Reducing the incidence of work-related LBDs among roofers requires a new focus on identifying and describing stooping and squatting postures as specific LBD risk factors in the workplace (Fathallah et al. 2004).
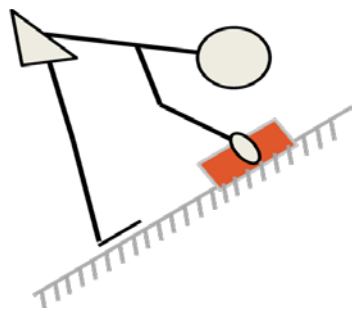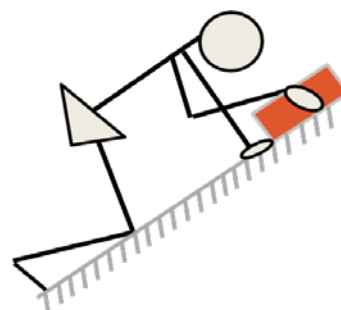


Figure 1: Stoop posture on the roof       Figure 2: Kneel posture on the roof

### 3.2    Environmental Conditions: Roof Slope

For the work environmental setting, the risk of working on a slant roof surface to the LBDs is not well investigated. There are studies on fatal fall risks exploring the effects of the roof slope. One of these is to study the influence of the surface slopes (18º, 26º, 34º) and frequencies on postural balance in shingle installation with stooped postures (Choi et al. 2008). For each surface slope, the Maximum Acceptable

Roof Shingling Frequency (MARSF) was reported. It is found that as the slope slant increases, the MARSF decreases from 206 shingles per hour to 168 shingles per hour. The influence of the slope slant was revealed by this experiment, but it did not indicate that it is the same decreasing trend for the LBD risk as the slope rises.

### 3.3    Task-Related Factors: Facing Direction on the Roofs

The experimental setup was designed to mimic a shingle installation task in a laboratory setting. Based on our video database search and on-site observation, it is noted that different roofing materials require different installation methods on certain pitches (NINDS 2015). For three- or four-tab residential shingles, roofers are used to installing them parallel to the ridge, which requires the roofers stand facing uphill. For solar panels, the roofers usually stand perpendicularly to the ridge while installing them in order to avoid stepping on these panels. This means that the roofers will work on the roof facing side (hip). In the most recent ergonomics study, it is found that manual handling sudden loading on uneven surface can have a significant difference with on the ground on the LBD risk (Zhou et al. 2015), which provoke the needs for studies on jobs conducted on uneven surfaces such as roofs.

The identified three risk factors, each of which can have at least two factor levels, indicate that there can be different combinations of the slope slants with the roofer working behavior. In order to study the risk on a certain combination, a factorial experiment is designed to analyze the influence of each factor, expected to study the effects of and among different factors to the LBD risk.

### 3.4    Limitations of Existing Research

It is mentioned that the promoted guidelines and practices still lack practicality. Most guidelines are in rough description and still require expert observation to reveal on-site LBD risk factors and improper work design (CCOHS 2013; Wang et al. 2015). The workers' insurance compensation put much more emphasis on medical care than preventive efforts, and the injury statistics data is driven by an event or an acute injury rather than cumulative trauma (Fathallah et al. 2004).

Upon the review of the state of practice and research, the main risk factors in roofing industry have been summarized. However, the authors have identified that there are still several areas that need exploring in order to understand and eliminate the LBD risk among roofers. That is: 1) the development of risk measurement for LBDs among roofers, 2) the knowledge of the effects of different risk factors and their combinations on LBD risks (i.e., slope, posture, facing direction, frequency), and 3) comparison of two different postures (i.e., stooping and kneeling) on the effect of developing LBD risks.

Given above limitations, in this study, a sensor-based ergonomics experiment is designed to reveal the relationship between roofing activities and risk factors through lab empirical studies.

## 4    EXPERIMENT AND IMPLEMENTATION

The purpose of this study is to understand the relationship between the risk factors (i.e., roof slope, posture, facing direction, working frequency) and LBDs in roofing shingle installation. A factorial experiment is designed with advanced EMG to estimate the forces and loadings on the trunk, and motion capture system Vicon to capture the bending angle of the trunk.

Four factors are selected as the independent variables for factorial analysis from the view of individual factors, environmental settings, and task-related factors: 1) Slope: 0º, 15º, 30º; 2) Posture: stooped and kneeling; 3) Facing direction: uphill and side; 4) Frequency: slow (12 seconds/shingle), fast (6 seconds/shingle). Based on the site observation data and studies on maximum acceptable working frequency on roof slopes (Choi et al. 2008), a duration of 12 seconds is set for one shingle installation at slow frequency level; a duration of 6 seconds is set for fast frequency. Given that shingles are usually prepared beforehand, the process of carrying shingles and walking on the roof is ignored. In this simulation, we particularly focus on the nailing process. The participants are required to hold a same nail

gun while simulating shingle installation process on the platform. A total of 16 combinations of the four risk factors are tested and 2 repetitions for each condition are conducted.

In our experiment, there are two independent variables which are generated from data captured by Vicon and EMG.: 1) Maximum lumbar trunk flexion angle which measures the angular difference between the T12 and S1 motion sensors in the sagittal plane (Hu et al. 2014); 2) Average normalized EMG signals which measure the activeness of the muscles on the back (with detailed discussion in 4.4 Data processing). The two independent variables (response variables) are utilized to help establish measurements of the LBD risk and could also verify each other. In addition, the two variables are synchronized using Vicon Nexus software (Vicon, Oxford, 2002). Analysis of variance (ANOVA) is a popular statistics technique which is used to investigate the relationship between the independent variable(s) and the response variable (Miller 1997). In our study, ANOVA is conducted to study the effects of each factor and interaction among risk factors. For all statistical analysis in this study, the criteria p-value is set at 0.05.

## 4.1    Participants

There were 4 participants in this study. The age, stature and whole body mass (with standard deviation) of this study population were 25.2 year (1.3), 176.4 cm (3.4), and 70.6 kg (8.4). All subjects had no history of low back injury. The research involving human experiments was approved by the Institutional Review Board of West Virginia University (Hu et al. 2014).

## 4.2    Apparatus

The experimental setup was designed to simulate a shingle installation task in a laboratory setting. The shingle installation simulation was conducted on a 1.4m by 1.7m wood platform (Figure 3). The platform was connected to a hydraulic lift table. By elevating the lift table, the wooden roof could be lifted to a slope angle ranging from 0 to over $60^{o}$. In this experiment, a Vicon camera system was utilized to capture the human motion data; and EMG sensors were utilized to capture the signal of the main muscles on the back. Video streams were also recorded for off-time observation.

The Vicon system is a 3D motion capture system that involves multiple cameras surrounding the capture volume where human motion can be tracked (Richards 1999). Vicon data was recorded at a frequency of 100Hz. To capture the posture of the lumbar spine, five Vicon markers are attached to each participant. Three sensors were placed on the spine to calculate the trunk flexion angle: one at the C7 area (near the neck), one at the T12 area (around the chest) and the other at L5 area (lumbar). The three sensors provided measures of angle in the sagittal plane and were then used to estimate the lumbar flexion angle (Dolan et al. 1994). Another two sensors were placed on the shoulders to help recognize the postures and facing directions. They could be used to calculate the trunk twisting angle in the future.

EMG was mainly applied in human kinematics experiments by attaching a group of muscle sensors on the skin (Marras and Granata 1997), as shown in Figure 4. It features in synchronous recording of muscle tension and computerized analysis of myoelectric signals, and is widely used to evaluate muscle actions and the loading in body parts (Reaz et al. 2006). The EMG data was collected at a rate of 1000 Hz. In this experiment, 4 pairs of surface electrodes were placed on the abdomen and low back of the subjects that were used to collect the electromyographic (EMG) muscle activity of the sampled muscles. The sampled muscles included two pairs on the abdomen (Ab1, Ab2), and two pairs on the back (erector spinae (ES), multifidus (MF)). These muscles were chosen as they were reported to have a direct impact on spinal loading (ES, MF). In ANOVA analysis, signals of those muscles were hypothesized to be affected by shingle installation posture (Fathallah 2004; Zhou et al. 2015).
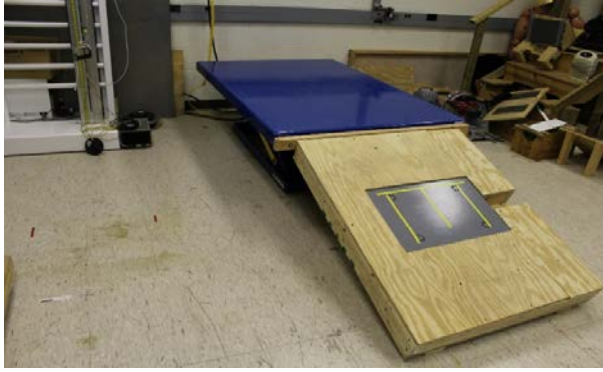
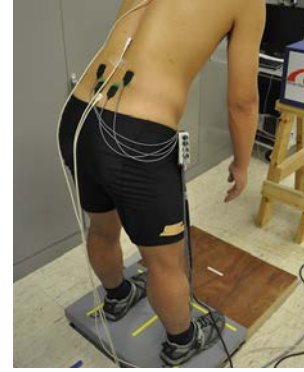Figure 3: Platform elevated by hydraulic lift


Figure 4: EMG system and surface sensors attached to the back

### 4.3 Procedure

The first phase of the experiment consisted of a series of static trials that focused on collecting the maximum voluntary capacity and static low back posture. The second phase of the experiment consisted of two repeated trials on each condition which is a combination of the selected factors, such as, stooping on a 15$^o$ slope at a fast working pace while facing uphill. At this phase, both Vicon markers and EMG surface sensors were placed on the subject's trunk and low back. This way, kinematics data and muscle signals were recorded simultaneously and synchronized for post-processing. The stooped trials were simulated first, and then kneeling postures.

### 4.4 Data Processing

The trunk kinematic data collected from the Vicon during the trials were used to compute the trunk flexion angle. The three markers placed on the trunk were reconstructed in the 3D space using Vicon Nexus. The derived 3D coordinates were used to track the trunk motion and compute the bending angle.

The EMG data collected during shingle installation cycle was rectified, filtered using butter filter, and averaged over the whole nailing period. These data were then normalized to the percentage of the Maximum Voluntary Capacity (MVC) of the muscle. During the experiment, the subjects were required to follow the same time schedule (trunk flexion, nailing, and trunk extension) during a working cycle. Nailing process was extracted by defining the starting and ending time of the nailing process. As denoted in Figure 5, two peaks were captured during a single shingle installation cycle. The first peak of EMG signal reflects the trunk flexion process, and the second peak reflects the trunk extension process. The flat curve between the peaks represents the nailing process.
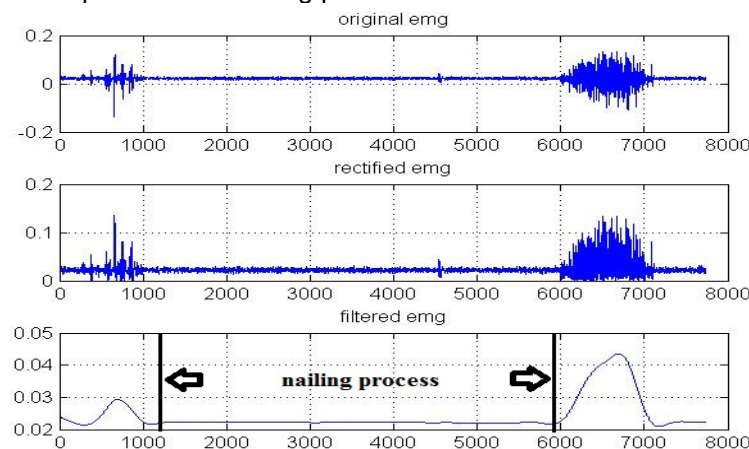

Figure 5: EMG signal process and nailing process extraction

## 5   RESULTS

Prior to conducting the formal analyses, the assumptions of the ANOVA technique (normality of residuals, and independence of observations) were evaluated using the graphical approach advocated by Montgomery (2001). Interval plot each factor vs each response variable was drawn to show the sample's tendency and variability. In addition, F-test was conducted to investigate the effects of each factor on the response variables (Flexion from Vicon, ES (erector spinae) and MU (multifidus) from EMG data) and presented in Table 1. "+++" denotes a significant effect and "/" denotes no significant effect. For example, frequency difference has no significant effects on the flexion angle captured by Vicon. It is because either for slow cycle or faster cycle, the participants followed the exact same posture and procedures, which would result in no noticeable difference.

Table 1: F-test for measuring the effects of the factors (p-value: 0.05)

| Factors | Flexion (Vicon) | ES (EMG) | MU (EMG) |
|---|---|---|---|
| Slope | +++ | ++ | ++ |
| Frequency | / | +++ | +++ |
| Direction | ++ | + | / |

The subsequent univariate ANOVA showed that the response of the erector spinae and the multifidus followed a consistent trend on most conditions. Besides, the Vicon and EMG data supports each other in effects of slope angles, but contradicts each other on certain conditions. As mentioned, both Vicon and EMG data serve as the risk measurements of the loading on the back. As stooping and crawling are two totally different postures, correspondingly, the back muscles and the rest of the body parts can differently be involved in the procedure. At this stage, the comparison of stooping and crawling is not discussed. In the following section, the results of stooping and kneeling postures are presented. For each posture, we respectively conduct ANOVA analysis to study the effect of each factor on the LBD injury development.

### 5.1   Stooping Posture

### 5.1.1   Influence of slant

The effects of slope angles on maximum flexion angle can be revealed in Figure 6. The flexion angle calculated from Vicon data shows the trend that the flexion angle is decreasing as the slope angle increases, which indicates a decreased LBD risk. Survey score from the subjects also indicates a same trend.
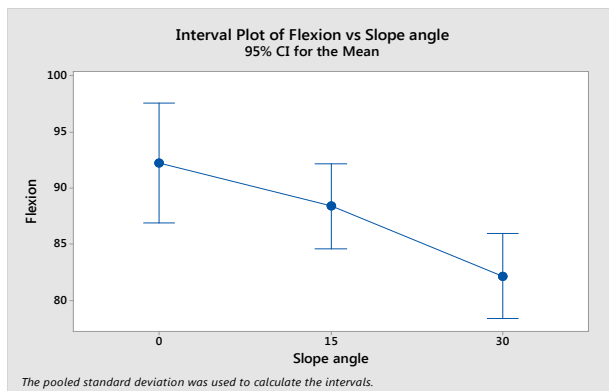
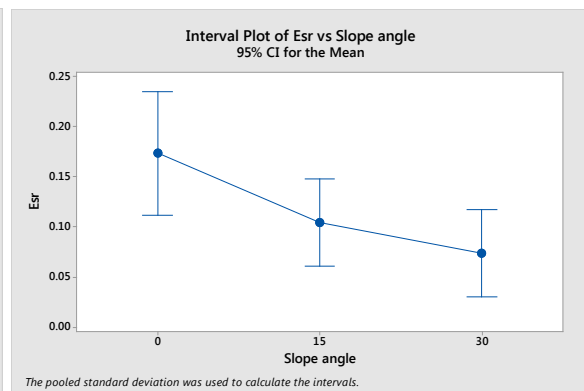Figure 6: Effects of slope angles on flexion angle (stooped)

Figure 7: Effects of slope angles on EMG (stooped)

This result is verified by EMG data as a same trend is detected both in ES and MU muscles, shown in Figure 7.

### 5.1.2    Influence of facing direction

From the flexion angle, we can detect that the flexion angle of working facing side tends to be higher than that of facing uphill, as shown in Figure 8. Besides, as to facing side, a more severe twisting of the trunk is reported by the subjects in the survey. For each degree of slope, except the flat ground, a higher risk for facing side than facing uphill is indicated. But as mentioned, the EMG data contradicts the trend on some conditions, which still needs further studies.
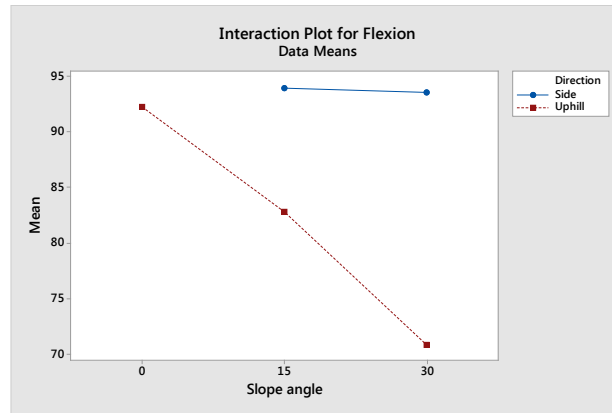


Figure 8: Effects of facing directions on flexion angle by slope angle (stooped)

### 5.1.3    Influence of speed

The Vicon data shows there to be no evident differences between slow and fast working paces in flexion angles. On the contrary, the response of EMG shows the a trend that the muscle signal in both MU and ES muscles become stronger as the working rate accelerates, which indicates an increased LBD risk (Figures 9 and 10).
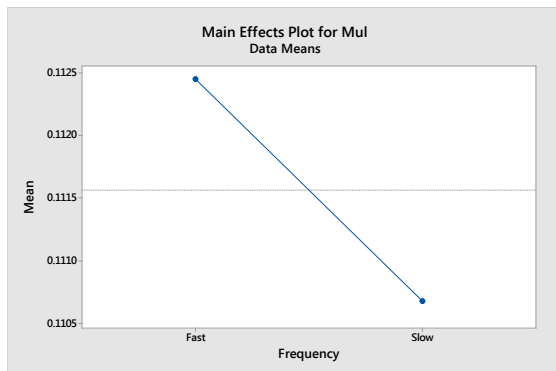


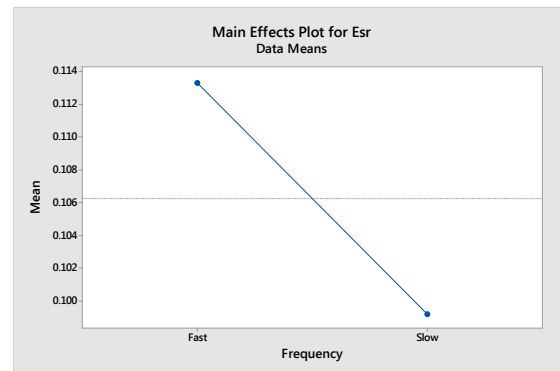Figure 9: Effects of frequencies on MU EMG signal (stooped)



Figure 10: Effects of frequencies on ES EMG signal (stooped)

### 5.2    Kneeling Posture

For kneeling postures, the facing direction was assumed to be uphill as only uphill was detected in video observation. The effects of the slant and frequencies are discussed respectively as follows.

### 5.2.1    Influence of slant

The response of Vicon shows the trend that the flexion angle decreases as the slope rises, which indicate a decrease LBD risk, as shown in Figure 11. For both fast and slow frequencies, Figure 12 shows that there is a consistent trend. That is, as the slope rise, the flexion angle decreases, indicating a decreased LBD risk. As we increased the slant to 40 degrees, the trend is consistent. EMG signals verify this finding as well.
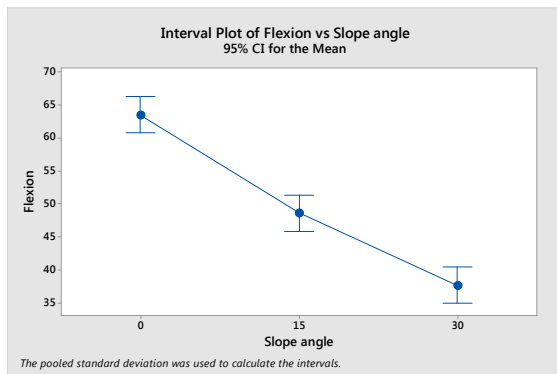
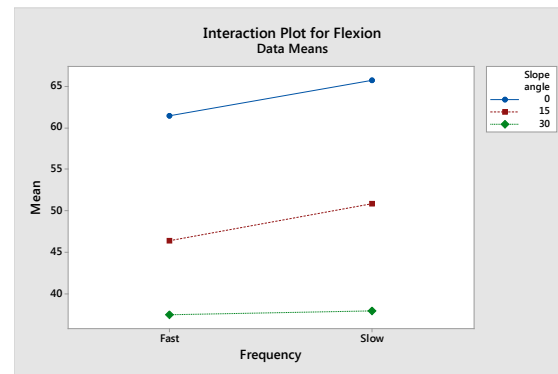Figure 11: Effects of slope angles on flexion angle (kneeling)



Figure 12: Effects of slope angles on flexion angle by frequencies (kneeling)

### 5.2.2 Influence of frequency

Similar to stooped postures, the response of EMG shows a trend that the muscle signal becomes stronger as the working rate accelerates, which indicate an increased LBD risk for kneeling postures.

## 6    DISCUSSIONS AND CONCLUSIONS

This paper proposed a method to examine the effects of the common risk factors in roofing jobs. A factorial experiment was designed to reveal the effects of a combination of the identified factors. From the result analysis, the effects of each factor were revealed. From this study, faster working pace resulted in a higher LBD injury risk. As the slope angle increases from $0^0$ to $15^0$, and then $30^0$, a decrease in LBD risk was detected. The facing side working condition posed extra pressure on the lower back due to a twisting angle. These findings might be helpful to develop specific guidelines and prevention training for tackling the LBD risk among roofers. The existing study did show a significant effect of the selected factors on the changes of the response variables, which indicated an influence on LBD risk. Some of the findings contradicted people's common sense. For example, people tend to believe that it is risky on steep roofs and poses more injury risk to the trunk. But through the laboratory study, a relief in pressure on the back was observed for a larger slope. It is worth noting that similar guidelines exist; That is, to avoid working on the floor/inclination degree, when possible, raise the work height by using a workbench (CPWR 2015).

However, there is still room that could be further improved both in the experiment design and post analysis. 1) The twisting angle of the trunk is not captured in this experiment, which is expected to differentiate side and uphill posture better. 2) Only the trunk muscle is studied and used for the risk analysis. However, the ankle and knee are also prone to WMSD risks due to heavy use in two roofing postures. 3) As in a dynamic experiment, the duration of a single trial is short, which could add difficulty to reflecting the difference of factor levels by EMG. (4) Currently, the sample size is relatively low. In the future, an expanded experiment involving more subjects with a diverse distribution in age, stature, body fat percentage, etc. would be carried out.

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