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Evaluating Work-Related Risk Factors Associated with Low Back Disorders in the Roofing Industry

Di Wang

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Evaluating Work-Related Risk Factors Associated with Low Back Disorders in the Roofing Industry

Di Wang

**Thesis submitted
to the Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University**

in partial fulfillment of the requirements for the degree of

Master of Science in Engineering

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**Morgantown, West Virginia
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Low Back Pain, Trunk Flexion**

ABSTRACT

Evaluating Work-Related Risk Factors Associated with Low Back Disorders in the Roofing Industry

Di Wang

Roofers have long suffered from low back disorders (LBDs), which is a primary non-fatal injury in construction. The harsh work environment exposes the roofers to a diversity of physical exposures which may cause severe LBD injuries. Until now, most of research on roofing safety has been 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 this population. Existing ergonomics studies have identified several physical risk factors associated with LBDs in workplaces and developed predictive models for general LBD risk assessments. However, these models cannot be directly used for assessments in roof workplaces because they are designed for general tasks without considering the variance of roofer working postures and the effects of working on slanted ground surfaces (i.e., rooftops).

The objective of this thesis study is to understand the relationship between the roofing work-related risk factors and the LBD risks during the performance of roof shingle installation. The roofing work-related risk factors comprise slope angles, postures, facing directions, and working pace. An in-lab factorial experiment is conducted with the aid of Vicon and Electromyography (EMG) sensors. The trunk flexion angle and muscle activities in the low back are measured as indicators, which are then analyzed to implicate the LBD risk.

The experiment results revealed the risk factors with significant effects on the LBD development. Also, this study uncovered the relationships between trunk flexion angles, muscle activities and combinations of different risk factors. This knowledge will be useful for better understanding and education of roofing non-fatal LBD development in the industry and the research community. This knowledge may also have the potential for development of detailed safety guidelines and interventions for the LBD injury prevention among the roofer population.

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CHAPTER 1

INTRODUCTION

1.1 Problem Definition

Low back disorders (LBDs) is a primary non-fatal injury in roofing industry. 31% (i.e., 3,300 of 10,815) cases of injuries and illnesses for roofers were reported to occur in the trunk (Fredericks et al. 2005). Prolonged bending of the back while installing tile or shingles can cause injuries to muscles, nerves, discs, and ligaments of the low back (Wang et al. 2015a; Choi et al. 2014).

Roofing work has high physical demands. The harsh working environment and task requirements expose the roofers to high LBD risks. It is reported that roofers spend over 60% of their working hours on rooftops (BLS 2015b; Fredericks et al. 2005). The time roofing workers spent on crawling, squatting, stooping and kneeling is among top 7 of all industrial activities (O*NET 2013). In roofing, shingles are widely used as roof covering materials. Shingle installation, a daily task for roofers, is a time-consuming activity during which lots of injury cases can take place (OSHA 2015; CPWR 2015). Workers who install shingle roofs face LBD hazards from lifting, carrying, stooped postures, and kneeling postures, etc. However, it is difficult to associate a specific event with the LBD injury. LBD is not typically the result of a fall or acute injury, but is a cumulative trauma injury which can be caused by high repetition and overuse of the back (Theodore 1992). Roofers risk developing LBDs due to a diversity of risk factors from the work itself and the work environment. However, without enough knowledge and

education on the pathology of LBDs, roofers are prone to adapt themselves to the harsh workplace environments (e.g., steep rooftops) and fast work pace at the sacrifice of their own health.

1.2 Research Motivation

LBD among roofers are complex due to a number of risk factors involved in the work and working environment. Several main research gaps were identified that need to be bridged before major advances in roofing LBD studies. Firstly, until now, in the roofing industry, it has not been systematically investigated which factors are prone to cause LBDs, let alone the interventions. Secondly, although there are LBD protection guidelines available, they are designed for general industrial tasks (e.g., manual material handling) (Cheung 2007), ignoring the differences of environmental settings, working procedures, job rotations, and alternative postures. Thirdly, the established LBD predictive models, for example, NIOSH lifting equation, are designed for general industrial use. Those models fail to take into account the effects of different roofer working postures (e.g., stooped, kneeling) and working on slanted rooftops. Lastly, the research on roofing safety mainly focuses on fatal injuries, while existing efforts in non-fatal studies focus on the pathology studies.

This thesis study is built on my previous researches during the master study. The manuscript is significantly influenced by Wang et al. 2015a, which revealed the severity of musculoskeletal disorders in construction and reviewed the existing risk assessment methods, and by Wang et al. 2015b, which is a preliminary study on effects of selected roofing activities on LBD incidence by analyzing the muscle activations and trunk motion data. If you want to reuse the figures, tables, and data or so which has been published in the above papers, please refer to UBC (University of British Columbia) library copyright or request permission from

ASCE JCEM (Journal of Construction Management and Engineering) and put appropriate citations.

1.3 Research Objective

The objective of this thesis study is to understand the relationship between the roofing related risk factors (i.e., slope, posture, facing direction, and work pace) and the LBD risks during the performance of roofing tasks. To achieve this, the main risk factors in the roofing shingle installation are first identified. Then, a factorial experiment is designed to study their effects on LBDs, in which advanced motion capture system Vicon and skeletal muscle signal recording system Electromyography (EMG) are utilized to conduct the LBD risk measurements. The experiment is expected to result in findings with respect to how the risk factors affect the LBDs and the risk levels given different work conditions.

The scope of the thesis study is to identify the work-related risk factors with a significant effect on the low back disorder development. The other body parts, such as arms, shoulders and lower extremities, are not included in the analysis.

1.4 Thesis Organization

This thesis is organized as follows: First, it reviews the severity of LBDs in the roofing industry. Then, a comprehensive state of practice and research is synthesized in understanding, reducing and preventing LBDs among the roofers. Thirdly, the main existing ergonomic injury risk assessment methods are reviewed with a discussion on their advantages, disadvantages, and applicability. The suitable methods are selected for this experiment. Fourth, the thesis introduces the experiment design and implementation with the aid of Vicon and surface EMG sensors, followed by data analysis and result interpretation. Finally, the findings and limitations of the

studied are discussed. The conclusion and contribution to the body of knowledge in the roofing industry are also stated.

CHAPTER 2

SEVERITY OF LOW BACK DISORDERS IN THE ROOFING INDUSTRY

Low back disorders (LBDs) are one type of work-related musculoskeletal disorders (WMSDs), which refers to a group of painful disorders of soft tissues developed usually over from highly physical tasks (CCOHS 2013). WMSDs have long been a primary cause of non-fatal injuries in construction. The main causes of most WMSDs are from the everyday work itself and working environment (UWYO 2015, Wang et al. 2015a), either caused by high force during a single event such as lifting, lowering, pulling, and carrying, etc., or resulting from repetitively performing a task (HSE 2014). WMSDs can bring about a large number of injury cases and economic losses to the contractors and the society (WCRC 2012).

The back is the primary body part affected by WMSDs in construction with a significant proportion of 58% in 2003 and 45% in 2010 (CPWR 2013b). Concluding from statistics of all private industries in the state of West Virginia, the incidence rate of pain in the trunk (mostly in the back) is much higher than that in other body parts (i.e., 5 times that of the second - shoulder) (BLS 2013d; Wang et al. 2015a). Roofers are a primary construction workforce and it is reported that this population suffers from the 2nd highest WMSD incidence rate along with a high back injury rate. Then, the harsh roofing working environment involved with severe LBD exposures is introduced, followed by the highlighting of the severity of LBD in the roofing industry.

2.1 Introduction of the harsh working environment

In the United States, there was a total of approximately 132,700 workers employed in 2012 as roofers whose main jobs included repair and installation of 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°) and residential roofing on a relatively steep roof (10°~45°) (NCINC 2015).

The roofing contractors' job is strenuous and physically demanding, which requires long-time stooping, kneeling, lifting, twisting, and drilling (BLS 2015a). Shingles are the typical roof covering material, which can be made of wood, slate, flagstone, fiber cement, metal, plastic, and composite material such as asphalt shingles (Kang et al. 2008). According to a survey conducted among roofers (Fredericks et al. 2005), roofers spent 61% of their time on roofs and typically spend 3-4 hours daily on manual lifting/carrying. The time roofing workers spent 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 lead to lower back pains, and also can increase forces in the knee (CPWR 2015).

2.2 Severity of LBDs among roofers

Roofers engage in many activities that may expose them to not only fatal hazards, such as falling from rooftops, unguarded machinery, being struck by heavy construction equipment, but also non-fatal occupational hazards, including LBD risks.

Roofers are at a greater risk of slipping or falling from scaffolds, ladders, or roofs (Choi and Fredericks 2008). The number of fatalities was increasing during construction in the United States with roofers between 1992 and 2001. Roofers are six times more likely to get fatal injuries than average workers (BLS 2004). In addition, typical injuries caused by roof work are

extremely severe, which requires long periods of treatment and recovery and resulting in substantial medical costs and lost work time (Gillen et al. 1997).

Occupational non-fatal injuries take place more often and are extremely difficult to prevent (CPWR 2015). Although the daily physical demanding operations, such as manual material handling and lifting, would not cause acute pain shortly, high repetition could cause the stresses to accumulate on the musculoskeletal system in the back and expose workers to non-fatal occupational injury like LBDs (David 2005).

Low back disorder occurs in the lumbar spine and its surrounding structures, which are commonly referred as the low back region (NINDS 2014). LBD can be either acute or chronic. It is reported that about 80% of adults have experienced low back pain during their lifetimes (NIH 2015). Low back pain is reported to a main cause of job-related disability, missed work days and an inability to stand upright (PHC4 2015). LBD causes up to 240 million days away from work per year (Gilkey et al. 2007). Back injuries account for half of WMSDs in all body parts that result in days away from work (CPWR 2013b). Occupational LBDs account for 34% of all work-related injury and illness cost (Meyers et al. 2004). Its estimated costs were US \$49 billion annually in 1992 (Leigh et al. 1997).

LBDs in roofing are causing tremendous economic loss and productivity loss. Wang et al. (2015a) reported that, among all construction activities, roofing workers have one of the highest WMSD incidence rate (i.e., 50.7 per 10,000 full worker year) (BLS 2013a), and it is only second to flooring workers. The rate of nonfatal injuries and illnesses involving days away from work of roofers is 209.4 per 10,000 FTEs which is above the average level of all construction (CPWR 2015).

CHAPTER 3

STATE OF PRACTICE AND RESEARCH

3.1 State of Practice

Ergonomics studies the human working efficiency and safety issues in their working environment (Wang et al. 2015; UMLHE 2000). Construction ergonomics practices include general guidelines promoted by NIOSH and OSHA which are designed to bring under the overall occupational injury rate in the industry. In addition, generic causes of LBD hazards are documented.

In terms of specified practices for LBD prevention among roofers, ISHA suggests that when stripping and removing materials from roofs, use upright scraping tools whenever possible, to provide mechanical leverage and reduce the need to bend (IHSA 2013). ISHA (2010) also recommend avoiding working on the floor, which can result in injuries to the back, hips, and knees. Instead, it suggests to increase the work height by using a workbench.

3.2 State of Research

3.2.1 Studies on LBDs among Roofers

The implemented roofing fatal injury studies (e.g., fall, slips) covered a diversity of aspects including risk assessment, communication, and prevention (Hisao 2014). In

contrast, the studies of non-fatal injuries in roofing activities mainly focus on surveillance and pathology at present.

The existing LBD studies in roofing industry are conducted with an emphasis on the nature, severity and causes of LBD, with the aid of surveys and observations. Hunting et al. (2004) have conducted a survey study on injuries among construction workers. It is found that half of non-fatal injuries among the roofers are in the back and most non-fatal cases are caused by overexertion, strenuous movement and high repetition. Fredericks et al. (2005) has analyzed the U.S. Bureau of Labor Statistics (BLS) data in roofing and has revealed the primary source of injuries among roofers is motion/position, which is associated with body postures and repetitive motions (Wang et al. 2015 a, b).

Another study reported that WMSD are the most common injuries and health problems in roofing activities that force roofers into early retirement. Sixty percent of roofers who exited the trade within one year left their jobs due to chronic pain, work-related musculoskeletal disorders, and poor health (Welch et al. 2010).

A survey study among Latino residential roofing workers showed that they value productivity over safety and reduce their use of personal protective equipment (PPE) when they feel that it reduces productivity and when it is uncomfortable (Arcury et al., 2013). The weak safety belief can have a negative influence on injury risk. It is reported that Hispanic roofers have both a higher non-fatal injury rate and a higher fatal injury incidence rate than white and non-Hispanic (Dong et al. 2010a, b).

There are also some recommended exercises to help prevent LBD injury. A study done by Hayden et al (2015) showed that a supervised stretching (and exercise) program

may reduce lower back pain. The exercise therapies in chronic low back pain were also reviewed in their study.

3.2.2 Work Related LBD Risk Factors in Roofing Activities

Decades of research have identified a potential link between certain physical workplace factors and LBD risk. A review by the National Institute for Occupational Safety and Health (NIOSH) of epidemiological (Putz-Anderson 1997) found evidence for an association between LBDs and heavy physical work, lifting and forceful movements, bending and twisting (awkward postures), and whole-body vibration (Wang et al. 2015 a, b).

The potential LBD risk factors are identified through roofing site visits, online video observations and the literature review. The typical work-related risk factors in the roofing shingle installation can be summarized as: slope angle, work pace, facing direction, and posture. Existing literature indicates a potential relationship between these factors and the LBD risk. For example, it is found that a reduced postural balance is observed as the slopes increase (Choi et al. 2008). Details about these factors are discussed below.

I) Stooped vs. Kneeling Postures

Stooped postures are put into common use at workplaces in agriculture, construction, mining, and other industries (Parekh and Phatak 2014). It is found that in agricultural activities, work requiring stooped postures has a strong association with high LBD incidence. For working at low levels, kneeling and squatting are often adopted to avoid severe bending (Fathallah et al. 2004). Studies demonstrate that there are good biomechanical reasons to view these postures as significant contributors to low back

pains (Jin et al. 2009). During a one-year low back pain study among 1773 construction workers, a dose-response relationship was found between severe low back pain and either stooping or kneeling (Holmström et al. 1992).

Through the review of literature, survey and on-site observations, roofers are typically involved with two main postures in shingle installation: stooped and kneeling. Roofers can use different working postures due to personal preference. Stooped posture,

Figure 1 (a): Stooped posture in roofing   **(b): Kneeling posture in roofing**

which requires the roofers to bend forward while holding their legs straight, is illustrated in Figure 1(a). In contrast, kneeling typically requires the workers to kneel on the roof and maintain trunk in parallel to the roof (Figure 1(b)). However, the existing risk assessment methods do not include any information regarding the relationship between injuries and stooping or/and kneeling. The LBD risk of each posture in the roofers' working environment is not well studied. Therefore, reducing the incidence of LBDs among roofers requires a new focus on identifying and describing stooped and kneeling postures as specific LBD risk factors in the workplace (Fathallah et al. 2004).

II) Roof Slope

The residential slope can vary from 12 °~40 °(NCINC 2015). There is a study on fall from the roof with slope degree and maximum frequency (Choi et al. 2008). The purpose of this study was to investigate the influence of surface slopes (18 °, 26 °, 34 °) on the shingling frequency and postural balance of males performing a simulated roof-shingling task. Maximum Acceptable Roof Shingling Frequency (MARSF) was recorded during the experiment. It was reported that the average MARSF at 18 ° slope was 206 shingles per hour, while that at the 26 ° and 34 ° slopes were 195 and 168 shingles/h, respectively. This finding indicates a reduced postural balance at steep slopes (Wang et al. 2015 a, b).

III) Facing Direction

Based on the online video search and on-site observation, it is noted that different roofing materials can have different installation methods on rooftops (NINDS 2014). For three- or four-tab residential shingles, roofers often install them parallel to the ridge, which requires the roofers to stand facing uphill. For solar panels, it is found through video observation that the roofers often stand perpendicularly to the ridge while installing them in order to avoid stepping on these panels.

In addition, in the recent ergonomics study, it is found that manual handling of sudden loading on uneven surface can have a significant difference from on the ground in terms of LBD risk (Zhou et al. 2015), which provokes the needs for studies on jobs conducted on uneven surfaces such as roofs. Moreover, the symmetry was detected during bending on uneven slopes (Hu et al. 2013; Ning et al. 2011). A displacement of the C7 joint (in the neck area) to the upper edge of the slope was found when bending on uneven slopes than on the flat ground. It showed that people tend to incline to upper edge

when standing and bending on uneven slopes. Also, the left-sided and right-sided lumbar muscles were reported to have different tensions and non-simultaneous cessation of muscle activities. These findings indicate that different facing directions can have different bending motions which can bring about different trunk flexions and muscle activities (Wang et al. 2015 a, b).

IV) Work Pace

Dai et al. (2010) have reported that the horizontal load speed can have a significant on the spinal loadings. A deeper flexion and higher muscle activations were found in fast manual materials handling and lifting. Whether this finding applies to roofing shingle installation process is unknown. The reported frequencies in (Choi et al. 2008) will be used as benchmark for the design of frequency levels in this study.

CHAPTER 4

LBD RISK ASSESSMENT METHODS

Epidemiological studies have identified certain physical risk factors for LBDs in workplaces and some predictive models are developed based on the selected factors. However, the models cannot be directly used for roofing activities due to dissimilarity in the survey sample that determines the coefficients and also, these selected risk factors need modification before applying to roofing tasks. To be specific, these models do not take into account roofer working postures (e.g., stooped, kneeling) and slanted rooftops. Through the literature review and the site observation, the main risk factors in roofing tasks are identified and summarized as work pace, facing direction, posture, and slope angle (Wang et al. 2015 a, b).

However, in order to evaluate these risk factors, an appropriate risk assessment method needs to be selected. The existing WMSD assessment tools are reviewed and evaluated based on the needs of the planned LBD study. Table 1 (adapted from [Wang et al. 2015a]) provides a summary of the risk assessment methods in terms of their principle, applicability, pros, and cons, etc. Appropriate methods are selected after a follow-up discussion in terms of their suitability.

4.1 Survey

Self-report is widely applied in studies because it is inexpensive, easy to conduct, applicable to the large population. However, self-report requires the workers to stop the

ongoing works and spend time to answer the questions or fill in the questionnaires. Wang et al. (2015) reviewed a number of wide-used non-fatal injury survey tools, the Nordic Musculoskeletal Questionnaire (Kuorinka et al. 1987; Aarås et al. 1998; Kucera et al. 2009; Reme et al. 2012), Task Analysis (Silverstein 1985), internet survey, recorded videos and video conferences (HSE 2014) (Wang et al. 2015 a, b).

There is a series of survey work on roofers' nonfatal injury for diagnosis of LBD nature and injury formation (GMU 2015; IN 2008). The advantage of the self - report method is that a large number of workers can report issues and problems that are difficult to observe (e.g., pain and perceived workload), and this method is cost-effective and applicable to a wide range of occupations. The downside of the self-report method is that the results are based on subjective assessment and thus can vary significantly among individuals. Also, the survey responses can be biased due to personal implications, undermining the reliability of these methods in comparison to other methods such as direct measurement and advanced sensing techniques (Spielholz et al. 2001; Jones and Kumar 2010).

This study has conducted surveys (APPENDIX II) among the participants to rate and report discomfort on lower back and other body parts on different working conditions.

4.2 Observation

Observation is a systematic recording of postures at workplace (i.e., region, frequency, severity, duration) (David 2005). There are a large number of observational tools developed for industrial use featuring postural loading assessment tools. The OWAS, PATH evaluated the WMSD risk level of different body segments (back, arms, and legs) by assessing postures of workers during their task performance. A whole body

postural analysis tool called Rapid Entire Body Assessment (REBA) was developed to mainly analyze unpredictable working postures detected in the health care and service industries (Hignett and McAtamney 2000). These observational tools have less interference with worker task performance and are cost effective as minimal instrumentation is required. Therefore, observations are widely used in field studies. However, observational tools rely on experts' visit and sometimes the evaluation is subjective and has large inter-rater differences. Besides, the limitation is that the assessment cannot be performed continuously and only a limited number of jobs can be assessed during the experts' visit.

In this experiment, the observational study is conducted to assess the postural loading of lower extremities (i.e., legs, ankles) of two postures to reveal the difference.

4.3 Direct Measurement

Direct measurement is often used to assist or replace expert observation as it provides higher accuracy and repeatable measurements. When conducting direct measurement, markers or sensors are directly attached onto the human body (skin or clothes) to record human location, body segment 3D motions, muscle activities, and heart beat etc. Electromyography (EMG), optical markers, goniometers, inclinometers, optical scanners, and sonic sensors which are frequently used in direct measurement to analyze biomechanics and tissue and joint loading (CPWR 2013a). Among them, EMG is mainly applied in studying muscle exertions by attaching a group of sensors on the skin over the sampling muscles (Ning and Mirka 2010, Ning et al. 2014; Marras and Granata 1997a,b). It records myoelectric signals, and is widely used to evaluate muscle tension and muscle fatigue (Ning 2011; Nimbarte et al. 2014; David 2005).

Various optical-marker-based direct measurement methods are commercially available such as Vicon, APAS (2014), CODA, Motion Analysis, and Qualisys. Three-dimensional (3D) coordinates of all body markers can be recorded in real time using dedicated computing algorithms to track the position and angular movement of different body segments (Li and Buckle 1999). The kinematics data will then be combined with muscle EMG data to estimate muscle and joint loadings using biomechanical models (Lloyd and Besier 2003; Wang et al. 2015 a, b).

4.4 Biomechanical Model

Those models are prototypes that model reality activities and assignment weights to different risk factors. Below are several examples of the well-known tools associated with trunk loadings. The NIOSH Lifting Equation is designed assess the manual material handling risks during lifting and lowering tasks in the workplace by occupational health professionals. This equation records certain job task variables to evaluate the risk of the lifting practices. It can be used to estimate the recommended weight to be lifted. Besides, 4D WATBAK is a biomechanical modelling tool which can be used to estimate both acute and cumulative loads at main body joints (4D WATBAK). It can be used to estimate the risk of injury associated with a variety of occupational actions, including pushing, pulling, lifting, lowering, holding, carrying, etc. The development of biomechanical modeling to the back has made it possible to assess spine loading using remote sensing method (Ning and Guo 2013). Nowadays, biomechanical models are usually applied for post-processing of human motion data collected by direct measurement or remote sensing methods. But it highly relies on the accuracy and processing efficiency of the captured sensing data (Wang et al. 2015 a, b).

4.5 Selection of Risk Assessment Methods

In the thesis study, LBD risk assessment methods are selected for data collection and analysis. Vicon is reported to have an accurate localization and tracking of the multiple joints and segments, which can be used accurately and continuously to calculate the joint angles. EMG is a well-established muscle sensor which can be used to measure the muscle activity, fatigue, and muscle utilization patterns. Specifically for our LBD study, the Vicon system is utilized to record trunk angle data, and EMG can be used to accurately and reliably record the muscle signals of the back muscles. Also, the video observation is applied to measure the postural loading of the lower extremities in kneeling and stooped postures. The survey is conducted to record the perceived discomfort in the back and other body parts (Wang et al. 2015 a, b).

Table 1: An overview of LBD risk assessment methods (adapted from [Wang et al. 2015a])

Methods	Principle	Example	Pros	Cons	Applicability
Survey	Self-reported approach to help diagnose pain	Questionnaire (Spielholz et al. 2001); interview (Dane et al. 2002);	Efficient and cost-effective	Imprecise perceptions; personal implications	Easy to implement
Observation	Systematically records awkward postures and evaluate risk	PATH, REBA	Inexpensive; minimal disturbance	Expert required, inter-rater difference	Site visit
Direct measurement	Directly attach sensors on the human body to capture movement or muscle activities	EMG, Vicon	Accurate and various exposure data collection	Markers attached directly and tightly on the skin	Short and repetitive movements
Predictive/ Biomechanical model	Measure the risk as a weighted sum or formula of selected risk factors, e.g., load, posture, distance, etc.	Utah lifting index, NIOSH lifting equation, Open-Sim, 4D Watbak	Flexibility, can be used to simulate extreme conditions	Rely on accurate and complex measurement of parameters defined by the model	Manual handling and lifting; large data collection

CHAPTER 5

EXPERIMENT DESIGN AND IMPLEMENTATION

The shingle installation process was selected as the task to be simulated in lab considering that it is a primary roofing task and requires constant bending. The purpose was to understand the relationship between the selected risk factors (i.e., roof slope, posture, facing direction, and work pace) and LBDs among roofers. To this end, a factorial experiment was conducted, in which the selected ergonomic risk assessment techniques were utilized to capture the dependent variables for estimating the LBD risk in different work conditions (Wang et al. 2015b).

5.1 Variables

Four risk factors (independent variables) are evaluated in the experiment: 1) Slope: 0°, 15°, 30°, as denoted in Figure 2; 2) Posture: stooped and kneeling, as denoted in

Roof slopes

Figure 2: Roof slope angles

Figure 1; 3) Facing direction: uphill and sideways; 4) Frequency: slow (12 seconds/shingle), fast (6 seconds/shingle). The frequency is set according to site observations and studies on maximum acceptable working frequency on roof slopes (Choi et al. 2008).

Figure 3: Maximum trunk flexion angle (stooped)

Two types of response variables (dependent variables), i.e., maximum trunk flexion angle and normalized EMG signals, were measured to reflect the effects of the risk factors and indicate the LBD risk. The maximum trunk flexion angle (or maximum trunk inclination angle) was the maximum of the trunk flexion angles during a whole shingle installation cycle. The trunk flexion angle was defined as the angle between the vertical line and the line between the C7 and L5/S1 joints (Hu et al. 2013; Ning et al.

2011), as shown in Figure 3. A natural upright posture generates an approximate zero trunk inclination. The lumbar joint moment, which is directly associated with spinal loading, increases as the trunk inclination increases from 0° to 90° (Ning and Guo 2013). Larger trunk flexion angle indicates higher spinal moment and the higher associated spinal injury risks. The normalized EMG measures the activation levels of two pairs of lumbar extensor muscles (Erector spinae and multifidus), with one sensor on each side. These two independent variables were used to help establish LBD risks (Wang et al. 2015b).

5.2 Participants

There were 15 participants in this study. The subjects for the experiment are voluntary researchers and students. The age, stature and whole body mass (with standard deviation) of this study population were 25.2 years (3.3), 176.4 cm (3.4), and 70.6 kg (8.4). Female participants were excluded from the study as 99.5% of roofers are male (BLS 2015d). All subjects had no history of chronic low back injury. The research involving human experiments was approved by the Institutional Review Board of West Virginia University (Hu et al. 2014; Wang et. Al 2015).

5.3 Instruments

The participants' trunk kinematics data were collected using an optical motion analysis system – Vicon (T-Series Camera System, Oxford, 2002). Two retroflective Vicon markers were placed on the participant's trunk: one at the C7 joint (around the neck) and the other at the L5/S1 joint. Real-time 3D coordinates of the two joints can therefore be obtained. These data were used to calculate joint locations, joint angles, and movement velocities, etc. Additional markers were placed on the shoulders, arms, and

legs for the convenience of the recognition of postures and facing direction. Vicon data were recorded at a frequency of 100Hz.

Muscular activities of the lumbar paraspinal muscles (erector spinae and multifidus muscles) were recorded using a surface electromyography (EMG) system (Bagnoli, Delsys, Boston, MA, USA). Bipolar surfaced EMG electrodes were placed 4 cm lateral from the L3 spinous process measuring the erector spinae (ES) muscles and 2 cm lateral from the L4 spinous process measuring multifidus muscles (MUL) (Hu et al. 2013). These muscles were selected to estimate the muscle tension and the activation of the lumbar muscles (Hu et al. 2013; Hu et al. 2014). The EMG data was collected at a rate of 1000 Hz and was synchronized with Vicon data on the software platform of Vicon Nexus (Vicon, Oxford, 2002). Participants' maximum voluntary contraction data of the lumbar muscles was collected using a dynamometer (HUMAC Norm, Computational Medicine, Stoughton, MA, USA).

A 1.2 m by 1.6 m custom-made wooden platform was built to mimic the rooftop on which the simulated shingle installation was conducted (Figure 4). The platform was connected to a hydraulic lift. By elevating the lift, the connected wooden structure could form a slope angle ranging from 0° to over 60°. Anti-skidding tape was attached to the platform surface to increase the friction and avoid slips or falls. Video streams of the experimental trials were recorded by the Canon video camera (Canon, VIXIA HF R500, 2005), which is used for the observation study.

Figure 4: Wooden roof platform elevated by hydraulic lift

5.4 Procedure

Figure 5 shows the procedure of the experiment. It is divided into two parts: preparation and shingle installation. The preparation work includes the platform set-up and initialization of the Vicon and EMG system. The main part of the work is to simulate the shingle installation task with the combinations of different risk factors.

5.4.1 Preparation

1) The wooden platform was adjusted to three slope levels. 2) Before the shingle installation trials, the maximum voluntary contraction (MVC) was collected using a dynamometer (HUMAC Norm, Computer Medicine, Stoughton, MA, USA). MVC is the greatest amount of tension a muscle can generate and hold (Dic 2015). Each muscle's MVC was saved and used to normalize the EMG signals recorded during the shingle installation process. The details are introduced in Section 5.5. 3) Vicon camera system was calibrated, including: a) static calibration, which calculates the center of the capture

volume, and determines the orientation of the 3D workplace; b) dynamic calibration, which is to calculate the relative positions and orientation of the camera by moving a calibration wand throughout the whole capture area.

Figure 5: Procedure

5.4.2 Shingle installation

The shingle installation process is the main part of the experiment. The protocol is described as below. The experimental procedure was introduced to the participants upon their arrival to the lab. After a warm-up session (5 min), surface EMG electrodes and Vicon markers are secured to the designated locations on the back using double-sided tape. During the data collection, each participant performed the shingle installation simulations on different working conditions, which are the combinations of the four independent variables, such as stooping facing uphill on 15° slope at slow work pace. The protocol defined that a complete shingle installation trial includes three steps: trunk flexion, nailing, and trunk extension. Specifically, it required the participant to use 1/6 of

a given time (slow cycle: 12 seconds; fast cycle: 6 seconds) to flex the trunk from an upright standing to reach the first nailing, $\frac{2}{3}$ time to nail at four spots which are evenly distributed from the left edge to the right edge of an asphalt shingle (shingle length: 36 inches), $\frac{1}{6}$ time to come back to upright standing position. This study particularly focuses on the nailing process during which the roofers constantly bend their trunk. The participants were required to hold a nail gun and use it to touch the nailing spots during the shingle installation process.

The stooped postures and kneeling postures were separately simulated due to their dissimilarity in working motions, body movement, and muscle utilizations. Firstly, the stooped postures were simulated on combinations of 3 factors, that is, the slope, the facing direction, and the work pace. For each participant, stooped postures were conducted on 12 combinations of factors and had 24 trials. Secondly, for kneeling, no facing sideways working mode is found through the literature review or site visits. Therefore, kneeling postures were performed on combinations of 2 factors, slope and work pace. In total, kneeling postures were conducted on 6 combinations of factors and had 12 trials. Lastly, the survey study was conducted among the participants to collect the perceived discomfort in the back and other body parts on different working condition. Video streams of the shingle installation processes were also recorded and used for observational study. The observation data can be used to validate the Vicon data and capture the flexion of other body parts.

5.5 Data Processing

Trunk flexion angle: The trunk kinematic data collected from the Vicon during the trials were used to compute the trunk flexion angle. The two markers placed on the

trunk returned 3D coordinates of C7 joint denoted as (x_1, y_1, z_1) and L5/S1 joint (x_2, y_2, z_2) . The trunk flexion angle, is calculated as, $Angle = 90 - (360 / 2\pi) * \text{atan} \{(z_2 - z_1) / \sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2}\}$. Provided the continuously recorded location of C7 and L5/S1, the trunk flexion angles of a complete shingle installation process were computed and the maximum was used as the response variable. As an example, one stooped trial was plotted in Figure 6. The maximum angle 85.36° was marked. From the plot, the trunk bending pattern for each phase can be recognized. In the trunk flexion phase, a fast increased trunk flexion angle was detected. In the nailing process, a constant severe bending was detected, and the maximum flexion angle was also detected during the process. The trunk extension is a reversed flexion with a decreased trunk flexion angle.

Figure 6: A time series plot of trunk angle during shingle installation process

Muscle activity: The EMG data collected during a shingle installation trial were rectified, filtered, normalized, and averaged over the nailing period. The full wave

rectification took the absolute value of the signals and the nonnegative rectified EMG signals are plotted in Figure 7. Then, the EMG signals were filtered using 4th order Butterworth filter, a band-pass filter (Math Works, 2013). After filtering, the data is smoothed and the outliers can be reduced. The profile of the EMG data after filtering is plotted in Figure 7. Thirdly, this filtered data was normalized in order to compare different individuals. There are many factors (e.g., electrode configuration, electrode placement, temperature, and perspiration, etc.) and individual differences that can influence the raw EMG data, making the direct comparison of raw data error-prone (Mark and Karen, 2005; Sousa and Tavares 2012). In order to compare EMG activities of different individuals and different muscles, the EMG needs to be normalized. For each muscle, the MVC is collected as a reference value which is to be divided by EMG signals during a task. The normalized EMG data is the relative measure of the muscle activation divided by the MVC. Lastly, to compute average normalized EMG signals over the nailing process. Nailing process, accounting for 2/3 of the total cycle, was extracted by defining a uniform starting and ending time point in the whole cycle. As denoted in Figure 7, two peaks were captured during a single shingle installation cycle. The first peak of EMG signal represents the trunk flexion process, and the second peak represents the trunk extension process. The flat curve between the peaks represents the nailing process. The averaged normalized EMG signal during the nailing process is used as the response variable in this experiment to estimate the muscle activation and spinal loadings. A computational MATLAB program is developed to process and analyze Vicon and EMG data. The source code is attached in APPENDIX I. The processed data, including

the computed trunk flexion angle and normalized EMG data, are attached in APPENDIX III.

Figure 7: Processed EMG signals

5.6 Statistical Analysis

Due to the multivariate nature of the data collected in this study, both MANOVA and univariate ANOVA techniques were used. Prior to conducting statistical analysis, the assumptions of the ANOVA technique (normality of residuals, homogeneity of variances and independence of observations) were evaluated using the graphical approach advocated by Montgomery (2005). Multivariate analyses of variance (MANOVA, $p < 0.05$ for Wilks' Lambda statistic) were conducted. And for those independent variables and interactions that were found to be significant in MANOVA, univariate ANOVA ($p < 0.05$ for F statistic) were conducted for their effects on each dependent variable. In the analysis, each repetition was treated as a single observation. The effect of each

independent variable on each dependent variable was then investigated using repeated measures ANOVA with 'subject' considered as a random factor. The statistical analysis is performed in the Minitab® 17.1.0 software environment.

5.6.1 MANOVA test

Multivariate analysis of variance (MANOVA) can be viewed as ANOVA with several dependent variables. The factorial design includes two types of dependent variables, that is, trunk flexion angle (1 vector) and EMG signals (4 vectors). As such, MANOVA tests are applied to study the difference in 5 vectors of means. In addition, every two independent variables could have interaction effects on the dependent variables. An interaction effect is a change in the simple main effect of one variable over the levels of the second (Gelman and Hill 2005). In other words, the effect of one independent variable on the dependent variable may not be the same at all levels of the other independent variable. The interaction effects between different independent variables were also studied using MANOVA analysis. The null hypothesis is that the two factors have no interaction between each other. If the p-value returned from MANOVA analysis is less than 0.05, the null hypothesis is rejected. Hence, an interaction is found in this case. After MANOVA tests find an independent variable or interaction to be significant, subsequent ANOVA tests are conducted on each dependent variable.

5.6.2 Univariate ANOVA test

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(s) (Miller 1997). ANOVA is utilized as the tool for the factorial analysis in that

t-test only compares 2 different levels of one IV (independent variables) whereas ANOVA compares multiple levels of one IV. In this study, the slope has three angles.

ANOVA analysis was conducted to find out the factors with significant influence on the response variables (i.e., maximum trunk flexion angle and normalized EMG data). In ANOVA analysis, the F ratio is an output which tests whether the means of different factor levels are significantly different from one another. The F ratio is computed by dividing mean square between groups by mean square within groups, denoted as **F ratio** = $MS_{bet}/MS_{w/in}$ (Montgomery 2005). Mean square between groups is computed as $MS_{bet} = \sum n (\text{cell means} - \text{grand mean})^2$, n denotes the total number of observations, cell means denotes the mean of each factor level, and grand mean denotes the mean of the cell means. The mean square within groups is computed by the equation: $MS_{w/in} = \sum (X - \text{respective cell means})^2$. X denotes an observation value, and respective cell means represents the means of the corresponding factor level. A large F ratio demonstrates that the variation among group means is not by chance, therefore, different groups have a significant difference (SPSS, 2015). The p value is determined from the F ratio and degrees of freedom. All the factors are hypothesized to have a significant effect on the response variables (Fathallah 2004; Zhou et al. 2015). ANOVA tests the null hypothesis that there is no significant difference between means of the factor levels. The null hypothesis is rejected when the returned P -value is less than a pre-defined significant level (i.e., 0.05), denoting a significant difference between different factor levels. A small p value means that the factor has a significant influence on the response variable.

As described in the experiment procedures, the stooped observations and kneeling observations were separated due to their dissimilarity in body movement and muscle

utilization, and ANOVA analysis was respectively conducted on each posture category. When conducting ANOVA analysis on a certain independent variable, the total stooped or kneeling observations were divided into groups by the factor level. A confidence interval defines an estimated range of values which an unknown population mean has a high chance to fall into. The 95% confidence interval was used in the study, which has 95% likelihood to include the population mean (George 1997). For each independent variable tested to have a significant effect on the response variables, the confidence interval plots of its different factor levels were drawn to show the sample's tendency and variability.

5.6.3 Post Hoc Test

For an independent variable of three or more factor levels (e.g., slope angle has three levels), the observations were divided into three or more groups by the factor level and ANOVA analysis was conducted. However, ANOVA analysis only concludes whether at least two groups are significantly different, but does not show which specific groups are significantly different (Montgomery 2005). In this study, given that ANOVA analysis has determined that the three slope groups were significantly different in terms of the maximum trunk flexion angle, we can still not conclude whether 0° group is significantly different from 15°, or 15° group is significantly different from 30°, or 0° group is significantly different 30°. Therefore, post hoc test is required to determine which specific groups are significantly different from one another when the factor has three or more factor levels.

In this study, the Tukey's HSD test, a post hoc test was used on trunk flexion angles to further investigate the differences between three slope groups (Lowry 2008). Tukey's test is essentially multiple pairwise t-test. Tukey's test compares the means of

every angle group to the means of every other group and identifies any difference between two means that is greater than the expected standard error. $t = (M_1 - M_2) / \sqrt{MS_w(1/n)}$

CHAPTER 6

RESULTS

6.1 Statistical Analysis Results

In this study, MANOVA and ANOVAs were conducted to study the effects of each factor and investigate the interaction between independent variables. For all statistical analysis in this study, the criteria p-value is set to be 0.05. The MANOVA and subsequent ANOVA results are presented in Table 2 for stooped postures and Table 3 for kneeling postures. In this study, two pairs of surface EMG sensors were used to measure the activities of two pair of lumbar spinal muscles: erector spinae (ES) and multifidus (MUL), as described in Section 5.3. Each pair consisted of a left-sided one and a right-sided one. Throughout the entire analysis, the left-sided and right-sided EMG signals were consistent with each other. Therefore, the statistical analysis and the following figures report the average of EMG signals on two sides.

The ANOVA analysis revealed that: 1) the maximum trunk flexion angle was significantly affected by slope angles, both for stooped and kneeling postures; 2) the maximum trunk flexion angle was significantly affected by facing directions in stooped trials; 3) EMG data demonstrated that the erector spinae and multifidus muscles are significantly affected by frequency on stooped trials; 4) EMG data also demonstrated that the multifidus EMG signals are significantly affected by task frequency on kneeling trials.

From Table 2 and Table 3, the slope is found to have a significant effect on the trunk flexion angle. As described in 5.6.3, ANOVA analysis does not show which specific groups are different from one another given an independent variable of three more factor levels. As such, the Tukey's HSD test, a post hoc test was used on trunk flexion angle to further investigate the differences between three slope angles. For 3 slope angles, all the pairwise comparisons are performed using Tukey's Test and an overall risk level of 5%. The detailed results are presented in the Section 6.2.1 and 6.3.1.

In addition, the interaction between every two factors was tested for both stooped postures with 3 combinations and kneeling postures with 1 combination in the format of "A*B". The results are presented in Table 2 and Table 3. A strong interaction between Slope and Facing direction on trunk flexion angle is found, which will be discussed in details in Section 6.2.2. Besides this, no other interactions are found in trunk flexion angle either in stooped postures or kneeling postures.

In the following section, the results of stooped and kneeling postures are respectively presented. For each posture, ANOVA analysis is conducted to study the effects of each factor on the response variables and 95% confidence interval is plotted for each factor level. Detailed results are reported in the following.

Table 2: MANOVA and ANOVA results for trunk flexion angle and EMG (stooped): statistical significance and interactions of the factors (left and right sides combined)

Factors	MANOVA	ANOVA		
		Trunk Angle	ES (EMG)	MU (EMG)
Slope	+++	+++	/	/
Frequency	+	/	++	++
Direction	++	+++	/	/
Slope*Direction	++	+++	/	/
Slope*Frequency	/	/	/	/
Direction*Frequency	/	/	/	/

(Note: +++: $p < 0.001$; ++: $p < 0.01$; +: $p < 0.05$; /: $p \geq 0.05$)

Table 3: MANOVA and ANOVA results for trunk flexion angle and EMG (kneeling): statistical significance and interactions of the factors (left and right sides combined)

Factors	MANOVA	ANOVA		
		Trunk Angle	ES (EMG)	MU (EMG)
Slope	+++	++	/	+
Frequency	++	/	/	++
Slope*Frequency	/	/	/	/

(Note: +++: $p < 0.001$; ++: $p < 0.01$; +: $p < 0.05$; /: $p \geq 0.05$)

6.2 Stooped Postures

Table 4: The mean (SD) values of dependent variables at different independent variable levels (ESl, ESr, MUI and MUr refer to left erector spinae, right erector spinae, left multifidus and right multifidus respectively) (Stooped)

Factors	Conditions	Trunk angle(°)	ESl (%)	ESr (%)	MUI (%)	MUr (%)
Slope Angle	0°	92.23 (2.89)	10.90 (5.42)	13.00 (5.55)	15.31 (6.50)	14.12 (9.86)
	15°	88.40 (7.16)	9.70 (5.93)	12.6 (7.59)	15.79 (8.38)	12.43 (8.55)
	30°	82.21 (12.50)	9.32 (5.84)	11.55 (7.30)	14.9 (7.61)	11.76 (8.50)
Facing direction	side	93.75(4.12)	9.33 (5.91)	11.91 (7.37)	15.86 (8.71)	12.97 (8.71)
	uphill	81.98(9.85)	10.17 (5.70)	12.70 (6.88)	15.05 (7.09)	13.68 (8.73)
Frequency	fast	86.16(10.35)	11.00 (6.08)	13.4 (7.00)	16.67 (7.99)	14.37 (8.66)
	slow	87.22(9.58)	8.71 (5.35)	11.4 (7.02)	14.01 (7.31)	12.45 (8.68)

Table 4 summarizes the effects of all the three independent variables on all the dependent variables for stooped postures. Significant effects of slope, facing direction and frequency were found per the results of MANOVA (Table 2). The follow-up univariate ANOVAs revealed the interactions and effects of the independent variables on each dependent variable.

6.2.1 Influence of slope angles

a) Trunk flexion angle: The statistical analysis (Table 2) determines that the slope to have a significant impact on the maximum trunk flexion angle. All the stooped observations were divided into 3 groups by the slope angle level. The 95% confidence intervals were constructed for each slope level. The Tukey's test was performed and identified that 0° and 15° can be grouped as Group A, whereas 30° is grouped as Group B. It means that mean of trunk flexion in Group A is significantly different from that in Group B. Within the group, each level has no significant difference from the other.

The maximum flexion angle calculated from Vicon data shows the trend that the maximum flexion angle is decreasing as the slope angle increases, shown in Figure 8. This result

is demonstrated by observations on recorded video streams. It is worth noting that, all the stooped trials simulated on the roof slope are observed to have a maximum bending angle of larger than 70° during the nailing process, which is categorized as high degree of trunk bending by ergonomic observational tools, e.g., PATH, OWAS, REBA.

Figure 8: Effects of slope angles on maximum trunk flexion angle (Stooped)

(Note: X-axis denotes three slope angles, and Y-axis denotes the corresponding maximum trunk flexion angle; the mean of each factor level is marked by a dot. 95% confidence interval for the mean plotted.)

b) EMG signals: The trend revealed by Vicon is consistent with EMG data as the same trend is detected both in erector spinae and multifidus (Figure 9) muscles. However, the EMG signal difference between different slope levels is almost negligible (within 3%). Statistical analysis as shown in Table 2 states that the slope angle does not show a statistical significance on

muscle activation in this study. In addition, the survey conducted among the participant does not show a significant difference of discomfort in back on different slopes.

Figure 9: Effects of slope angles on EMG signals (stooped)

6.2.2 Influence of facing direction

a) **Trunk flexion angle:** The statistical analysis (Table 2) shows that facing direction has a significant effect on the maximum trunk flexion angle. Figure 10 shows that, the maximum trunk flexion angle in trials facing sideways (denoted as A) is significantly higher than that of facing uphill (denoted as B), which indicates that the peak spinal loading in facing sideways working is higher than the peak in facing uphill.

Figure 10: Effects of facing directions on maximum trunk flexion angle (stooped)

Figure 11: Interaction plot of Slope and Facing directions (Stooped)

MANOVA and subsequent ANOVA analysis found that the facing direction and slope angle have interactions on the maximum trunk flexion angle. The interaction effect is plotted in Figure 11. At each slope level, the maximum trunk flexion angles of two facing directions were compared. It is found that, on 15 ° and 30 ° slopes, the maximum trunk flexion angle of facing sideways is significantly higher than that of facing uphill. Besides, it is worth noting that: 1) For facing uphill, as slope's slant angle increases, the trunk flexion angle decreases, which echoes the finding of 6.2.1; 2) For sideways, the maximum flexion angle maintains approximately the same for all three slope levels.

Figure 12: Time series plot of max trunk flexion angle for facing sideways

Figure 13: Time series plot of max trunk flexion angle for facing uphill

The possible mechanism of finding is that, when bending on the laterally slanted surface (or facing sideways), the participant needs to stretch towards left to reach the leftmost nailing spot, which is at a lower position. In this study, all the participants are right handed and their right foot is placed at a higher position than left when standing on uneven slopes. When installing shingles on uneven slopes, a deeper flexion is required at the left-sided nailing spots than at the right-sided. In order to validate the above mechanism, the trunk flexion angle for one shingle installation cycle was plotted. Figure 12 shows the profile of trunk flexion angle during shingle installation when facing sideways. Figure 13 shows the trunk flexion during shingle installation when facing uphill. In both figures, fast and slow trials were plotted and observed to have the similar trend. The maximum trunk flexion angle was marked in the figures. Through comparison, distinct facts for facing sideways from facing uphill were discovered: 1) during the nailing process (denoted in Figure 6), a higher variance is discovered in facing sideways mode (SD: 11.4 °) than that in facing uphill (SD: 4.2 °) on a slanted surface (i.e., 15 ° and 30 °). The computed variance is the average of variances on 15 ° and 30 ° slopes, and 0 ° is excluded as facing direction and facing uphill have no difference on flat ground; 2) The maximum trunk flexion angle in facing sideways trials was detected at the beginning of the nailing process; 3) The trunk flexion angle throughout the nailing process in facing uphill trials maintains almost the same. 4) The average nailing-phase trunk flexion angle of all participants is computed, and the sample mean is summarized as below: sideways: 82.1 °; uphill: 79.1 °.

It is revealed that the average trunk flexion angle for facing sideways is still higher than that of facing uphill, which indicates a higher cumulative spinal loading. But this difference is significantly less than that of the maximum trunk flexion angle in Figure 10. (i.e., sideways: 93.3 °; uphill: 82.0 °).

b) EMG signals: The EMG data does not show significant difference between two facing directions. Hu et al. (2014) conducted a LBD study comparing bending on a slanted surface (15 °and 30 °) against on flat ground (0 °) and states that EMG data of left side paraspinals demonstrated significantly lower values on a slanted surface. Further study of left and right side back muscles comparison on different facing directions is needed.

6.2.3 Influence of work pace

a) EMG signals: The shingle installation consists of a series of different operations: flexion, nailing, and extension. The participants are required to conduct a complete shingle installation process at a different work pace. The nailing process was extracted and average normalized EMG data for nailing phase is used for the factorial analysis. The frequency was demonstrated to have a significant impact by EMG data as shown in Table 2. Erector spinae and multifidus EMG signals showed a consistent trend in both erector spinae and multifidus muscles that fast work pace generates significantly higher normalized EMG data (Figure 14). The EMG signals of the fast group (denoted as A) are significantly higher than that of the slow group (denoted as B). Those findings indicated relatively strong muscle activation at fast work pace and have implications for higher LBD risk.

Figure 14: Effects of work pace on EMG signals (Stooped)

b) Trunk flexion angle: Statistical analysis shows that work pace has no significant effects on flexion angle captured by Vicon. For slow and fast cycles, the participants employed the exact same posture and procedures, which would only result in a negligible difference in movement.

6.3 Kneeling Postures

Table 5: The mean (SD) values of dependent variables at different independent variable levels (ESl, ESr, MUI and MUr refer to left erector spinae, right erector spinae, left multifidus and right multifidus respectively) (Kneeling)

Factors	Conditions	Trunk angle(°)	ESl (%)	ESr (%)	MUI (%)	MUr (%)
Slope Angle	0°	37.87 (15.86)	10.36 (5.7)	16.25 (6.94)	10.61 (4.05)	9.93 (5.93)
	15°	25.42 (11.71)	11.24 (4.87)	16.56 (6.53)	11.38 (2.78)	10.06 (3.33)
	30°	23.61 (9.31)	12.47 (5.25)	17.72 (6.45)	13.60 (1.56)	10.88 (2.83)
Frequency	fast	28.34 (13.33)	11.40 (5.26)	16.97 (6.61)	12.51 (2.84)	11.15 (4.02)
	slow	29.60 (14.75)	11.31 (5.41)	16.72 (6.69)	11.22 (3.45)	9.43 (4.32)

For kneeling postures, the facing direction was assumed to be only uphill as only uphill was observed in roofing shingle installation. Besides, the preliminary trials of kneeling towards sideways on the slope have found that a significant amount of effort is needed to maintain balance. There, facing sideways was excluded from the experiment design for kneeling postures. The effects of the slope angles and work pace are discussed as follows. Table 5 summarizes the effects of the slope angles and work pace on all the dependent variables for kneeling postures. Significant effects of slope and frequency were found according to the results of MANOVA for kneeling postures (Table 3). The follow-up univariate ANOVAs revealed the interactions and effects of the independent variables on each dependent variable.

6.3.1 Influence of slope angles

The kneeling observations were divided into three groups according to the slope angles and 95% confidence interval was plotted for each slope group. The response of Vicon showed the trend that the flexion angle decreases as the slope rises, which indicates a less severe bending,

as shown in Figure 15. The Tukey's test was performed, and it determined that 0° slope was grouped as Group A, whereas 30° and 15° were grouped as Group B. The result means that mean of trunk flexion in Group A is significantly different from that in Group B. But within the group, the slope groups have no significant difference.

Figure 15: Effects of slope angle on maximum trunk flexion angle (Kneeling)

The effects of slope angles on EMG signals are demonstrated in Figure 16. It indicates a trend that ES_l, ES_r, MU_l and MU_r signals grow as slope angles increases. A significant higher MU muscle activation (both sides) was found in the 30° (marked as Group B) than 0° and 15° (Group A).

Figure 16: Effects of slope angles on EMG signals (Kneeling)

6.3.2 Influence of work pace

Figure 17 demonstrates that work pace has a significant effect on multifidus EMG signals. It has implications for more active muscle utilization at fast work pace than slow work pace for kneeling postures. The EMG signals of the fast group (denoted as A) are significantly higher than that of the slow group (denoted as B). However, for erector spinae, no significant difference was detected between fast and slow trials (Table 3).

The mechanism can be explained as below. Different from stooping, when kneeling, the trunk of the subject is so close to the rooftop that the bending and extending phases are no longer needed, especially for steep slopes. During the whole cycle, the participant's trunk has no

obvious movement. Instead, the arm and shoulder movement speed is adjusted to adapt the work pace changes. In order to differentiate the muscle activities at fast and slow frequencies, one possible solution is to extend the length of the shingle so that the participant needs to significantly move their trunk to reach the two ends of the shingle. Another possible solution is to maximize the time difference between two frequencies, for example, make the fast frequency even faster (i.e., 4 seconds/shingle).

Figure 17: Effects of work pace on EMG signals (Kneeling)

6.4 Summary of the Findings

From above, it was revealed that: (1) as the slope angle increases, the maximum trunk flexion angle gradually decreases for both stooped and kneeling postures; (2) facing sideways results in higher maximum trunk flexion angle and slightly higher average trunk flexion angle

than facing sideways; (3) fast work paces generally generates higher muscle activation and utilization in both stooped and kneeling postures. (4) For stooped trials, there is an interaction effect between facing direction and slope angles on the trunk flexion angle.

CHAPTER 7

DISCUSSION

In this study, two response variables, maximum trunk flexion angle and normalized EMG signals were adopted to implicate the spinal injury risk. The results demonstrated that, all independent variables (the risk factors) have a significant effect on at least one response variable. In the following, the LBD risk associated with a certain working condition and possible interventions are discussed. The kneeling and stooped postures are also compared through video observations.

a) Stooped posture: The Vicon data showed a highly consistent trend among all participants in facing direction and slopes. As the slope increases, the distance of the participants' upper body (i.e., arms, shoulders and trunk) from the nailing spots on the rooftops become closer. Therefore, the participant needs a smaller bending angle to reach the nailing spots. In practice, for roofers working on a low pitch, a higher maximum bending angle is likely to occur. In contrast, a less postural balance and higher fall risk is reported that working on a steep roof (Choi et al. 2008). A similar trend was suggested by EMG data with an insignificant effect. This finding indicates a smaller spinal injury risk on a higher pitch than on a lower pitch or the flat ground.

However, this study only measured the trunk bending angle and back muscle activeness, ignoring the ankle flexion angles and the balance related measures. The survey results showed that 13 out of 15 participants perceived an imbalance and higher ankle stress on steeper slopes.

Besides, an existing study indicated a reduced balance on the high pitch roof than the low pitch (Choi et al. 2008). In addition, a high ankle flexion angle was observed on higher slopes. Considering the increased ankle flexion and the imbalance which increases fall or slip risk, the steep slope may be considered unfavorable. This information is important for the development of LBD interventions in that the ankle bearing should be maintained at a reasonable level. One possible intervention could be, to install a wooden platform on steep rooftops to form a flat surface for the roofers to step on. This way, it is possible to not only reduce LBD risk as it needs less severe bending to reach the rooftop according to the finding of 6.2.1, but also reduce the ankle flexion and ease the discomfort.

In terms of the facing directions, the Vicon data showed that, in facing sideways trials, the participants reached the maximum bending angle at the leftmost nailing spot (the bottom one), where a twisting in the trunk was also perceived. Both a significantly higher maximum angle and a slightly higher average trunk flexion angle were found in facing sideways conditions, which is unfavorable in practices. For the EMG data, the activity of the left-sided muscles was found to be different from the right-sided ones. For example, the left-sided multifidus has a relatively higher EMG signal than the right-sided. This can be due to a severe tension in the left at lower nailing spots. However, in this study, the twisting of the trunk was not studied. Hu et al. (2013) reported that bending on uneven slope can cause asymmetric trunk motion, and the ipsilateral lumbar muscles cease activity earlier than the contralateral lumbar muscles.

In the stooped postures, EMG signals significantly differentiate fast and slow frequencies in both nailing process and in-place flexion-extension trials. The EMG signals showed stronger muscle activeness in fast trials.

b) Kneeling posture: In kneeling trials, the slope angle was found to have a significant effect on the trunk flexion angle with a lower trunk flexion angle on higher slopes, which is similar to stooped postures. However, EMG signals of the multifidus muscles were found to be higher on the 30° slope. In addition, severe ankle stress and imbalance was reported by several participants on the 30° slope. The existing study suggests that the increase of multifidus' activities can help elevate spinal stability (Ning et al., 2010). This was validated by video observation results. The lower extremities in kneeling postures, including legs and ankles, were observed to have a higher loading than that of stooped postures. Possible interventions for kneeling postures could be, wearing knee pads or kneeling on the cushion. For one thing, it can reduce the impact on the knee; for another, by increasing the height of the knee, the ankle flexion can be reduced.

For the kneeling postures, the EMG signals indicate that fast trials result in higher muscle activations and higher LBD risk. But the difference between the fast and slow trials is less than that of stooped trials, especially EMG signals of erector spinae muscles. This can be due to that the time lengths for fast and slow trials are close to each other. Further study can either speed up the frequency for fast trials or enlarge the shingle size to explore the difference.

c) Stooped vs. Kneeling Postures: The kneeling postures (<50° in Figure 16) have a significantly less trunk flexion angle than the stooped postures (>70° in Figure 8), which indicate a smaller spinal loading in kneeling postures. Due to the limit of the research scope, this study only measured the flexion and muscle activities in the lower back. However, the lower extremities can have a negative effect. The survey study was conducted among the participants about the discomfort in the back and other body parts. It was found that the participants perceived an imbalance and high pressure on the ankle while working on steep slopes for two

postures, especially on the 30° slope. The observational study was conducted on the postures of the lower extremities, that is, leg and ankles. It was found that the steep slope exposes the participants to a more severe ankle flexion both for stooped and kneeling postures than flat ground. The lower extremities for kneeling postures were found to have high loading impacts than that of the stooped due to severe bending in legs and ankles. In summary, from the perspective of alleviating LBD risk, the kneeling posture is preferred rather than the stooped, but it requires sufficient protective gears for the knee and ankle. It is recommended to wear knee pads or place cushion under the knee while installing shingles using kneeling postures.

d) Limitations: The current study has several limitations: 1) Participants are not actual roofers, but students from the West Virginia University. Their operations might not be professional. In the future, the real site assessment can be achieved, as the development of outdoor ergonomic assessment equipment, such as wireless EMG system. 2) The participants were assumed to have a uniform time distribution for flexion, nailing, and extension phases. However, during the trials, participant could hardly maintain a strictly steady work pace, which might result in either delay or finish ahead of time. The time difference can bring about errors in the data processing. Ideally, in this study, the time distribution for three phases was set to be 1:4:1, which means that 2/3 of the time series was extracted as nailing process. However, assume that the flexion phase was prolonged and the real time distribution was 2:3:1, the nailing process extracted from the ideal distribution (1:4:1) would contain part of flexion and cause errors. In future, a trigger can be used to record the exact starting and ending time points of each phase. 3) Muscle fatigue is not studied in this experiment. The trial period is relatively short and cannot detect fatigue during the simulation. Future work can include prolonged trials and static severe bending on different working conditions. 4) The twisting angle of the trunk is not measured in

this experiment, which is expected to differentiate side and uphill posture better. In future, more markers can be attached to upper body parts such as shoulders to measure the twisting of the trunk. 5) Only the trunk muscle is studied and used for the risk analysis. However, the ankle, legs and knee are also prone to WMSD risks due to heavy use in two roofing postures. In future, the ankle flexion can included in the analysis, and muscle activity of the legs is expected to be measured.

CHAPTER 8

CONCLUSION

8.1 Conclusions

The roofing industry is a highly physical demanding industry and the working environment of roofers exposes them to various LBD hazards. This thesis begins with an introduction to the nature, and severity of LBD in the roofing industry. The harsh working environment of roofers and the LBD risk factors involved are reviewed. Through site visits and video observations, four physical risk factors are summarized to study their effects on LBD incidence. However, the literature review shows that there is a lack of enforced training, practices and promoted prevention programs in the roofing industry. In addition, existing roofing research mostly focused on fatal falls, and a very few studied the effects of risk factors on the non-fatal injury incidence.

In order to identify LBD risk factors among roofers, this thesis designed a factorial experiment. Through statistical analyses, several LBD risk factors were revealed. It is found that, faster working pace resulted in a higher low back muscle activation level. As the roof angle increases from 0° to 15° , and then 30° , a decrease in trunk flexion angle was detected. The side-facing work condition posed extra pressure on the lower back due to a more severe bending. However, although a decreased trunk flexion angle was detected on steep slopes, a higher stress on the ankles and decreased perceived stability was experienced and reported by the participants.

These findings might be helpful to develop specific guidelines and prevention training for tackling the LBD risk among roofers.

The findings will help roofers avoid unfavorable scenarios with severe LBD risks. Also, potential interventions which can relieve spinal loading while posing a small stress on the lower extremities warrant further investigation.

8.2 Contribution

This thesis highlights the severity of LBD among roofers, and summarizes the LBD risk factors in the roofing industry. The risk factors are evaluated through a factorial experiment to reveal the ones with significant effects on spinal loadings and LBD risk. The findings of the study are expected to better educate the construction industry about the LBD risks involved in their daily tasks.

In summary, the contribution of this study is to generate knowledge to help better understand the effect of risk factors on LBD development. This knowledge can be used for education and to also serve as a point of departure for the development of LBD guidelines and interventions.

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APPENDIX I: EMG and VICON Data Processing Code (MATLAB R2013a)

```
%%  
%%data import and vicon data processing  
clc  
close all  
clear all  
format long  
n=32;  
flexion(1:n,1)=0;  
ave_data(1:n,1:4)=0;  
%%  
%%MVC  
MVC=zeros(5,8);  
[mvcfile] = xlsread('./data/b1.xlsx');  
MVC(2,1:8)=max(mvcfile(10:end,2:9));  
[mvcfile] = xlsread('./data/b2.xlsx');  
MVC(3,1:8)=max(mvcfile(10:end,2:9));  
[mvcfile] = xlsread('./data/f1.xlsx');  
MVC(4,1:8)=max(mvcfile(10:end,2:9));  
[mvcfile] = xlsread('./data/f2.xlsx');  
MVC(5,1:8)=max(mvcfile(10:end,2:9));  
MVC(1,1:8)=max(MVC(2:5,1:8));  
for trial=1:32  
  
%filt_EMG=zeros(:,1:8);  
  
directory=['./data/',num2str(trial),'.xlsx'];  
[file] = xlsread(directory);  
filesize = size(file);  
sheet=trial;  
[file] = xlsread(directory,num2str(sheet),'A9:O',num2str(filesize(1,1)),'');  
[row, col] = find(isnan(file));%find the tail of the vicon data, row(1)=1537  
k=1;  
for i=1:10:row(1);  
%trunk inclination angle  

$$x = \frac{\text{file}(i,9) - \text{file}(i,15)}{\sqrt{(\text{file}(i,7) - \text{file}(i,13))^2 + (\text{file}(i,8) - \text{file}(i,14))^2}};$$

```

```

% lumbar flexion angle
x=(file(i,6)-file(i,9))/sqrt((file(i,5)-file(i,8))^2+(file(i,4)-file(i,7))^2);
angle(trial,k)=90-abs(360*atan(x)/(2*pi));
k=k+1;
end
%disp(sprintf('Angle of file: %d.xlsx', data))
%display(angle); %display one angle every ten data
flexion(trial,1)= max(angle(trial,:));
%disp(sprintf('%d max flexion angle: %d', data,m))
%disp(sprintf('%d',m))
% end
% row(1)+
% size(file)
% %% EMG processing
%% EMG Processing

[file, text] = xlsread(directory,num2str(sheet),'A9:U',num2str(filesize(1,1)),'');
aa = size(file);
EMG = file(row(1)+2:end,2:9);
[m,n]=size(EMG);

% %%%%%%%%%%%%%%% EMG=abs(EMG);
% %Raw EMG data
% [m,z]=size(EMG);
% freq = 1000; %sampling frequency
% n=floor(m/freq); %n=2; %duration (sec)
% N = n*freq/2; % number of samples in half of FFT
% f = freq*(0:N)/2/N;
% ch=z;%number of channels
% nn = n*freq;
% EMG=EMG(1:nn,:);%
% %%%%%%%%%%%%%%%
%%test%%%%%%%%%%
Rectified_EMG=abs(EMG);
%% subplot
% Fs = 1024; % Sampling frequency
% T = 1/Fs; % Sample time
% L = m; % Length of signal
% t =(0:L-1)*T;

```

```

% y=t*EMG(:,k);

for k=1:8
Fe=1000; %Sampling frequenc
Fc=2; % Cut-off frequency (from 2 Hz to 6 Hz depending to the type of your electro)
N=4; % Filter Order
[B, A] = butter(N,Fc*2/Fe, 'low'); %filter's parameters
Filter_EMG=Rectified_EMG;
Filter_EMG(:,k)=filtfilt(B, A, Rectified_EMG(:,k));
end

    for i = 1:m
        if Filter_EMG(i,k) > MVC(1,k)
            Filter_EMG(i,k) = MVC(1,k); % If there is any EMG larger than MVC, set it as
MVC
        end
    end
    start_nail=floor(0.23*m);
    end_nail=floor(0.67*m);
for k=5:8
ave_data(trial,k-4)= mean(Filter_EMG(start_nail:end_nail,k));%changeable coefficient
Nail_EMG(trial,k-4) = ave_data(trial,k-4)/MVC(1,k); %print Normalized EMG
% subplot(3,1,1); plot(EMG(:,8)), grid on, title('original emg')
% subplot(3,1,2);plot(Rectified_EMG(:,8)), grid on, title('rectified emg')
% subplot(3,1,3);plot(Filter_EMG(:,8)), grid on, title('filtered emg')
end
% %% Filtering using butterworth filter of order 4
% % High-pass filter
%   filt1 = fdesign.highpass('n,f3db',4,2*10*(1/1024)); %high-pass filter, cut off frequency at
10Hz, sampling frequency of 1000Hz
%   H1 = design(filt1,'butter');
%   highpass_EMG = filter(H1,EMG(:,k)); % sampling frequency of 1000Hz
% % Low-pass filter
%   filt2 = fdesign.lowpass('n,f3db',4,2*500*(1/1024)); %low-pass filter, cut off frequency at
500Hz
%   H2 = design(filt2,'butter');
%   lowpass_EMG = filter(H2,highpass_EMG);
% % Notch Filter (50Hz)
%   filt3 = fdesign.notch(4,0.05,10); %notch filter (50Hz)

```

```

% H3 = design(filt3);
% filtered_EMG(:,k) = filter(H3,lowpass_EMG);
% figure; plot(filtered_EMG(:,k)), grid on, title('filtered EMG') ;
% ave_data=mean(filtered_EMG(:,k));
% end
% Fe=1000; %Samling frequency in Hz
% Fc=3; % Cut-off frequency (from 2 Hz to 6 Hz depending to the type of your electrod)
% N=4; % Filter Order
% [B, A] = butter(N,Fc*2/Fe, 'low'); %filter's parameters
% EMG=filter(B,A, Rectified_EMG); %in the case of real-time treatment
%% EMG data
export %%%%%%%%%%%
%%%%%%%%test%%%%%%%%
xlswrite('filtered_emg.xlsx',Filter_EMG,num2str(trial),'A1');
xlswrite('intervalangle.xlsx',angle,'Angle','A1');
end
xlswrite('nail_emg.xlsx',Nail_EMG,'nail_emg','A1');
xlswrite('maxangle.xlsx',flexion,'Angle','A1');
%xlswrite('maxemg.xlsx',max_EMG,'EMG','A1');

```

APPENDIX II: Survey Form of LBD Study on Roofing Activities

Note: 1-20 trials are stooped postures

21-32 trials are crawling postures

For each condition, there are two repetitions, you just need to provide one rating for them

Rating from 0-9: 0 means very comfortable, 9 means most risky

Number	Slope angle	Direction	Frequency	Back Rating(0-9)	Other body parts Rating(0-9)
1	0	Uphill	Slow		
2	0	Uphill	Slow		
3	0	Uphill	Fast		
4	0	Uphill	Fast		
5	15	Uphill	Slow		
6	15	Uphill	Slow		
7	15	Uphill	Fast		
8	15	Uphill	Fast		
9	15	Side	Slow		
10	15	Side	Slow		
11	15	Side	Fast		
12	15	Side	Fast		
13	30	Uphill	Slow		
14	30	Uphill	Slow		
15	30	Uphill	Fast		
16	30	Uphill	Fast		
17	30	Side	Slow		
18	30	Side	Slow		
19	30	Side	Fast		
20	30	Side	Fast		
21	30	Uphill	Slow		
22	30	Uphill	Slow		
23	30	Uphill	Fast		
24	30	Uphill	Fast		
25	15	Uphill	Slow		
26	15	Uphill	Slow		
27	15	Uphill	Fast		
28	15	Uphill	Fast		
29	0	Uphill	Slow		
30	0	Uphill	Slow		
31	0	Uphill	Fast		
32	0	Uphill	Fast		

APPENDIX III: Trunk Flexion Angle and Normalized EMG data (15 Subjects)

- Stooped trials

Subject	Number	Tilt angle	Direction	Frequency	Flexion	Esl	Esr	Mul	Mur
1	1	0	Uphill	Slow	74.019	0.13004	0.19541	0.11814	0.16148
1	2	0	Uphill	Slow	71.8817	0.12521	0.17726	0.11505	0.12405
1	3	0	Uphill	Fast	75.885	0.11327	0.16379	0.09554	0.10962
1	4	0	Uphill	Fast	76.9389	0.11264	0.16311	0.09564	0.10905
1	5	15	Uphill	Slow	57.4242	0.09861	0.14782	0.07789	0.09107
1	6	15	Uphill	Slow	57.4069	0.09789	0.14737	0.07711	0.09416
1	7	15	Uphill	Fast	61.9798	0.09863	0.14705	0.07686	0.12576
1	8	15	Uphill	Fast	55.7313	0.09851	0.14673	0.07625	0.10392
1	9	15	Side	Slow	71.5617	0.09604	0.14384	0.07379	0.08653
1	10	15	Side	Slow	67.2295	0.096	0.14364	0.07331	0.08646
1	11	15	Side	Fast	70.7439	0.09752	0.14362	0.07604	0.0872
1	12	15	Side	Fast	70.3363	0.09495	0.1428	0.07262	0.0858
1	13	30	Uphill	Slow	46.9547	0.09159	0.13885	0.06895	0.08152
1	14	30	Uphill	Slow	48.3032	0.09106	0.13814	0.0677	0.08059
1	15	30	Uphill	Fast	47.7797	0.09059	0.13775	0.06776	0.08018
1	16	30	Uphill	Fast	45.2556	0.09025	0.13801	0.06734	0.07982
1	17	30	Side	Slow	67.0608	0.08988	0.13734	0.06694	0.07938
1	18	30	Side	Slow	65.1174	0.09029	0.13713	0.06554	0.07884
1	19	30	Side	Fast	68.7709	0.09008	0.13723	0.06618	0.08759
1	20	30	Side	Fast	65.4084	0.08924	0.13636	0.06498	0.07961
2	1	0	Uphill	Slow	72.9247	0.09045	0.09348	0.08687	0.07739
2	2	0	Uphill	Slow	71.5025	0.09181	0.09256	0.09151	0.07587
2	3	0	Uphill	Fast	73.1322	0.08953	0.09287	0.13662	0.07829
2	4	0	Uphill	Fast	73.1607	0.09282	0.0921	0.11784	0.07528
2	5	15	Uphill	Slow	61.0615	0.08226	0.08535	0.13651	0.09698
2	6	15	Uphill	Slow	63.0663	0.08359	0.08502	0.11484	0.08275
2	7	15	Uphill	Fast	62.9447	0.07852	0.08372	0.29884	0.14783
2	8	15	Uphill	Fast	64	0.07924	0.08104	0.26269	0.16473
2	9	15	Side	Slow	74.3976	0.08645	0.08268	0.2259	0.07922
2	10	15	Side	Slow	74.5507	0.09352	0.08223	0.2358	0.0834
2	11	15	Side	Fast	72.5554	0.08231	0.08171	0.43879	0.13392
2	12	15	Side	Fast	72.3181	0.07195	0.07873	0.2741	0.09549
2	13	30	Uphill	Slow	48.8025	0.08918	0.0762	0.12911	0.09995

2	14	30	Uphill	Slow	47.0155	0.08705	0.07803	0.10981	0.09721
2	15	30	Uphill	Fast	47.9082	0.08727	0.07811	0.09691	0.07273
2	16	30	Uphill	Fast	47.2088	0.08523	0.07809	0.15707	0.12467
2	17	30	Side	Slow	71.3006	0.08621	0.07968	0.24871	0.10938
2	18	30	Side	Slow	67.5492	0.08299	0.07666	0.21342	0.089
2	19	30	Side	Fast	66.2309	0.08109	0.07931	0.25937	0.1093
2	20	30	Side	Fast	68.378	0.0916	0.07774	0.20266	0.08974
3	1	0	Uphill	Slow	66.4519	0.3075	0.33839	0.15374	0.14698
3	2	0	Uphill	Slow	67.2491	0.30602	0.3372	0.15174	0.14653
3	3	0	Uphill	Fast	69.7719	0.30539	0.33525	0.15146	0.14869
3	4	0	Uphill	Fast	68.1967	0.30387	0.33524	0.15032	0.1453
3	5	15	Uphill	Slow	60.6838	0.29979	0.33112	0.14722	0.14307
3	6	15	Uphill	Slow	57.0544	0.29904	0.33044	0.14645	0.14215
3	7	15	Uphill	Fast	57.3167	0.29896	0.33071	0.14806	0.14344
3	8	15	Uphill	Fast	54.096	0.29802	0.32959	0.14604	0.14269
3	9	15	Side	Slow	65.2977	0.29792	0.32712	0.14498	0.14029
3	10	15	Side	Slow	62.9366	0.29606	0.32604	0.14448	0.13982
3	11	15	Side	Fast	62.7898	0.30149	0.32907	0.16423	0.15529
3	12	15	Side	Fast	63.9154	0.29749	0.32564	0.14763	0.1435
3	13	30	Uphill	Slow	43.7205	0.29258	0.32345	0.1437	0.14154
3	14	30	Uphill	Slow	43.8627	0.29124	0.32289	0.14171	0.14825
3	15	30	Uphill	Fast	48.7404	0.29133	0.32277	0.14217	0.13798
3	16	30	Uphill	Fast	45.8118	0.29202	0.32305	0.14166	0.13791
3	17	30	Side	Slow	58.6115	0.28993	0.32085	0.14082	0.13706
3	18	30	Side	Slow	57.2655	0.29202	0.32116	0.14549	0.14123
3	19	30	Side	Fast	59.6538	0.2892	0.32014	0.14052	0.13689
3	20	30	Side	Fast	60.5769	0.29137	0.32015	0.14052	0.13639
4	1	0	Uphill	Slow	76.28	0.10303	0.27592	0.17767	0.20017
4	2	0	Uphill	Slow	76.753	0.10366	0.27173	0.18778	0.30702
4	3	0	Uphill	Fast	75.1153	0.10393	0.27046	0.17324	0.30705
4	4	0	Uphill	Fast	68.9795	0.09837	0.265	0.17586	0.17222
4	5	15	Uphill	Slow	62.9858	0.0967	0.25755	0.16356	0.14757
4	6	15	Uphill	Slow	63.8999	0.09902	0.25603	0.15918	0.13857
4	7	15	Uphill	Fast	63.549	0.09524	0.25516	0.15874	0.15092
4	8	15	Uphill	Fast	64.0593	0.0938	0.25429	0.15652	0.13909
4	9	15	Side	Slow	71.5642	0.0992	0.2519	0.15405	0.13317
4	10	15	Side	Slow	70.3485	0.09502	0.25126	0.15483	0.13612
4	11	15	Side	Fast	66.4571	0.09444	0.25271	0.16123	0.149
4	12	15	Side	Fast	66.5151	0.0962	0.25289	0.17142	0.15423

4	13	30	Uphill	Slow	51.479	0.09055	0.24782	0.16126	0.15747
4	14	30	Uphill	Slow	52.6718	0.09077	0.24628	0.14877	0.12897
4	15	30	Uphill	Fast	50.7548	0.09047	0.24605	0.1532	0.13623
4	16	30	Uphill	Fast	48.9671	0.08886	0.24537	0.15447	0.15219
4	17	30	Side	Slow	71.7307	0.09485	0.26142	0.17299	0.16217
4	18	30	Side	Slow	72.1501	0.09315	0.24684	0.14993	0.14035
4	19	30	Side	Fast	70.6639	0.09747	0.24469	0.14745	0.1331
4	20	30	Side	Fast	66.743	0.09694	0.25441	0.17895	0.16387
5	1	0	Uphill	Slow	58.9294	0.19406	0.20414	0.12546	0.06828
5	2	0	Uphill	Slow	66.4327	0.198	0.20598	0.12512	0.0686
5	3	0	Uphill	Fast	69.9702	0.22827	0.20872	0.12963	0.06984
5	4	0	Uphill	Fast	67.5823	0.22726	0.20801	0.12878	0.07119
5	5	15	Uphill	Slow	46.516	0.20031	0.20931	0.13063	0.07142
5	6	15	Uphill	Slow	43.7075	0.20053	0.20908	0.12975	0.07102
5	7	15	Uphill	Fast	45.1659	0.20939	0.20839	0.12995	0.07111
5	8	15	Uphill	Fast	45.8712	0.21218	0.20865	0.13139	0.07115
5	9	15	Side	Slow	60.4713	0.19962	0.20776	0.12825	0.07046
5	10	15	Side	Slow	65.9534	0.20193	0.20768	0.12853	0.07026
5	11	15	Side	Fast	61.1466	0.20259	0.20671	0.12834	0.07035
5	12	15	Side	Fast	62.8639	0.2118	0.20727	0.1283	0.07012
5	13	30	Uphill	Slow	49.0948	0.22983	0.2258	0.1479	0.08005
5	14	30	Uphill	Slow	43.8529	0.21864	0.22416	0.1453	0.0786
5	15	30	Uphill	Fast	45.4863	0.2195	0.22353	0.14473	0.07842
5	16	30	Uphill	Fast	44.0711	0.21559	0.22296	0.14356	0.07825
5	17	30	Side	Slow	66.1438	0.21332	0.22005	0.14191	0.07696
5	18	30	Side	Slow	68.9926	0.21139	0.21897	0.1406	0.07636
5	19	30	Side	Fast	63.288	0.21468	0.21879	0.14029	0.07622
5	20	30	Side	Fast	62.7129	0.21398	0.21784	0.13975	0.07569
6	1	0	Uphill	Slow	60.8017	0.36348	0.49053	0.31335	0.38133
6	2	0	Uphill	Slow	60.8357	0.36278	0.48924	0.31158	0.38043
6	3	0	Uphill	Fast	60.6464	0.36114	0.48712	0.3144	0.37938
6	4	0	Uphill	Fast	61.6385	0.35955	0.48669	0.31218	0.3767
6	5	15	Uphill	Slow	52.2205	0.34278	0.46109	0.30536	0.36352
6	6	15	Uphill	Slow	50.7886	0.33754	0.45771	0.29139	0.35599
6	7	15	Uphill	Fast	41.7886	0.33795	0.45626	0.30781	0.3615
6	8	15	Uphill	Fast	45.7488	0.336	0.45573	0.297	0.3486
6	9	15	Side	Slow	60.4758	0.33403	0.45364	0.28733	0.36027
6	10	15	Side	Slow	60.3331	0.33264	0.45204	0.28761	0.36693
6	11	15	Side	Fast	55.5317	0.33186	0.45083	0.28836	0.35125

6	12	15	Side	Fast	55.402	0.33765	0.44976	0.31243	0.375
6	13	30	Uphill	Slow	50.0347	0.33128	0.4451	0.30654	0.34303
6	14	30	Uphill	Slow	45.6695	0.32762	0.44263	0.30648	0.35657
6	15	30	Uphill	Fast	32.0615	0.3296	0.44158	0.30984	0.3403
6	16	30	Uphill	Fast	29.4275	0.32525	0.44157	0.28923	0.34747
6	17	30	Side	Slow	46.3134	0.32389	0.43945	0.2927	0.35665
6	18	30	Side	Slow	44.4034	0.32163	0.43814	0.28818	0.34746
6	19	30	Side	Fast	46.9491	0.32176	0.4376	0.28916	0.35028
6	20	30	Side	Fast	49.6187	0.32625	0.43671	0.29822	0.35419
7	1	0	Uphill	Slow	92.7864	0.11272	0.11693	0.13236	0.11911
7	2	0	Uphill	Slow	94.2338	0.11135	0.1238	0.13455	0.10984
7	3	0	Uphill	Fast	92.1396	0.82211	0.64261	0.10484	0.06499
7	4	0	Uphill	Fast	94.8238	0.71054	0.49445	0.10488	0.0642
7	5	15	Uphill	Slow	84.5226	0.11193	0.11992	0.13365	0.10802
7	6	15	Uphill	Slow	85.3022	0.11282	0.11461	0.13477	0.1091
7	7	15	Uphill	Fast	83.7794	0.13188	0.12555	0.14494	0.10914
7	8	15	Uphill	Fast	84.4354	0.11664	0.12463	0.13545	0.1107
7	9	15	Side	Slow	92.0476	0.11122	0.12093	0.13325	0.10718
7	10	15	Side	Slow	94.2177	0.10276	0.1125	0.13226	0.10674
7	11	15	Side	Fast	91.6664	0.10212	0.11373	0.13238	0.10941
7	12	15	Side	Fast	91.6664	0.10212	0.11373	0.13238	0.10941
7	13	30	Uphill	Slow	69.7008	0.11474	0.13426	0.13206	0.10664
7	14	30	Uphill	Slow	76.3196	0.10765	0.11671	0.13137	0.10639
7	15	30	Uphill	Fast	71.4388	0.10254	0.11264	0.13122	0.1056
7	16	30	Uphill	Fast	71.616	0.10409	0.11665	0.1309	0.10599
7	17	30	Side	Slow	92.6252	0.10278	0.11173	0.13115	0.10815
7	18	30	Side	Slow	92.4904	0.10147	0.11548	0.13123	0.11699
7	19	30	Side	Fast	93.5966	0.10764	0.11967	0.1331	0.1251
7	20	30	Side	Fast	92.524	0.10351	0.11107	0.1341	0.12463
8	1	0	Uphill	Slow	89.845	0.05405	0.05865	0.06412	0.06435
8	2	0	Uphill	Slow	91.0925	0.05185	0.05641	0.06073	0.06135
8	3	0	Uphill	Fast	87.1457	0.04871	0.0537	0.05691	0.05815
8	4	0	Uphill	Fast	86.9677	0.04808	0.05253	0.05535	0.05677
8	5	15	Uphill	Slow	78.0048	0.31387	0.537	0.04404	0.06067
8	6	15	Uphill	Slow	74.4209	0.04187	0.04648	0.04579	0.04913
8	7	15	Uphill	Fast	75.1998	0.04069	0.0456	0.04492	0.04806
8	8	15	Uphill	Fast	76.7265	0.04006	0.0449	0.04381	0.04731
8	9	15	Side	Slow	91.8805	0.03932	0.04226	0.04067	0.04389
8	10	15	Side	Slow	91.5441	0.03831	0.04154	0.03895	0.04278

8	11	15	Side	Fast	91.0885	0.03879	0.0408	0.03793	0.04186
8	12	15	Side	Fast	91.2596	0.03929	0.04038	0.03842	0.04145
8	13	30	Uphill	Slow	66.8546	0.04021	0.03755	0.03563	0.03635
8	14	30	Uphill	Slow	68.0612	0.03389	0.03625	0.03134	0.03527
8	15	30	Uphill	Fast	64.6233	0.03567	0.03538	0.03225	0.03447
8	16	30	Uphill	Fast	62.5131	0.0354	0.03499	0.03198	0.03377
8	17	30	Side	Slow	89.4686	0.0447	0.03355	0.03546	0.03187
8	18	30	Side	Slow	87.4945	0.04205	0.03261	0.0322	0.03095
8	19	30	Side	Fast	86.9358	0.04065	0.03071	0.03555	0.02849
8	20	30	Side	Fast	88.9155	0.03486	0.03034	0.03016	0.0277
9	1	0	Uphill	Slow	93.8334	0.08659	0.14097	0.08283	0.09662
9	2	0	Uphill	Slow	94.522	0.08587	0.1227	0.19291	0.09309
9	3	0	Uphill	Fast	95.0177	0.07237	0.10944	0.07292	0.08898
9	4	0	Uphill	Fast	94.4017	0.07719	0.1105	0.16329	0.08695
9	5	15	Uphill	Slow	87.1203	0.07055	0.09689	0.13974	0.07514
9	6	15	Uphill	Slow	91.2497	0.06101	0.09177	0.12463	0.06351
9	7	15	Uphill	Fast	87.1363	0.0718	0.0941	0.17126	0.07594
9	8	15	Uphill	Fast	86.2851	0.05733	0.08772	0.15556	0.05945
9	9	15	Side	Slow	100.163	0.05704	0.09164	0.35494	0.07463
9	10	15	Side	Slow	96.2571	0.05946	0.0866	0.1372	0.05979
9	11	15	Side	Fast	96.5198	0.05892	0.09486	0.1371	0.07741
9	12	15	Side	Fast	99.1793	0.05715	0.08583	0.12767	0.05945
9	13	30	Uphill	Slow	76.1898	0.07942	0.08702	0.13057	0.08309
9	14	30	Uphill	Slow	75.5204	0.05282	0.07523	0.17746	0.04907
9	15	30	Uphill	Fast	73.6273	0.05357	0.08331	0.18992	0.04999
9	16	30	Uphill	Fast	73.9116	0.05982	0.08795	0.20274	0.05129
9	17	30	Side	Slow	99.1964	0.001	0.00155	0.0319	0.06365
9	18	30	Side	Slow	99.5923	0.04882	0.07278	0.19268	0.04565
9	19	30	Side	Fast	98.8366	0.05193	0.07794	0.23295	0.05998
9	20	30	Side	Fast	100.904	0.0472	0.08323	0.22854	0.0529
10	1	0	Uphill	Slow	74.019	0.13004	0.19541	0.11814	0.16148
10	2	0	Uphill	Slow	71.8817	0.12521	0.17726	0.11505	0.12405
10	3	0	Uphill	Fast	75.885	0.11327	0.16379	0.09554	0.10962
10	4	0	Uphill	Fast	76.9389	0.11264	0.16311	0.09564	0.10905
10	5	15	Uphill	Slow	57.4242	0.09861	0.14782	0.07789	0.09107
10	6	15	Uphill	Slow	57.4069	0.09789	0.14737	0.07711	0.09416
10	7	15	Uphill	Fast	61.9798	0.09863	0.14705	0.07686	0.12576
10	8	15	Uphill	Fast	55.7313	0.09851	0.14673	0.07625	0.10392
10	9	15	Side	Slow	71.5617	0.09604	0.14384	0.07379	0.08653

10	10	15	Side	Slow	67.2295	0.096	0.14364	0.07331	0.08646
10	11	15	Side	Fast	70.7439	0.09752	0.14362	0.07604	0.0872
10	12	15	Side	Fast	70.3363	0.09495	0.1428	0.07262	0.0858
10	13	30	Uphill	Slow	46.9547	0.09159	0.13885	0.06895	0.08152
10	14	30	Uphill	Slow	48.3032	0.09106	0.13814	0.0677	0.08059
10	15	30	Uphill	Fast	47.7797	0.09059	0.13775	0.06776	0.08018
10	16	30	Uphill	Fast	45.2556	0.09025	0.13801	0.06734	0.07982
10	17	30	Side	Slow	67.0608	0.08988	0.13734	0.06694	0.07938
10	18	30	Side	Slow	65.1174	0.09029	0.13713	0.06554	0.07884
10	19	30	Side	Fast	68.7709	0.09008	0.13723	0.06618	0.08759
10	20	30	Side	Fast	65.4084	0.08924	0.13636	0.06498	0.07961
11	1	0	Uphill	Slow	74.019	0.13004	0.19541	0.11814	0.16148
11	2	0	Uphill	Slow	71.8817	0.12521	0.17726	0.11505	0.12405
11	3	0	Uphill	Fast	75.885	0.11327	0.16379	0.09554	0.10962
11	4	0	Uphill	Fast	76.9389	0.11264	0.16311	0.09564	0.10905
11	5	15	Uphill	Slow	57.4242	0.09861	0.14782	0.07789	0.09107
11	6	15	Uphill	Slow	57.4069	0.09789	0.14737	0.07711	0.09416
11	7	15	Uphill	Fast	61.9798	0.09863	0.14705	0.07686	0.12576
11	8	15	Uphill	Fast	55.7313	0.09851	0.14673	0.07625	0.10392
11	9	15	Side	Slow	71.5617	0.09604	0.14384	0.07379	0.08653
11	10	15	Side	Slow	67.2295	0.096	0.14364	0.07331	0.08646
11	11	15	Side	Fast	70.7439	0.09752	0.14362	0.07604	0.0872
11	12	15	Side	Fast	70.3363	0.09495	0.1428	0.07262	0.0858
11	13	30	Uphill	Slow	46.9547	0.09159	0.13885	0.06895	0.08152
11	14	30	Uphill	Slow	48.3032	0.09106	0.13814	0.0677	0.08059
11	15	30	Uphill	Fast	47.7797	0.09059	0.13775	0.06776	0.08018
11	16	30	Uphill	Fast	45.2556	0.09025	0.13801	0.06734	0.07982
11	17	30	Side	Slow	67.0608	0.08988	0.13734	0.06694	0.07938
11	18	30	Side	Slow	65.1174	0.09029	0.13713	0.06554	0.07884
11	19	30	Side	Fast	68.7709	0.09008	0.13723	0.06618	0.08759
11	20	30	Side	Fast	65.4084	0.08924	0.13636	0.06498	0.07961
12	1	0	Uphill	Slow	72.9247	0.09045	0.09348	0.08687	0.07739
12	2	0	Uphill	Slow	71.5025	0.09181	0.09256	0.09151	0.07587
12	3	0	Uphill	Fast	73.1322	0.08953	0.09287	0.13662	0.07829
12	4	0	Uphill	Fast	73.1607	0.09282	0.0921	0.11784	0.07528
12	5	15	Uphill	Slow	61.0615	0.08226	0.08535	0.13651	0.09698
12	6	15	Uphill	Slow	63.0663	0.08359	0.08502	0.11484	0.08275
12	7	15	Uphill	Fast	62.9447	0.07852	0.08372	0.29884	0.14783
12	8	15	Uphill	Fast	64	0.07924	0.08104	0.26269	0.16473

12	9	15	Side	Slow	74.3976	0.08645	0.08268	0.2259	0.07922
12	10	15	Side	Slow	74.5507	0.09352	0.08223	0.2358	0.0834
12	11	15	Side	Fast	72.5554	0.08231	0.08171	0.43879	0.13392
12	12	15	Side	Fast	72.3181	0.07195	0.07873	0.2741	0.09549
12	13	30	Uphill	Slow	48.8025	0.08918	0.0762	0.12911	0.09995
12	14	30	Uphill	Slow	47.0155	0.08705	0.07803	0.10981	0.09721
12	15	30	Uphill	Fast	47.9082	0.08727	0.07811	0.09691	0.07273
12	16	30	Uphill	Fast	47.2088	0.08523	0.07809	0.15707	0.12467
12	17	30	Side	Slow	71.3006	0.08621	0.07968	0.24871	0.10938
12	18	30	Side	Slow	67.5492	0.08299	0.07666	0.21342	0.089
12	19	30	Side	Fast	66.2309	0.08109	0.07931	0.25937	0.1093
12	20	30	Side	Fast	68.378	0.0916	0.07774	0.20266	0.08974
14	1	0	Uphill	Slow	74.019	0.13004	0.19541	0.11814	0.16148
14	2	0	Uphill	Slow	71.8817	0.12521	0.17726	0.11505	0.12405
14	3	0	Uphill	Fast	75.885	0.11327	0.16379	0.09554	0.10962
14	4	0	Uphill	Fast	76.9389	0.11264	0.16311	0.09564	0.10905
14	5	15	Uphill	Slow	57.4242	0.09861	0.14782	0.07789	0.09107
14	6	15	Uphill	Slow	57.4069	0.09789	0.14737	0.07711	0.09416
14	7	15	Uphill	Fast	61.9798	0.09863	0.14705	0.07686	0.12576
14	8	15	Uphill	Fast	55.7313	0.09851	0.14673	0.07625	0.10392
14	9	15	Side	Slow	71.5617	0.09604	0.14384	0.07379	0.08653
14	10	15	Side	Slow	67.2295	0.096	0.14364	0.07331	0.08646
14	11	15	Side	Fast	70.7439	0.09752	0.14362	0.07604	0.0872
14	12	15	Side	Fast	70.3363	0.09495	0.1428	0.07262	0.0858
14	13	30	Uphill	Slow	46.9547	0.09159	0.13885	0.06895	0.08152
14	14	30	Uphill	Slow	48.3032	0.09106	0.13814	0.0677	0.08059
14	15	30	Uphill	Fast	47.7797	0.09059	0.13775	0.06776	0.08018
14	16	30	Uphill	Fast	45.2556	0.09025	0.13801	0.06734	0.07982
14	17	30	Side	Slow	67.0608	0.08988	0.13734	0.06694	0.07938
14	18	30	Side	Slow	65.1174	0.09029	0.13713	0.06554	0.07884
14	19	30	Side	Fast	68.7709	0.09008	0.13723	0.06618	0.08759
14	20	30	Side	Fast	65.4084	0.08924	0.13636	0.06498	0.07961
15	1	0	Uphill	Slow	72.9247	0.09045	0.09348	0.08687	0.07739
15	2	0	Uphill	Slow	71.5025	0.09181	0.09256	0.09151	0.07587
15	3	0	Uphill	Fast	73.1322	0.08953	0.09287	0.13662	0.07829
15	4	0	Uphill	Fast	73.1607	0.09282	0.0921	0.11784	0.07528
15	5	15	Uphill	Slow	61.0615	0.08226	0.08535	0.13651	0.09698
15	6	15	Uphill	Slow	63.0663	0.08359	0.08502	0.11484	0.08275
15	7	15	Uphill	Fast	62.9447	0.07852	0.08372	0.29884	0.14783

15	8	15	Uphill	Fast	64	0.07924	0.08104	0.26269	0.16473
15	9	15	Side	Slow	74.3976	0.08645	0.08268	0.2259	0.07922
15	10	15	Side	Slow	74.5507	0.09352	0.08223	0.2358	0.0834
15	11	15	Side	Fast	72.5554	0.08231	0.08171	0.43879	0.13392
15	12	15	Side	Fast	72.3181	0.07195	0.07873	0.2741	0.09549
15	13	30	Uphill	Slow	48.8025	0.08918	0.0762	0.12911	0.09995
15	14	30	Uphill	Slow	47.0155	0.08705	0.07803	0.10981	0.09721
15	15	30	Uphill	Fast	47.9082	0.08727	0.07811	0.09691	0.07273
15	16	30	Uphill	Fast	47.2088	0.08523	0.07809	0.15707	0.12467
15	17	30	Side	Slow	71.3006	0.08621	0.07968	0.24871	0.10938
15	18	30	Side	Slow	67.5492	0.08299	0.07666	0.21342	0.089
15	19	30	Side	Fast	66.2309	0.08109	0.07931	0.25937	0.1093
15	20	30	Side	Fast	68.378	0.0916	0.07774	0.20266	0.08974

- **Kneeling trials**

Subject	Number	Tilt angle	Direction	Frequency	Flexion	Esl	Esr	Mul	Mur
1	21	30	Uphill	Slow	22.3857	0.13004	0.19541	0.11814	0.16148
1	22	30	Uphill	Slow	27.258	0.12521	0.17726	0.11505	0.12405
1	23	30	Uphill	Fast	27.7391	0.11327	0.16379	0.09554	0.10962
1	24	30	Uphill	Fast	26.4186	0.11264	0.16311	0.09564	0.10905
1	25	15	Uphill	Slow	23.1277	0.09861	0.14782	0.07789	0.09107
1	26	15	Uphill	Slow	27.1796	0.09789	0.14737	0.07711	0.09416
1	27	15	Uphill	Fast	25.2745	0.09863	0.14705	0.07686	0.12576
1	28	15	Uphill	Fast	27.4052	0.09851	0.14673	0.07625	0.10392
1	29	0	Uphill	Slow	33.792	0.09604	0.14384	0.07379	0.08653
1	30	0	Uphill	Slow	27.0399	0.096	0.14364	0.07331	0.08646
1	31	0	Uphill	Fast	28.1782	0.09752	0.14362	0.07604	0.0872
1	32	0	Uphill	Fast	27.5436	0.09495	0.1428	0.07262	0.0858
2	21	30	Uphill	Slow	18.4513	0.08525	0.24007	0.1458	0.1345
2	22	30	Uphill	Slow	18.2797	0.08489	0.23837	0.14276	0.1235
2	23	30	Uphill	Fast	16.0599	0.08485	0.23782	0.14103	0.12383
2	24	30	Uphill	Fast	17.1726	0.08493	0.23745	0.1435	0.124
2	25	15	Uphill	Slow	12.7225	0.08215	0.23554	0.13942	0.13273
2	26	15	Uphill	Slow	13.1847	0.08279	0.23644	0.13871	0.14389
2	27	15	Uphill	Fast	12.0729	0.08387	0.23492	0.14004	0.13488
2	28	15	Uphill	Fast	11.9017	0.08326	0.23513	0.13841	0.13743
2	29	0	Uphill	Slow	26.7952	0.08745	0.23707	0.14941	0.1724
2	30	0	Uphill	Slow	26.973	0.09121	0.23907	0.14934	0.18958
2	31	0	Uphill	Fast	24.9121	0.08639	0.24013	0.14166	0.20258
2	32	0	Uphill	Fast	26.4071	0.08527	0.23383	0.14581	0.17608
3	21	30	Uphill	Slow	14.8601	0.21057	0.21434	0.13539	0.07473
3	22	30	Uphill	Slow	14.8601	0.20737	0.21392	0.13509	0.07457
3	23	30	Uphill	Fast	12.9374	0.21032	0.21397	0.13447	0.07453
3	24	30	Uphill	Fast	12.034	0.21403	0.2134	0.13413	0.0815
3	25	15	Uphill	Slow	19.0521	0.19491	0.20484	0.12528	0.06944
3	26	15	Uphill	Slow	21.0823	0.19435	0.2044	0.12477	0.06867
3	27	15	Uphill	Fast	20.0634	0.19377	0.20378	0.12484	0.07049
3	28	15	Uphill	Fast	19.723	0.19437	0.20387	0.12483	0.06875
3	29	0	Uphill	Slow	29.9237	0.19386	0.20315	0.12333	0.06757
3	30	0	Uphill	Slow	29.9237	0.19294	0.20249	0.12387	0.06724
3	31	0	Uphill	Fast	33.0644	0.19319	0.20253	0.12324	0.06712
3	32	0	Uphill	Fast	33.0644	0.19316	0.20217	0.12315	0.06693

4	21	30	Uphill	Slow	38.0473	0.07813	0.07577	0.15296	0.07521
4	22	30	Uphill	Slow	38.6825	0.08326	0.06979	0.13161	0.06177
4	23	30	Uphill	Fast	35.0386	0.08099	0.07041	0.12166	0.08433
4	24	30	Uphill	Fast	37.6111	0.08938	0.07137	0.11401	0.08483
4	25	15	Uphill	Slow	47.7891	0.06699	0.06393	0.08533	0.04875
4	26	15	Uphill	Slow	43.7004	0.06748	0.06458	0.08022	0.061
4	27	15	Uphill	Fast	43.2067	0.07949	0.06649	0.08071	0.06899
4	28	15	Uphill	Fast	39.2914	0.08078	0.0672	0.09038	0.06906
4	29	0	Uphill	Slow	68.8994	0.03387	0.05666	0.03846	0.02765
4	30	0	Uphill	Slow	66.3993	0.0345	0.05667	0.03646	0.02676
4	31	0	Uphill	Fast	61.5049	0.04061	0.05653	0.05816	0.02954
4	32	0	Uphill	Fast	61.5214	0.04079	0.05576	0.06849	0.02972
5	21	30	Uphill	Slow	22.3857	0.13004	0.19541	0.11814	0.16148
5	22	30	Uphill	Slow	27.258	0.12521	0.17726	0.11505	0.12405
5	23	30	Uphill	Fast	27.7391	0.11327	0.16379	0.09554	0.10962
5	24	30	Uphill	Fast	26.4186	0.11264	0.16311	0.09564	0.10905
5	25	15	Uphill	Slow	23.1277	0.09861	0.14782	0.07789	0.09107
5	26	15	Uphill	Slow	27.1796	0.09789	0.14737	0.07711	0.09416
5	27	15	Uphill	Fast	25.2745	0.09863	0.14705	0.07686	0.12576
5	28	15	Uphill	Fast	27.4052	0.09851	0.14673	0.07625	0.10392
5	29	0	Uphill	Slow	33.792	0.09604	0.14384	0.07379	0.08653
5	30	0	Uphill	Slow	27.0399	0.096	0.14364	0.07331	0.08646
5	31	0	Uphill	Fast	28.1782	0.09752	0.14362	0.07604	0.0872
5	32	0	Uphill	Fast	27.5436	0.09495	0.1428	0.07262	0.0858
6	21	30	Uphill	Slow	18.4513	0.08525	0.24007	0.1458	0.1345
6	22	30	Uphill	Slow	18.2797	0.08489	0.23837	0.14276	0.1235
6	23	30	Uphill	Fast	16.0599	0.08485	0.23782	0.14103	0.12383
6	24	30	Uphill	Fast	17.1726	0.08493	0.23745	0.1435	0.124
6	25	15	Uphill	Slow	12.7225	0.08215	0.23554	0.13942	0.13273
6	26	15	Uphill	Slow	13.1847	0.08279	0.23644	0.13871	0.14389
6	27	15	Uphill	Fast	12.0729	0.08387	0.23492	0.14004	0.13488
6	28	15	Uphill	Fast	11.9017	0.08326	0.23513	0.13841	0.13743
6	29	0	Uphill	Slow	26.7952	0.08745	0.23707	0.14941	0.1724
6	30	0	Uphill	Slow	26.973	0.09121	0.23907	0.14934	0.18958
6	31	0	Uphill	Fast	24.9121	0.08639	0.24013	0.14166	0.20258
6	32	0	Uphill	Fast	26.4071	0.08527	0.23383	0.14581	0.17608
6	21	30	Uphill	Slow	14.8601	0.21057	0.21434	0.13539	0.07473
6	22	30	Uphill	Slow	14.8601	0.20737	0.21392	0.13509	0.07457
6	23	30	Uphill	Fast	12.9374	0.21032	0.21397	0.13447	0.07453

6	24	30	Uphill	Fast	12.034	0.21403	0.2134	0.13413	0.0815
6	25	15	Uphill	Slow	19.0521	0.19491	0.20484	0.12528	0.06944
6	26	15	Uphill	Slow	21.0823	0.19435	0.2044	0.12477	0.06867
6	27	15	Uphill	Fast	20.0634	0.19377	0.20378	0.12484	0.07049
6	28	15	Uphill	Fast	19.723	0.19437	0.20387	0.12483	0.06875
6	29	0	Uphill	Slow	29.9237	0.19386	0.20315	0.12333	0.06757
6	30	0	Uphill	Slow	29.9237	0.19294	0.20249	0.12387	0.06724
6	31	0	Uphill	Fast	33.0644	0.19319	0.20253	0.12324	0.06712
6	32	0	Uphill	Fast	33.0644	0.19316	0.20217	0.12315	0.06693
8	21	30	Uphill	Slow	38.0473	0.07813	0.07577	0.15296	0.07521
8	22	30	Uphill	Slow	38.6825	0.08326	0.06979	0.13161	0.06177
8	23	30	Uphill	Fast	35.0386	0.08099	0.07041	0.12166	0.08433
8	24	30	Uphill	Fast	37.6111	0.08938	0.07137	0.11401	0.08483
8	25	15	Uphill	Slow	47.7891	0.06699	0.06393	0.08533	0.04875
8	26	15	Uphill	Slow	43.7004	0.06748	0.06458	0.08022	0.061
8	27	15	Uphill	Fast	43.2067	0.07949	0.06649	0.08071	0.06899
8	28	15	Uphill	Fast	39.2914	0.08078	0.0672	0.09038	0.06906
8	29	0	Uphill	Slow	68.8994	0.03387	0.05666	0.03846	0.02765
8	30	0	Uphill	Slow	66.3993	0.0345	0.05667	0.03646	0.02676
8	31	0	Uphill	Fast	61.5049	0.04061	0.05653	0.05816	0.02954
8	32	0	Uphill	Fast	61.5214	0.04079	0.05576	0.06849	0.02972
9	21	30	Uphill	Slow	22.3857	0.13004	0.19541	0.11814	0.16148
9	22	30	Uphill	Slow	27.258	0.12521	0.17726	0.11505	0.12405
9	23	30	Uphill	Fast	27.7391	0.11327	0.16379	0.09554	0.10962
9	24	30	Uphill	Fast	26.4186	0.11264	0.16311	0.09564	0.10905
9	25	15	Uphill	Slow	23.1277	0.09861	0.14782	0.07789	0.09107
9	26	15	Uphill	Slow	27.1796	0.09789	0.14737	0.07711	0.09416
9	27	15	Uphill	Fast	25.2745	0.09863	0.14705	0.07686	0.12576
9	28	15	Uphill	Fast	27.4052	0.09851	0.14673	0.07625	0.10392
9	29	0	Uphill	Slow	33.792	0.09604	0.14384	0.07379	0.08653
9	30	0	Uphill	Slow	27.0399	0.096	0.14364	0.07331	0.08646
9	31	0	Uphill	Fast	28.1782	0.09752	0.14362	0.07604	0.0872
9	32	0	Uphill	Fast	27.5436	0.09495	0.1428	0.07262	0.0858
10	21	30	Uphill	Slow	18.4513	0.08525	0.24007	0.1458	0.1345
10	22	30	Uphill	Slow	18.2797	0.08489	0.23837	0.14276	0.1235
10	23	30	Uphill	Fast	16.0599	0.08485	0.23782	0.14103	0.12383
10	24	30	Uphill	Fast	17.1726	0.08493	0.23745	0.1435	0.124
10	25	15	Uphill	Slow	12.7225	0.08215	0.23554	0.13942	0.13273
10	26	15	Uphill	Slow	13.1847	0.08279	0.23644	0.13871	0.14389

10	27	15	Uphill	Fast	12.0729	0.08387	0.23492	0.14004	0.13488
10	28	15	Uphill	Fast	11.9017	0.08326	0.23513	0.13841	0.13743
10	29	0	Uphill	Slow	26.7952	0.08745	0.23707	0.14941	0.1724
10	30	0	Uphill	Slow	26.973	0.09121	0.23907	0.14934	0.18958
10	31	0	Uphill	Fast	24.9121	0.08639	0.24013	0.14166	0.20258
10	32	0	Uphill	Fast	26.4071	0.08527	0.23383	0.14581	0.17608
11	21	30	Uphill	Slow	14.8601	0.21057	0.21434	0.13539	0.07473
11	22	30	Uphill	Slow	14.8601	0.20737	0.21392	0.13509	0.07457
11	23	30	Uphill	Fast	12.9374	0.21032	0.21397	0.13447	0.07453
11	24	30	Uphill	Fast	12.034	0.21403	0.2134	0.13413	0.0815
11	25	15	Uphill	Slow	19.0521	0.19491	0.20484	0.12528	0.06944
11	26	15	Uphill	Slow	21.0823	0.19435	0.2044	0.12477	0.06867
11	27	15	Uphill	Fast	20.0634	0.19377	0.20378	0.12484	0.07049
11	28	15	Uphill	Fast	19.723	0.19437	0.20387	0.12483	0.06875
11	29	0	Uphill	Slow	29.9237	0.19386	0.20315	0.12333	0.06757
11	30	0	Uphill	Slow	29.9237	0.19294	0.20249	0.12387	0.06724
11	31	0	Uphill	Fast	33.0644	0.19319	0.20253	0.12324	0.06712
11	32	0	Uphill	Fast	33.0644	0.19316	0.20217	0.12315	0.06693
12	21	30	Uphill	Slow	38.0473	0.07813	0.07577	0.15296	0.07521
12	22	30	Uphill	Slow	38.6825	0.08326	0.06979	0.13161	0.06177
12	23	30	Uphill	Fast	35.0386	0.08099	0.07041	0.12166	0.08433
12	24	30	Uphill	Fast	37.6111	0.08938	0.07137	0.11401	0.08483
12	25	15	Uphill	Slow	47.7891	0.06699	0.06393	0.08533	0.04875
12	26	15	Uphill	Slow	43.7004	0.06748	0.06458	0.08022	0.061
12	27	15	Uphill	Fast	43.2067	0.07949	0.06649	0.08071	0.06899
12	28	15	Uphill	Fast	39.2914	0.08078	0.0672	0.09038	0.06906
12	29	0	Uphill	Slow	68.8994	0.03387	0.05666	0.03846	0.02765
12	30	0	Uphill	Slow	66.3993	0.0345	0.05667	0.03646	0.02676
12	31	0	Uphill	Fast	61.5049	0.04061	0.05653	0.05816	0.02954
12	32	0	Uphill	Fast	61.5214	0.04079	0.05576	0.06849	0.02972
13	21	30	Uphill	Slow	22.3857	0.13004	0.19541	0.11814	0.16148
13	22	30	Uphill	Slow	27.258	0.12521	0.17726	0.11505	0.12405
13	23	30	Uphill	Fast	27.7391	0.11327	0.16379	0.09554	0.10962
13	24	30	Uphill	Fast	26.4186	0.11264	0.16311	0.09564	0.10905
13	25	15	Uphill	Slow	23.1277	0.09861	0.14782	0.07789	0.09107
13	26	15	Uphill	Slow	27.1796	0.09789	0.14737	0.07711	0.09416
13	27	15	Uphill	Fast	25.2745	0.09863	0.14705	0.07686	0.12576
13	28	15	Uphill	Fast	27.4052	0.09851	0.14673	0.07625	0.10392
13	29	0	Uphill	Slow	33.792	0.09604	0.14384	0.07379	0.08653

13	30	0	Uphill	Slow	27.0399	0.096	0.14364	0.07331	0.08646
13	31	0	Uphill	Fast	28.1782	0.09752	0.14362	0.07604	0.0872
13	32	0	Uphill	Fast	27.5436	0.09495	0.1428	0.07262	0.0858
14	21	30	Uphill	Slow	18.4513	0.08525	0.24007	0.1458	0.1345
14	22	30	Uphill	Slow	18.2797	0.08489	0.23837	0.14276	0.1235
14	23	30	Uphill	Fast	16.0599	0.08485	0.23782	0.14103	0.12383
14	24	30	Uphill	Fast	17.1726	0.08493	0.23745	0.1435	0.124
14	25	15	Uphill	Slow	12.7225	0.08215	0.23554	0.13942	0.13273
14	26	15	Uphill	Slow	13.1847	0.08279	0.23644	0.13871	0.14389
14	27	15	Uphill	Fast	12.0729	0.08387	0.23492	0.14004	0.13488
14	28	15	Uphill	Fast	11.9017	0.08326	0.23513	0.13841	0.13743
14	29	0	Uphill	Slow	26.7952	0.08745	0.23707	0.14941	0.1724
14	30	0	Uphill	Slow	26.973	0.09121	0.23907	0.14934	0.18958
14	31	0	Uphill	Fast	24.9121	0.08639	0.24013	0.14166	0.20258
14	32	0	Uphill	Fast	26.4071	0.08527	0.23383	0.14581	0.17608
15	21	30	Uphill	Slow	14.8601	0.21057	0.21434	0.13539	0.07473
15	22	30	Uphill	Slow	14.8601	0.20737	0.21392	0.13509	0.07457
15	23	30	Uphill	Fast	12.9374	0.21032	0.21397	0.13447	0.07453
15	24	30	Uphill	Fast	12.034	0.21403	0.2134	0.13413	0.0815
15	25	15	Uphill	Slow	19.0521	0.19491	0.20484	0.12528	0.06944
15	26	15	Uphill	Slow	21.0823	0.19435	0.2044	0.12477	0.06867
15	27	15	Uphill	Fast	20.0634	0.19377	0.20378	0.12484	0.07049
15	28	15	Uphill	Fast	19.723	0.19437	0.20387	0.12483	0.06875
15	29	0	Uphill	Slow	29.9237	0.19386	0.20315	0.12333	0.06757
15	30	0	Uphill	Slow	29.9237	0.19294	0.20249	0.12387	0.06724
15	31	0	Uphill	Fast	33.0644	0.19319	0.20253	0.12324	0.06712
15	32	0	Uphill	Fast	33.0644	0.19316	0.20217	0.12315	0.06693