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Assessing Work-Related Risk Factors on Low Back Disorders among Roofing Workers

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Abstract

Roofers have long suffered from low back disorders (LBDs), which are a primary nonfatal injury in construction. Ergonomic studies have identified several risk factors associated with LBDs in workplaces and developed biomechanical 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 roofers' posture variance and effects of working on slanted roof surfaces. This paper examined the relationship between roofing work-related factors and LBD risk among roofers using a laboratory assessment. A pitch-configurable wood platform was built to mimic the rooftop. The maximum trunk flexion angle and normalized electromyography (EMG) signals were measured as indicators using a motion capture system and a skeletal muscle signal recording system under different settings, i.e., different roof slopes, postures, facing directions, and working paces. The results indicated the measured factors with significant effects on the LBD development and revealed unfavorable conditions (e.g., using a stooped posture to work on low-pitch rooftops at a fast pace) where the work on rooftops needs particular attention. Such information is useful for systematic understanding of roofing nonfatal LBD developments among construction professionals and may enable development of interventions and guidelines for reducing the prevalence of LBDs at roofing jobsites.

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Construction safety; Ergonomic assessments; Low back pains; Risk evaluation; Musculoskeletal disorders; Experimental studies; Nonfatal injuries

Introduction

Low back disorders (LBDs) are a severe nonfatal occupational problem among roofers (CPWR 2015). The unique work environment (i.e., slanted rooftops) requires roofers to spend more than 75% of their work time in crawling, squatting, stooping, and kneeling postures (CPWR 2013). These awkward postures combined with the repetitive motion of roof material installation have led to incidences of severe low back pain among this population (Dong et al. 2010c). Although there are LBD protection guidelines available, they are designed for general industrial tasks, such as manual material handling (NIOSH 2007), ignoring the differences in work settings, procedures, and postural requirements. Biomechanical models such as the National Institute for Occupational Safety and Health (NIOSH) Lifting Equation have been established to analyze joint loading in terms of force or moment to indicate risk of LBDs at jobsites. However, those models fail to consider postural variances (e.g., stooping and kneeling) and effects of performing tasks on slanted rooftops. Most efforts to improve safety of roofing-related activities have been focused on preventing fall-related fatal injuries (Hsiao 2014). In contrast, nonfatal, cumulative injuries such as LBDs are often overlooked among the roofer population.

Severity of Low Back Disorders among Roofers

Low back disorders (or low back pains) are common musculoskeletal disorders (MSDs) that involve pain, discomfort, or malfunction of spinal muscles, nerves, bones, discs, or tendons in the low back region (McGill 2015). Commercial and residential buildings typically use roofs with pitch angles of 0–10° (flat roofs) and 10–45° (steep roofs), respectively. Roofers (approximately 140,000 in the United States alone) spend more than 75% of their work time in stooping, crouching, kneeling, and crawling postures (BLS 2015; CPWR 2013). These awkward postures combined with the repetitive motions that roofers perform during roof material installation have led to MSDs, especially LBDs (Fredericks et al. 2005; Dong et al. 2010c). A recent review showed that roofing has the second highest incident rate of work-related MSDs in the entire construction industry, which is about 30% more than the average incident rate reported by all construction jobs (Wang et al. 2015). Of all work-related MSDs in construction, trunk injuries have the highest incident rate, about six times as high as that of the shoulder (Wang et al. 2015). Moreover, the cost of work-related injuries among roofing contractors is significant. Choi (2006) reported that roofing companies' insurance premiums were increasing (as high as 37% annually) as workers' compensation costs were on the rise. The insurance rate for roofers is nearly three times as high as the average rate for all construction trades in Washington State (Washington DL&I 2015), and more than three times of the average rate of all trades in the state of Ohio (Ohio BWC 2015). As a consequence, there is a pressing need for solutions to reduce the occurrence of MSDs, particularly LBDs, in the roofing contracting industry.

State of Practice in Occupational Low Back Disorder Prevention

To prevent occupational LBDs among roofers in construction, general ergonomic practices have been promoted by safety and health organizations such as Occupational Safety and Health Administration (OSHA) and NIOSH. Instead of focusing on hazards to LBDs, general ergonomic practices typically focus on risk exposures associated with all work-related MSDs. For example, NIOSH has published a booklet titled *Simple solutions: Ergonomics for construction workers*, which contains simple and inexpensive methods to aid in prevention of injuries at construction sites (Albers and Estill 2007). OSHA has offered training materials and programs to help workers recognize, avoid, and control safety and health hazards in their workplaces (OSHA 2012). For the roofing industry, the Infrastructure Health and Safety Association (IHSA) in Canada has published brochures that provide information on how to develop MSD prevention and hazard control plans based on hazards associated with common roofing tasks (IHSA 2015a, b). Despite these efforts, the current ergonomic practices designed for general tasks in construction still lack practicality for roofing tasks because (1) most guidelines are presented in a brief and generic manner, which can hardly guide on-site MSD prevention practices without experts' explication (CCOHS 2013); and (2) differences in regard to work settings (e.g., slanted rooftops), procedures, and postures are often overlooked. Therefore, efforts are still needed to improve the current guidelines to better fit the roofing work setting. The effect or risk of working on slanted rooftops needs further assessments.

State of Research in Roofing Ergonomic Injuries and Risk Factors

Studies of Ergonomic Injuries among Roofers

To date, studies on nonfatal ergonomic injuries in roofing-related activities have primarily focused on surveillance and pathology. Several studies have been conducted to evaluate the nature, severity, and causes of MSDs among roofers using surveys and observations. For instance, a survey study on occupational injuries among construction workers indicated that half of nonfatal injuries among roofers are in the back and are mostly caused by overexertion, strenuous movement, and high repetition (Hunting et al. 2004). Fredericks et al.'s (2005) analysis revealed that the primary source of ergonomic injuries among roofers is associated with awkward working postures and repetitive motions. Welch et al. (2010) reported that MSDs are the most-common injuries and health issues in roofing activities and have forced roofers into early retirement. Moreover, studies have shown that most roofers work as individual contractors or as employees of small companies (1–10 employees) (NIOSH 1999; Sa et al. 2009). Small companies could use insufficient protective measures, or fail to provide proper training for performing highly demanding tasks and unique challenges created by the slanted ground surfaces (Moore and Wagner 2014). In addition, a significant portion of the roofer population was observed to be ethnic minorities, whose occupational injury rates are among the highest in the construction industry (Arcury et al. 2014; Dong et al. 2010a, b). Thus, the health condition of roofers requires attention among safety and health regulators and researchers (Smith-Jackson et al. 2011).

Work-Related LBD Risk Factors in Roofing Activities

Epidemiological studies found evidence for associations between LBDs and workplace factors including heavy physical work, lifting and forceful movements, bending and twisting (awkward postures), and whole-body vibration (Bernard 1997). Furthermore, potential LBD risk factors in roofing have been identified, including posture, roof pitch, facing direction, and working pace, based on the analyses by Wang et al. (2015), site visits, and literature review.

Posture—There are good biomechanical reasons to examine working postures as a significant contributor to LBDs (Holmström et al. 1992; Jin et al. 2009). At the roof site, roofers are typically involved with two main postures in shingle installation: stooping and kneeling (Fig. 1). Stooped postures require roofers to bend forward while holding their legs straight, as shown in Fig. 1(a). In contrast, a kneeling posture typically requires roofers to kneel on the roof and maintain their trunk in parallel to the rooftop, as illustrated in Fig. 1(b). However, in spite of this observation, current studies have yet to include any information regarding the relationship between the LBD risks and the postures that roofers adopt. Reducing the incidence of LBDs among roofers requires endeavors to assess whether stooped and kneeling postures can be characterized as a LBD risk factor in the roofing workplace.

Roof Pitch—A study of the influence of surface slopes on the working pace and postural balance of male subjects performing a simulated roof-shingling task showed an inverse correlation between the slope slant and the maximum acceptable roof shingling pace, indicating a reduced postural balance at steep slopes (Choi and Fredericks 2008). Previous studies have found that manual handling of tasks on slanted ground surfaces can exhibit a significant difference from those conducted on the ground in terms of LBD risk (Ning and Mirka 2010; Zhou et al. 2015). These studies provoke the need for assessments of jobs conducted on uneven surfaces such as rooftops.

Facing Direction—Different roofing materials may require different installation methods on rooftops. For instance, roofers installing three-tab or four-tab residential shingles often face uphill (ridge); for solar panels, roofers often stand perpendicularly to the ridge (facing hip) in order to avoid stepping on these panels. An asymmetry was detected during bending on laterally slanted ground surfaces (Hu et al. 2013; Ning et al. 2011). A displacement of the C7 joint was found when bending on uneven slopes compared to that on the flat ground, indicating that workers tend to lean towards the 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 nonsimultaneous cessation of muscle activities, suggesting that facing direction affects the trunk flexions and muscle activities.

Working Pace—Dai et al. (2010) reported that the horizontal load speed can have a significant effect on the spinal loading. A deeper flexion and higher muscle activities were found in fast-paced manual materials handling and lifting. However, whether this finding applies to the roofing shingle installation process is unknown.

Problem Statement and Research Objective

All the presented data in the preceding section highlights the severity and risk of LBDs among roofers. Ergonomic studies have identified a number of work-related risk factors that could contribute to the occurrence of LBDs. However, when it comes to roofing, a systematic evaluation of work-related LBD risk factors has not been conducted. The combined effect of these factors and the slanted surface on LBD risks is still unknown. Without such knowledge, it is difficult to improve risk assessment methods and develop effective control strategies in reducing work-related LBDs in the roofing industry.

The objective of this research was to assess the impacts of roofing-related factors on the occurrence of LBDs among roofers. This research did not intend to account for human-related factors such as gender, aging, and social stressors; instead, it focused on physical and work-related factors, specifically slope, posture, facing direction, and working pace.

Experiment Design and Implementation

Variables

Four risk factors were evaluated in the experiment:

- Slope: 0°, 15°, and 30°;
- Posture: stooped and kneeling;
- Facing direction: uphill and sideways; and
- Frequency: slow (12 s/shingle) and fast (6 s/shingle).

These levels for slope, posture, and facing direction were set based on accounts of site practices experimental safety, and feasibility. The frequency levels were set according to the study on maximum acceptable working frequency on roof slopes (Choi and Fredericks 2008).

Two types of response variables, i.e., maximum trunk flexion angle (MTFA) and normalized electromyography (EMG) signals, were measured to reflect the effects of the risk factors and indicate the LBD risk. The MTFA was the maximum trunk flexion angle 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 Fig. 2. A natural upright posture results in an approximately 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 angles indicate higher spinal moment and higher associated spinal injury risks. The normalized EMG signals correlate the activation levels of the erector spinae (ES) and multifidus (MU) lumbar extensor muscles, with the implication that the stronger the signal, the higher the risk. The aforementioned two types of response variables were used to help establish the LBD risks.

Participants

A total of 15 male volunteers [25.2 years (3.3 years), 176.4 cm(3.4 cm), and 70.6 kg (8.4 kg)] participated in the study. Females were excluded from this study as over 97% of roofers are male (BLS 2016). All participants had no history of chronic low back injury. The research protocol was approved by the Institutional Review Boards of West Virginia University and NIOSH.

Instruments

The trunk kinematic data were collected using a Vicon optical motion analysis system (Vicon T-Series Camera System, Oxford, U.K.). Two retroflective motion markers were placed on the participant’s trunk: one at the C7 joint (around the neck) and the other at the L5/S1 joint (around the waist). Hence, the real-time three-dimensional (3D) coordinates of the two joints could be measured to calculate the trunk flexion angle. Additional markers were placed on the shoulders, arms, and legs for the convenience of recognition of posture and facing direction. The kinematic data were recorded at a frequency of 100 Hz, at which speed it sufficed to capture the motion in this task and determine the MTFA.

Muscular activities of the lumbar paraspinal muscles (ES and MU) were recorded using a surface EMG system (Bagnoli Desktop EMG System, Boston, Massachusetts). Bipolar surfaced EMG electrodes were placed 4 cm lateral from the L3 spinous process measuring the ES muscles and 2 cm lateral from the L4 spinous process measuring MU muscles. These muscles were selected to estimate the muscle tension and the activation of the lumbar muscles (Hu et al. 2013). The EMG data were collected at a rate of 1,000 Hz, which was a minimum sampling frequency recommended to avoid aliasing (De Luca 2003). The collected EMG data were then synchronized with the kinematic data on the Vicon *Vicon Nexus version 1.8.1* software platform.

Participants’ maximum voluntary contraction (MVC) data of the lumbar muscles was collected using a dynamometer (HUMAC Norm, Computational Medicine, Stoughton, Massachusetts). The MVC refers to the greatest amount of tension a muscle can generate and hold. Thanks to the strength difference among different participants, these data were needed for normalization of the EMG data to enable reasonable comparison.

A 1.2 × 1.6 m custom-made wood platform was built to mimic the rooftop on which the simulated shingle installation could be conducted (Fig. 3). This 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°. Antiskidding tape was attached to the platform surface to increase the friction and avoid slips or falls.

Procedure

The experiment particularly focused on the nailing process in which constant trunk bending was required. Prior to starting the experiment, a complete hazard assessment of the work environment was performed. The experimental procedure was introduced to the participants upon their arrival to the lab. After a warm-up session (5 min), the surface EMG electrodes and motion markers were secured to the designated locations on the trunk with a tape.

During the data collection, each participant performed the shingle installation on different settings. The protocol defined a complete shingle installation trial to include three steps: trunk flexion, nailing, and trunk extension. Specifically, it required the participant to use 1/6 of a given time (slow cycle of 12 s and fast cycle of 6 s) to flex his trunk from an upright standing position to reach the first nailing, 2/3 of the time to nail at four spots, which were evenly distributed from the left edge to the right edge of an asphalt shingle [shingle length of 91.4 cm (36 in.)], and 1/6 of the time to resume to upright standing position. The participants were required to hold a nail gun and use it to touch the nailing spots during the shingle installation process.

In the experimental trials, the stooped and kneeling postures were tested separately. First, the stooped posture was implemented in the nailing process with configurations of the slope (three levels), facing direction (two levels), and working pace (two levels), resulting in a total of 12 combinations, and every participant repeated each combination twice. Second, the kneeling posture was implemented. Because the kneeling posture always faces the roof ridge, this group contained six combinations (three levels for slope and two levels for working pace). Similarly, every participant repeated each combination twice.

Data Processing

The trunk flexion angle was calculated based on the returned 3D coordinates of the two markers placed on the joints C7 and L5/S1, denoted as (x_1, y_1, z_1) and (x_2, y_2, z_2) respectively. Hence, the trunk flexion angle (γ) was determined by

$$\gamma = 90° - \left(\frac{180°}{\pi}\right) \times \tan^{-1}\left[\frac{z_2 - z_1}{\sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2}}\right] \quad (1)$$

The EMG data collected from each shingle installation process was rectified, filtered, normalized, and averaged over the nailing period [Figs. 4(a–c)]. The full-wave rectification took the absolute value of the signals and the nonnegative rectified EMG signals are plotted in Fig. 4(b). The rectified EMG signals were then filtered with the fourth-order Butterworth filter, followed by smoothing to reduce outliers. The profile of the filtered EMG data is shown in Fig. 4(c). Next, the filtered data were normalized in order to enable comparison among different individuals. Several factors such as electrode configuration, electrode placement, temperature, perspiration, and individual strength differences can influence the raw EMG data, making the direct comparison of raw data error-prone (Sousa and Tavares 2012). Therefore, the filtered EMG data were further normalized on each muscle during each task. The normalized EMG data showed the relative measure of the activation to the MVC reference value. Last, to compute the average normalized EMG signals over the nailing process, data of the flat curve in Fig. 4(c) were extracted. This flat curve was between two ridges. The first ridge represented the trunk flexion process, the second ridge represented the trunk extension process, and the flat curve represented the nailing process. The average of the normalized EMG signals during the nailing process was used as the response variable to analyze the muscle activation and spinal loading.

Statistical Analysis

All response variables were examined to satisfy the assumptions of the analysis of variance (ANOVA) procedures using a graphical approach (Montgomery 2012). Multivariate ANOVA (MANOVA) was applied to evaluate the effects of the factors and their interactions on the response variables (i.e., MTFA, normalized EMG signals on ES and MU muscles). The independent variables that demonstrated significant effects were further analyzed using univariate ANOVA. For an independent variable with three or more levels (i.e., slope), Tukey–Kramer post hoc analysis was performed to further explore the effect differences between levels. The *p*-value was set 0.05 for all tests. The statistical analyses were performed in *Minitab 17*.

Results

Tables 1 and 2 present the effects of the factors and their interactions (denoted by an asterisk) on the response variables for stooped and kneeling postures, respectively. Because the analysis of EMG signals on the left and right ES and MU muscles remained consistent, this study reported the average of the left and right measurements instead of separately.

Stooped Posture

Influence of Roof Pitch—Fig. 5 shows the trend that the MTFA decreases as the slope angle increases. All stooped trials on rooftops were observed to have MTFAs larger than 70° during the nailing process. This was categorized as a high degree of trunk bending by ergonomic observational tools such as Posture, Activity, Tools, and Handling (PATH). Fig. 5 also plots the Tukey's test result, showing that levels at 0 and 15° can be treated as one group (denoted as Group A), whereas the level at 30° can be treated as another (denoted as Group B). This means that the influence at levels 0 and 15° (Group A) was significantly different from that at level 30° (Group B). Within Group A, the levels were not significantly different from each other.

Fig. 6 shows the effects of slope angle on activation of the lumbar muscles. The plot indicated a consistent trend for the relationships between the activations of both ES and MU muscles and MTFAs. However, the EMG signal difference between different slope levels is negligible (within 3%). This echoes the findings in Table 1, which show that the slope did not have statistical significance on muscle activation.

Influence of Facing Direction—Fig. 7 shows that MTFA in facing sideways was significantly higher than that in facing uphill. This indicated that the peak spinal loading in facing sideways is higher than the peak spinal loading in facing uphill.

The interaction effect is plotted in Fig. 8. At each slope level, the MTFAs in two facing directions were compared. At 15° and 30° slopes, the MTFA in facing sideways was significantly higher than that in facing uphill. Furthermore, the following were found: (1) for facing uphill, as slope angle increases, the MTFA decreases, which echoes the findings in the "Influence of Roof Pitch" section; and (2) for sideways, the MTFA maintains approximately the same for all three slope levels.

When bending on the laterally slanted surface (or facing sideways), a participant needed to stretch towards the left to reach the leftmost nailing spot, which was at a lower position. In this study, all the participants were right handed and their right foot was placed at a higher position than their left foot when standing on uneven slopes. When installing shingles on uneven slopes, a deeper flexion was required at the left-sided nailing spots than at the right-sided. Fig. 9 shows the trunk flexion angle for one shingle installation cycle for facing sideways and facing uphill, respectively, with the MTFA marked.

A similar trend for fast-pace and slow-pace trials were observed. By comparison, distinct facts for facing sideways from facing uphill were found. During the nailing process, a higher variance was found in facing sideways [standard deviation (SD) of 11.4°] than in facing uphill (SD of 4.2°) on a slanted surface (i.e., 15° and 30°). The computed variance was the average of variances on 15 and 30° slopes, and at 0° was excluded as facing sideways and facing uphill had no difference on the flat ground. The MTFA in facing-sideways trials was detected at the beginning of the nailing process. Furthermore, the trunk flexion angle throughout the nailing process in facing uphill trials maintained almost the same. Finally, the average nailing-phase trunk flexion angle of all participants was 82.1° for facing sideways and 79.1° for facing uphill. This indicated that the average trunk flexion angle when facing sideways is still higher than that in facing uphill, which indicated a higher cumulative spinal loading. However, this difference was significantly less than that of MTFAs in Fig. 7 (i.e., sideways: 93.3°; uphill: 82.0°).

The EMG data do not show a 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 the flat ground (0°) and stated that EMG data of left side of paraspinals demonstrated significantly lower values on a slanted surface. Hence, further study comparing left-side and right-side back muscles on different facing directions is needed.

Influence of Working Pace—The working pace was demonstrated to be associated with the EMG measure (Table 1). EMG signals showed consistently, in both ES and MU muscles, that a fast working pace resulted in significantly higher normalized EMG data than a slow working pace (Fig. 10). This finding indicates relatively strong muscle activation at a fast working pace and has implications for higher LBD risk.

Statistical analysis showed that the working pace had no significant effects on MTFA (Table 1). This is because for the slow-pace and fast-pace trials, participants employed the same postures and procedures, which would only result in a negligible difference in movement.

Kneeling Posture

Influence of Roof Pitch—The kneeling observations were divided into three groups according to the slope angles and the 95% confidence interval was plotted for each group. The trend is that the MTFA drops as the slope increases, which indicated a less-severe bending (Fig. 11). The Tukey’s test determined that 0° slope could be categorized into Group A, whereas 30° and 15° could be categorized into Group B. This means that the mean of MTFAs in Group A is significantly different from that in Group B. But within the same Group B, the slope levels have no significant difference.

The effects of slope angles on activation of lumbar paraspinal muscles indicated a trend that ESl, ESr, MUl, and MUr signals grow as the slope angle increases (Fig. 12). A significantly higher MU muscle activation (both sides) was found in the 30 than in 0 and 15°.

Influence of Working Pace—The effects of working pace on MU EMG signals implied that more-active muscles are utilized at the fast working pace than the slow working pace in the kneeling posture (Fig. 13). The EMG signals of the fast-pace group (denoted as A) were significantly higher that of the slow-pace group (denoted as B). However, for ES EMG signals, no significant difference was found between fast-pace and slow-pace trials. This also echoes the findings in Table 2.

Different from stooping, when a participant is kneeling, his trunk 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 participants' trunks had no obvious movement. Instead, the arm and shoulder movement speed was adjusted to adapt the working pace changes. In order to differentiate the muscle activities at fast and slow paces, one possible solution is to extend the length of the shingle so that the participants need to significantly move their trunk to reach the two ends of the shingle. Another possible solution is to increase the time difference between two paces, e.g., making the fast pace even faster, such as 4 s/shingle.

Discussions

Stooped Posture

The trunk kinematic data showed a highly consistent trend among all participants in facing directions and slopes. As the slope increases, the distance of a participant's upper body (i.e., arms, shoulders, and trunk) from the nailing spots on the rooftop becomes closer. As a result, a smaller MTFA and average trunk flexion are required on a high-pitch roof than that on a low-pitch roof. A similar trend was indicated by the EMG data, in which spinal injury risk was found to be smaller on a high pitch than that on a low pitch or the flat ground.

The trunk kinematic data also showed that, in facing sideways, the participants reached the maximum bending angle at the leftmost nailing spot, 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 practice. 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 an uneven slope can cause asymmetric trunk motion, and the ipsilateral lumbar muscles cease activity earlier than the contralateral lumbar muscles.

For the stooped posture, the EMG signals significantly differentiated fast and slow paces in both nailing process and in-place flexion-extension trials. The EMG signals showed stronger muscle activeness in fast-pace trials.

Kneeling Posture

In the 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 the stooped trials. However, the 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 lower extremities in kneeling postures, including legs and ankles, were observed to have a higher loading than during a stooped postures. Possible interventions for kneeling postures could be wearing knee pads or kneeling on a cushion. For one thing, such measures 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 posture, the EMG signals indicated that fast trials resulted in higher muscle activation and higher LBD risk. But the difference between the fast and slow trials was less than that of the stooped trials, especially EMG signals of erector spinae muscles. This can be due to the fact that the time lengths for fast and slow trials are close to each other. Further study could either speed up the frequency for fast trials or enlarge the shingle size to explore the difference.

Stooped Posture versus Kneeling Posture

The kneeling postures (<50° in Fig. 11) have a significantly smaller maximum trunk flexion angle than the stooped postures (>70° in Fig. 5), which indicates a smaller spinal loading in kneeling postures. From the perspective of alleviating LBD risks, the kneeling posture is preferred rather than the stooped, but it requires sufficient protective gear for the knee and ankle. Wearing knee pads or a placing cushion under the knee while installing shingles may help protect the knees while working at kneeling postures. However, limited by the research scope, lower extremities have not been covered by this study. The lower extremities for kneeling postures could have higher loading impacts than those for stooped postures due to severe bending in the legs and ankles.

Study Limitations

This study has several limitations. First, participants were not roofers, but university students who had no professional experience in roofing. Second, the assessment was performed on a wood platform instead of a real work site, though this platform was pitch-configurable and a nonslip mat was attached to its surface in place of shingles. Third, participants were assumed to have a uniform time distribution in flexion, nailing, and extension. However, during the trials, participant could hardly maintain a strictly steady working pace, which might result in either delay or earlier finish. 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 associated with the nailing process. However, assuming that the flexion phase was prolonged and the actual time distribution was 2:3:1, the extraction from the ideal distribution (1:4:1) would lead to the nailing time containing part of and flexion cause errors. To improve this, a trigger can be used to record the exact starting and ending time points of each phase.

In addition, muscle fatigue was not studied in this study. The trial period was relatively short and fatigue could not be detected during the experiment. The twisting angle of the trunk was also not measured in this experiment, which is expected to differentiate facing side and uphill postures better. In the future, more markers could be attached to upper body parts such as shoulders to measure the twisting of the trunk. Finally, only the trunk flexion and lower back muscle activeness were studied for the injury risk analysis, ignoring the ankle flexion angles and balance-related measures. The interview after the trials by each participant showed that 13 of the 15 participants perceived an imbalance and higher ankle stress while working on steeper slopes. An existing study indicated a reduced balance on the high pitch roof than the low pitch (Choi and Fredericks 2008). As a result, working on the steep slope may not be considered favorable. One possible intervention could be to install a wood 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, but also reduce the ankle flexion and ease the discomfort.

Conclusions and Future Research

The roofing industry is a highly physically demanding sector and the work environment exposes roofers to various LBD hazards. This research conducted a laboratory assessment to examine LBD risk factors among roofers at the Industrial Ergonomics Laboratory of West Virginia University. A pitch-configurable wood platform was built to mimic a rooftop. The maximum trunk flexion angle and normalized EMG signals were measured as indicators under different settings, i.e., different roof slopes, postures, facing directions, and working paces. By analyzing the collected measurements, this study provided useful information for systematic understanding of the work-related risk factors on low back disorders among roofers and therefore to help them avoid unfavorable work conditions that involve severe LBD risks (e.g., working with stooped posture on low-pitch rooftops at a fast pace). Such information may also enable development of interventions and guidelines for reducing the prevalence of LBDs at roofing jobsites.

Future work includes real site assessments with participation of experienced roofers as ergonomic interventions for roofing sites are developed. Personal protective equipment such as fall protection harnesses and lifelines were not used during the performance of the simulated roofing tasks; its impact on roofers' task performance warrants future investigation. As the work environment exposes roofers to both fall and MSD risks, the imbalance measure will be factored into further development of the risk assessment methods, which is achievable via observation of prolonged trials and static severe bending on different working conditions. Such an extension will facilitate the assessment of injury risks for tasks performed on steep rooftops exceeding 30°, which, though not included in this assessment, will be studied with fall protection measures in the future. In addition, potential interventions that will relieve spinal loading while posing a small stress on the lower extremities are worth further investigation.

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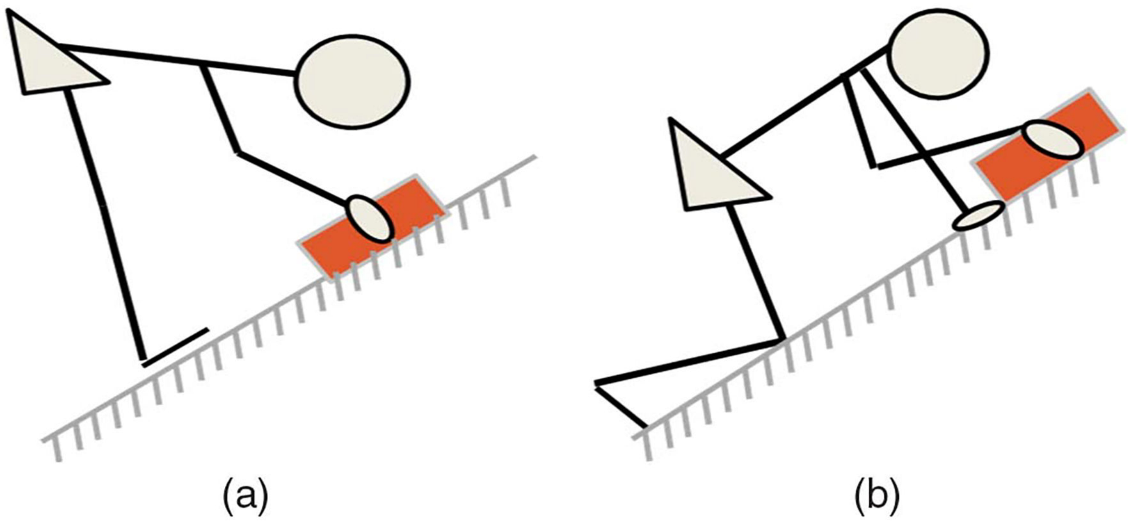

Fig. 1.
Roofing with (a) stooped; (b) kneeling postures

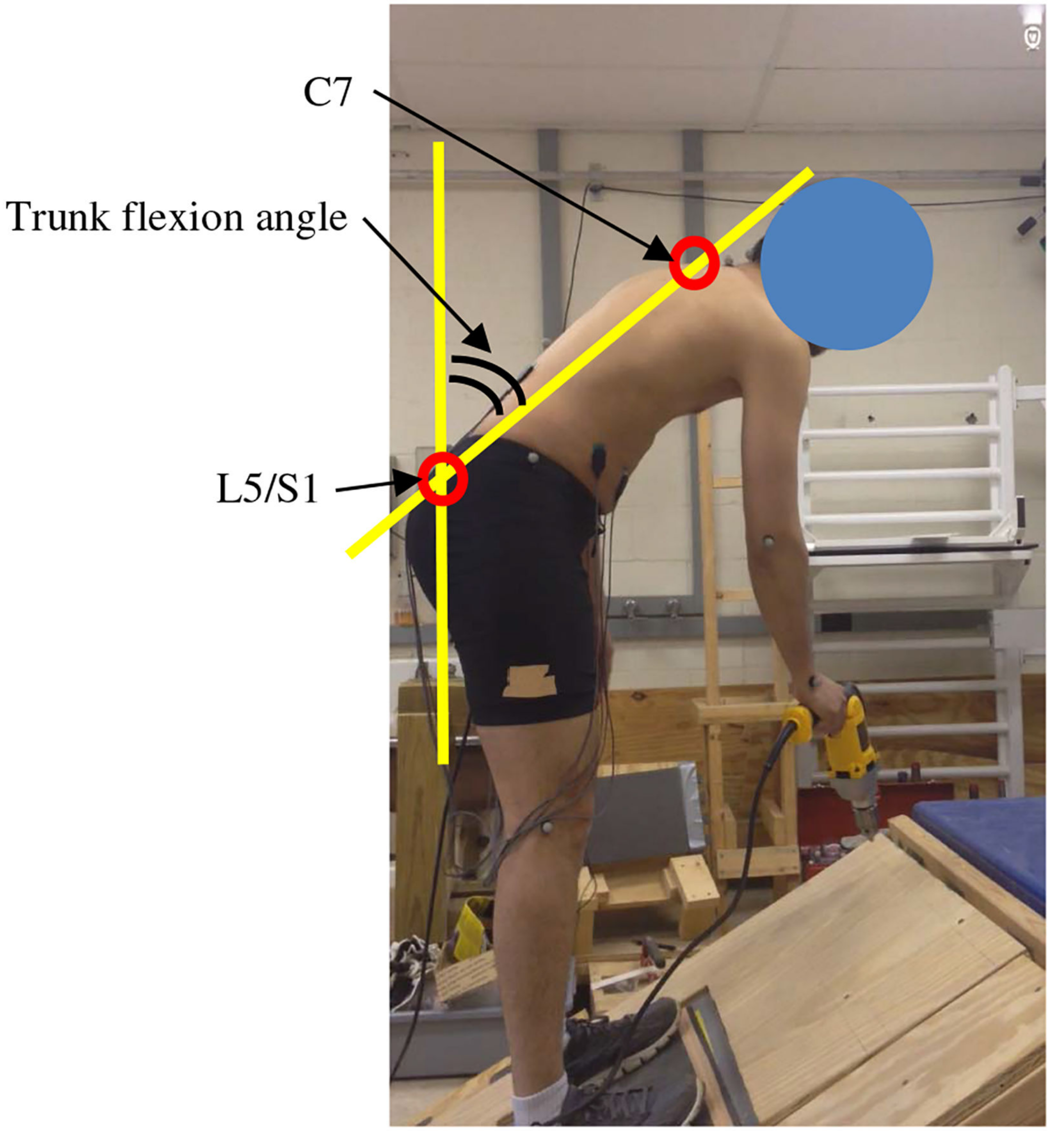

Fig. 2.
Trunk flexion angle (stooped posture)

Fig. 3.
Wooden roof platform elevated by hydraulic lift

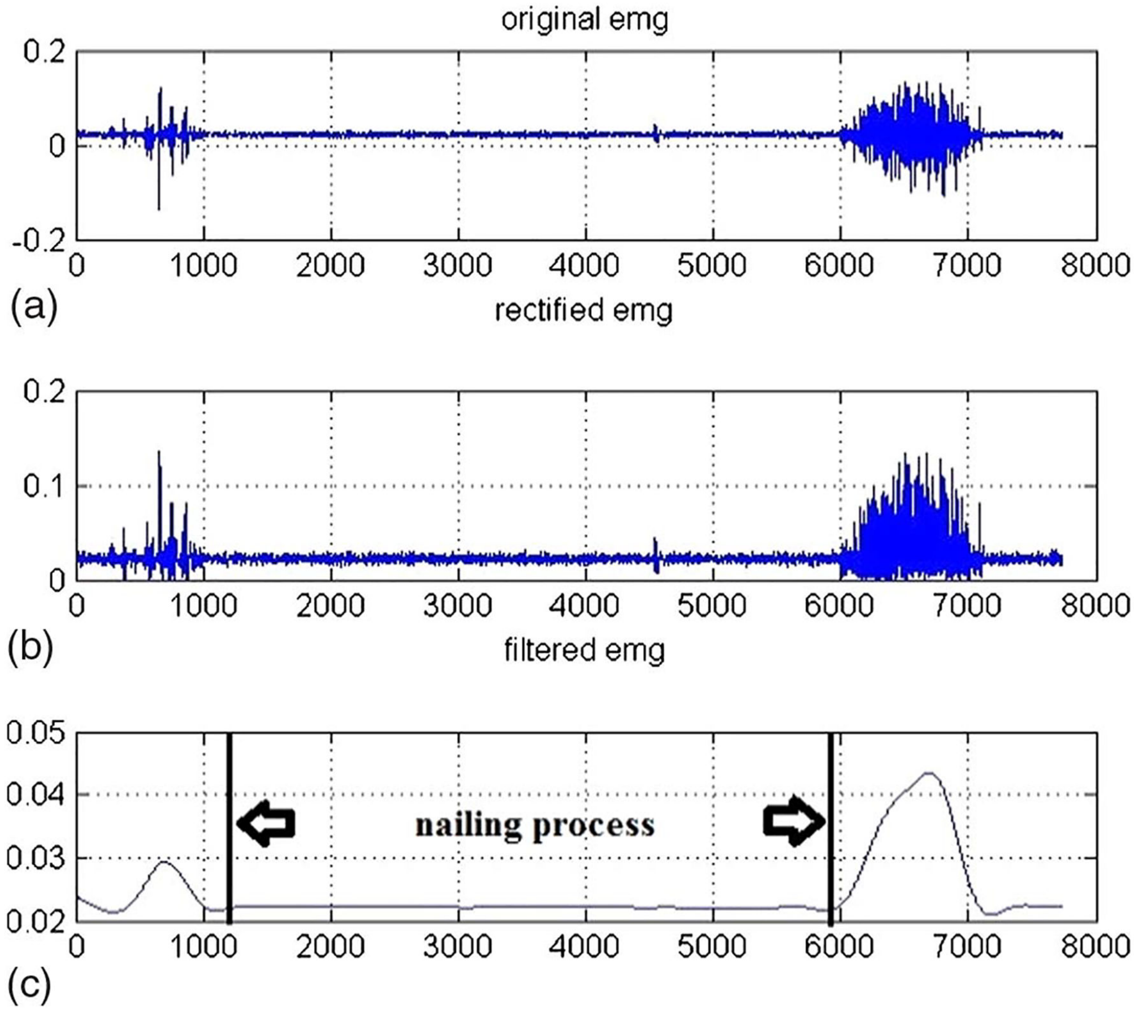

Fig. 4.

EMG signal processing: (a) original; (b) rectified; (c) filtered signals; *x*-axis is time in milliseconds and *y*-axis is the magnitude of the EMG signal in arbitrary unit

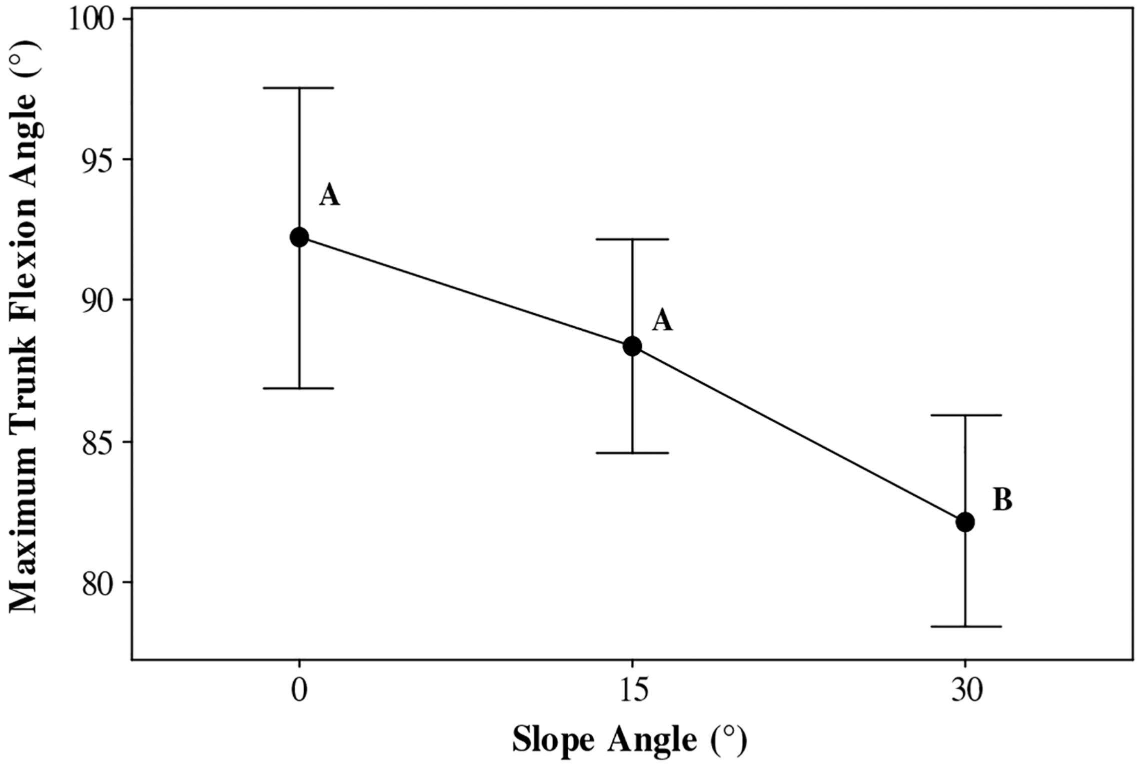

Fig. 5.

Effects of slope angle on maximum trunk flexion angle (stooped); all stooped observations were divided into three groups by the level of slope; the level mean was marked by a dot, enclosed by the 95% confidence interval

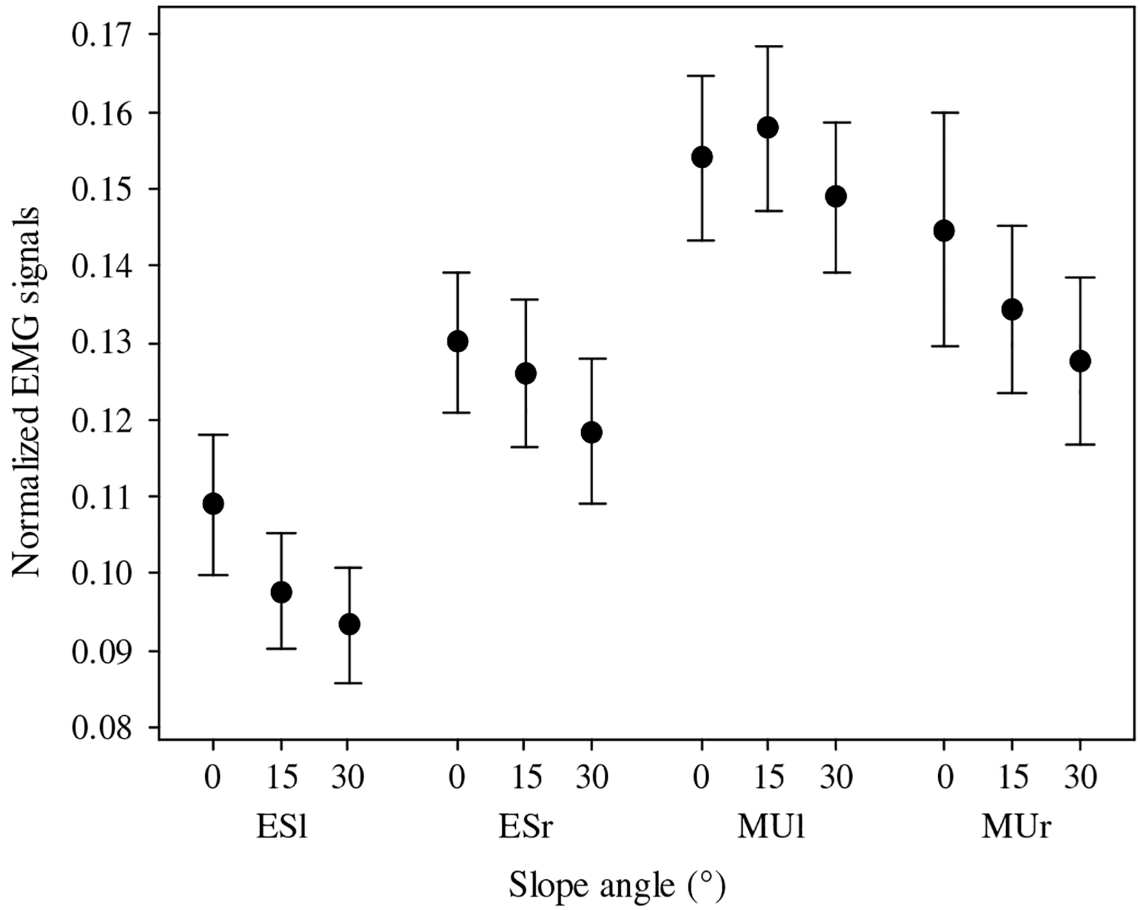

Fig. 6.

Effects of slope angle on lumbar muscle activation (stooped); ESl, ESr, MUl, and MUr denote left ES, right ES, left MU, and right MU, respectively

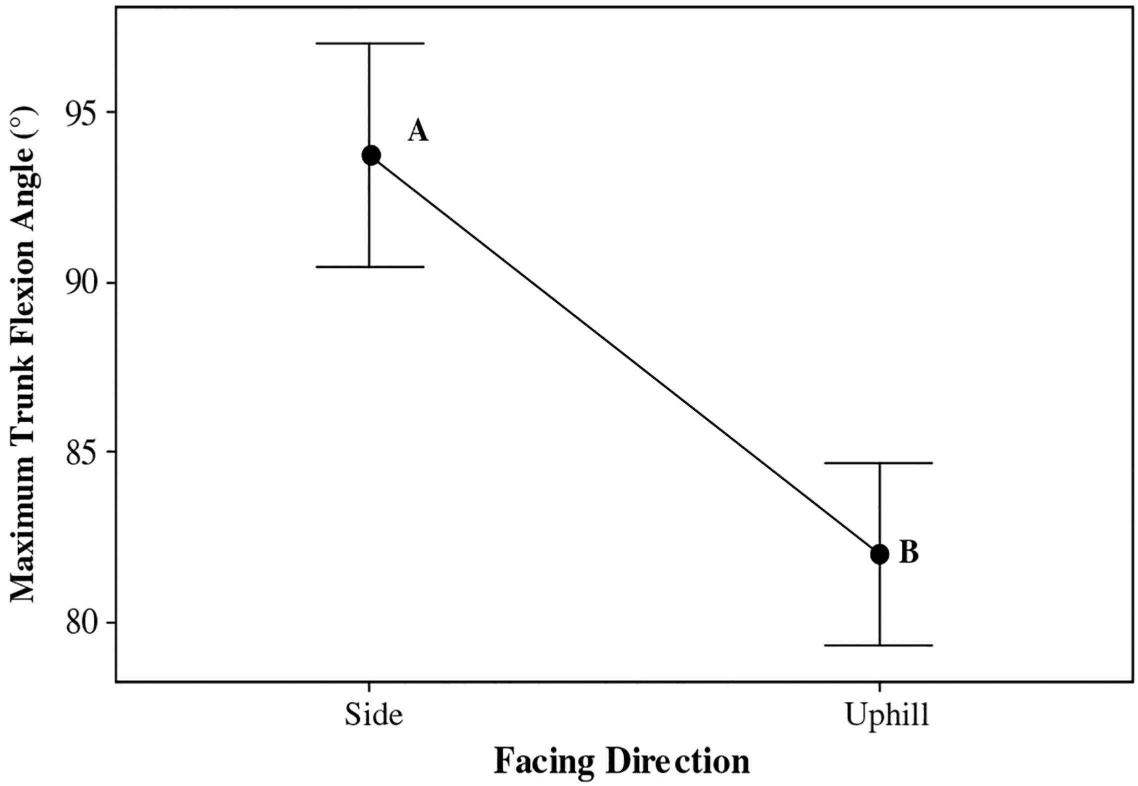

Fig. 7.
Effects of facing direction on maximum trunk flexion angle (stooped)

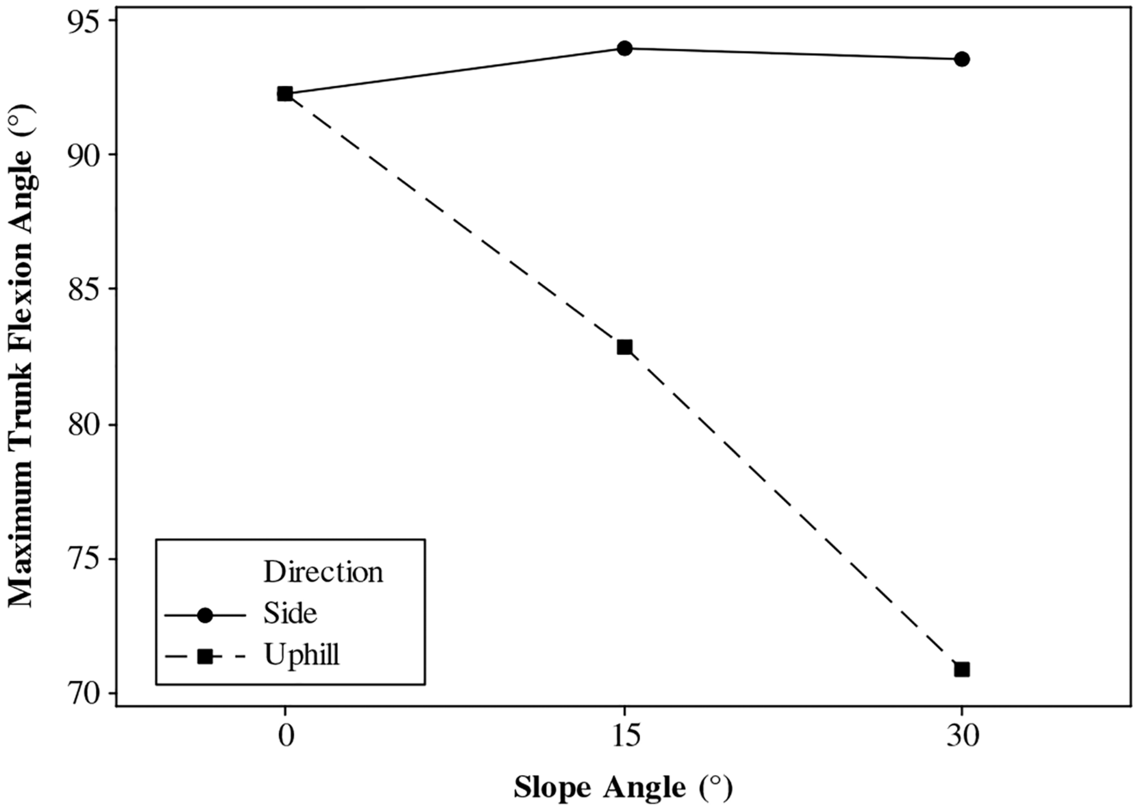

Fig. 8.
Interaction effect of slope angle and facing direction (stooped)

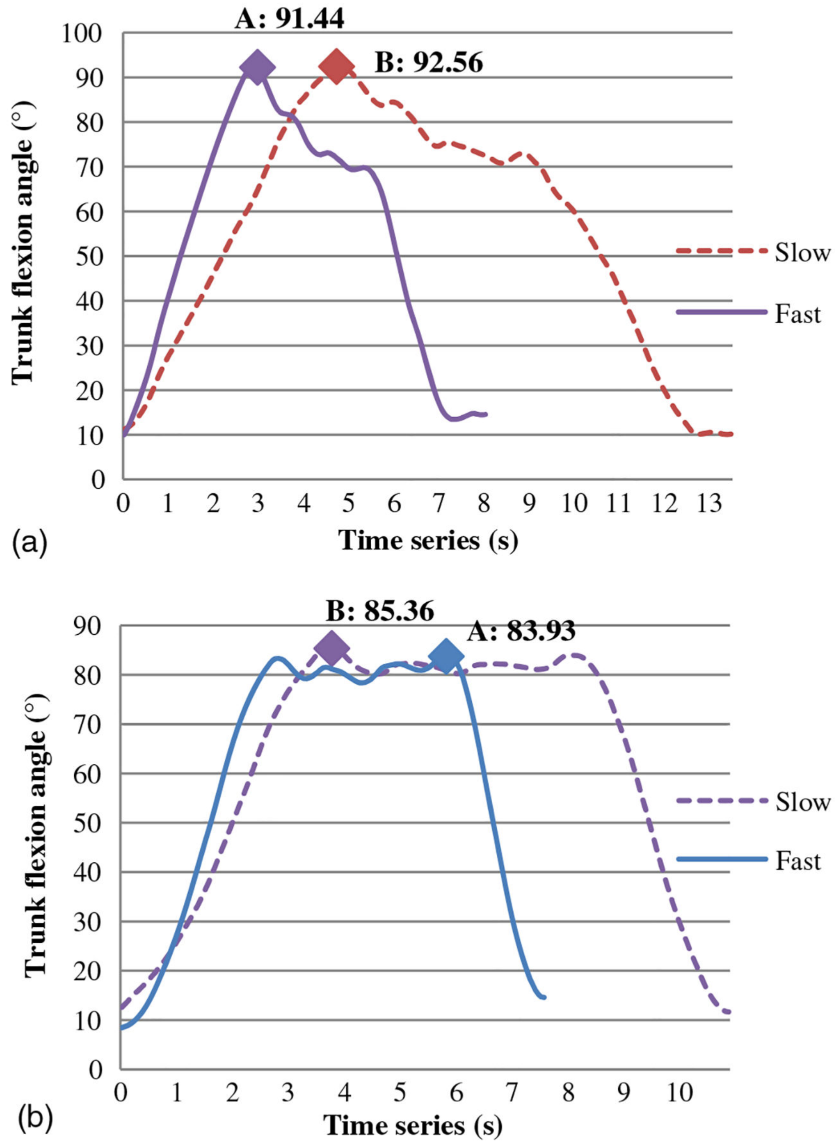

Fig. 9.

Time-series plots of trunk flexion angle for facing (a) sideways; (b) uphill

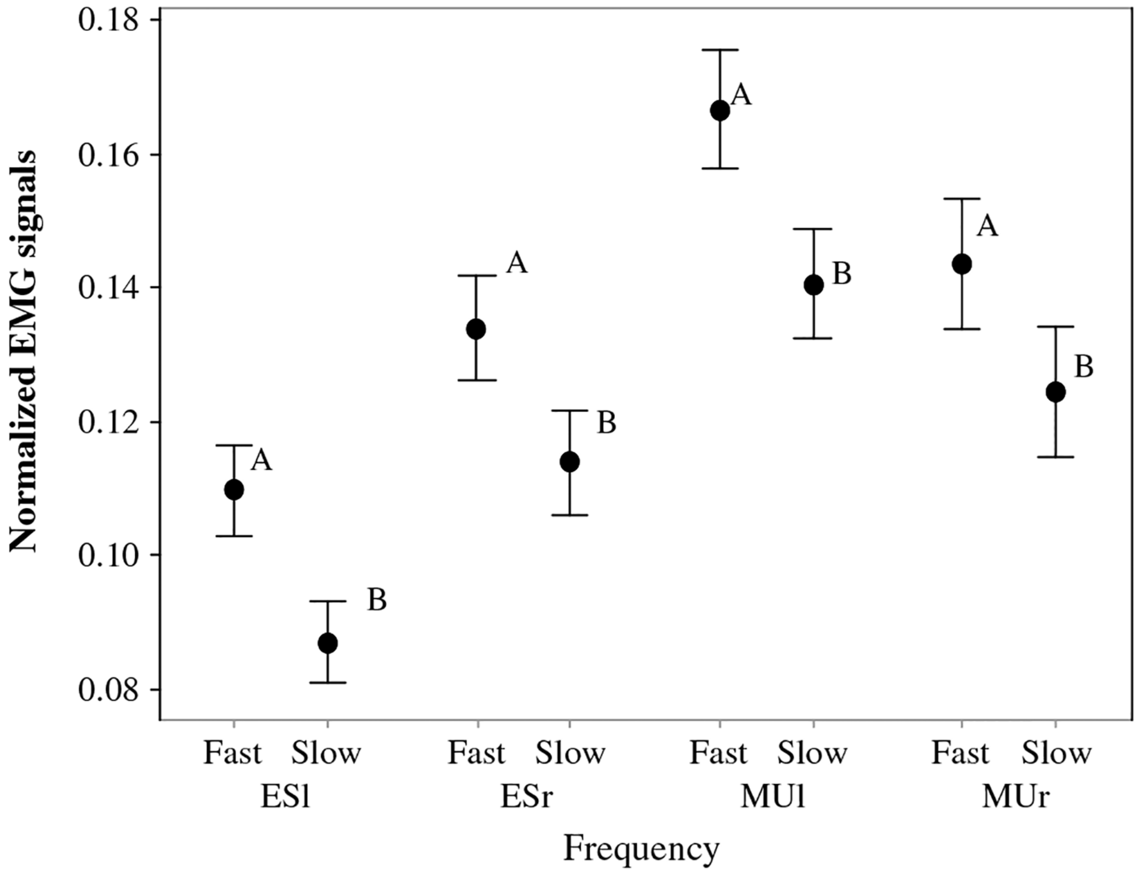

Fig. 10.
Effects of working pace on EMG signals (stooped)

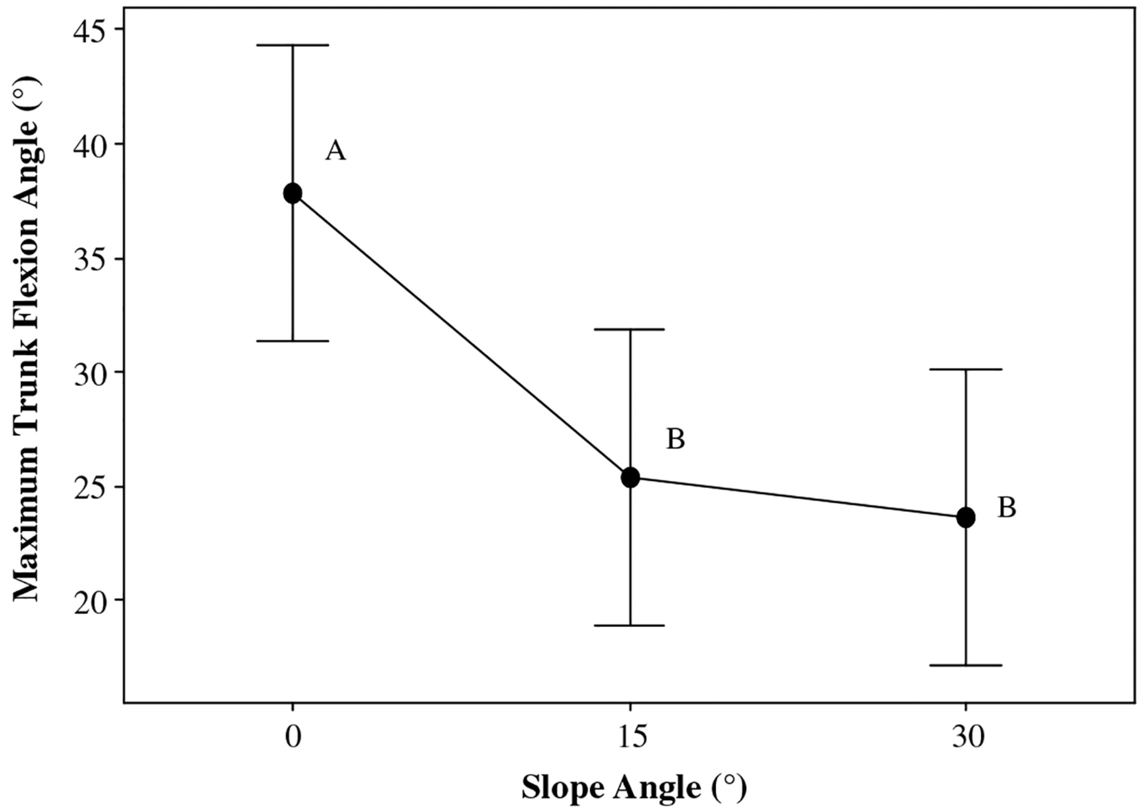

Fig. 11.
Effects of slope angle on maximum trunk flexion angle (kneeling)

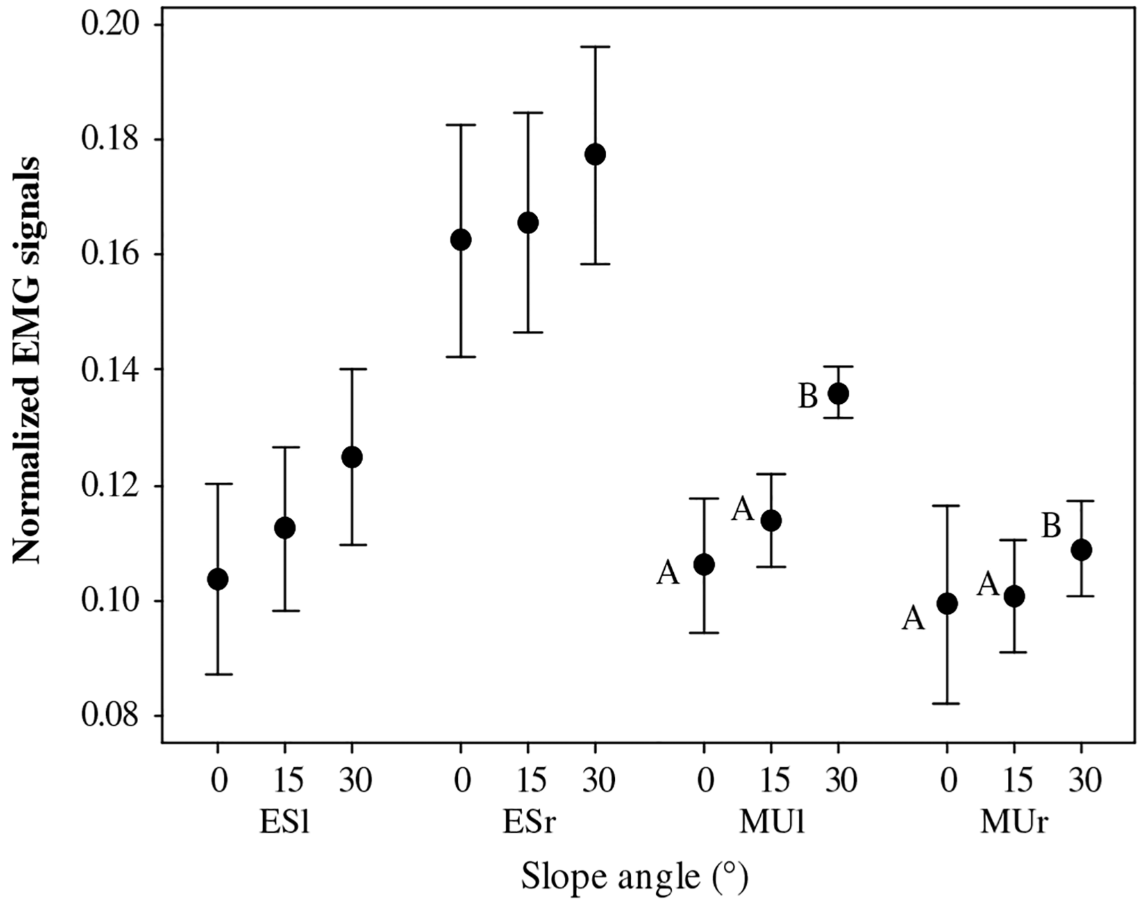

Fig. 12.
Effects of slope angle on EMG signals (kneeling)

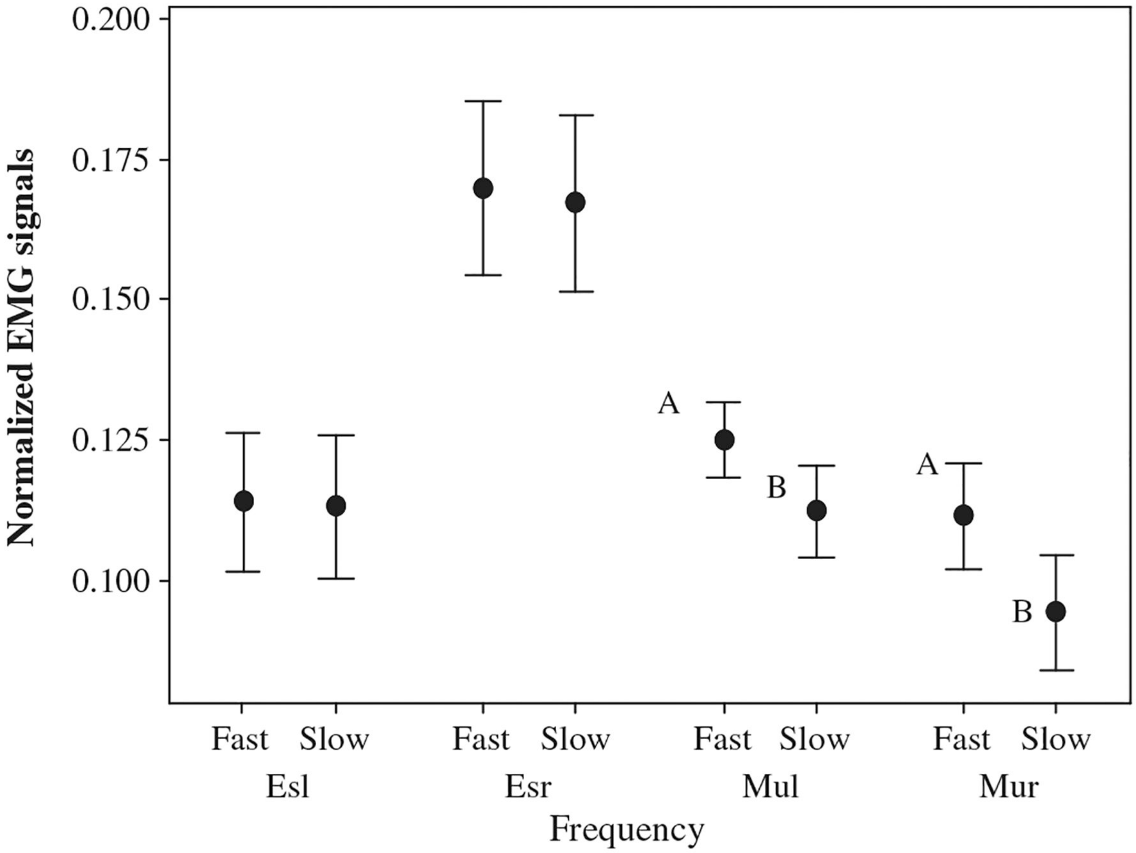

Fig. 13.
Effects of working pace on EMG signals (kneeling)

Table 1.

Effects of the Factors and Their Interactions on the Response Variables for Stooped Posture

		ANOVA			
Factor	**MANOVA**	**MTFA**	**ES (EMG)**	**MU (EMG)**
Slope	[a]	[a]	[b]	[b]
Frequency	[c]	[b]	[d]	[d]
Direction	[d]	[a]	[b]	[b]
Slope × direction	[d]	[a]	[b]	[b]
Slope × frequency	[b]	[b]	[b]	[b]
Direction × frequency	[b]	[b]	[b]	[b]

[a] $p < 0.001$.

[b] $p >= 0.05$.

[c] $p < 0.05$.

[d] $p < 0.01$.

Table 2.

Effects of the Factors and Their Interactions on the Response Variables for Kneeling Posture

		ANOVA		
Factor	**MANOVA**	**MTFA**	**ES (EMG)**	**MU (EMG)**
Slope	[a]	[b]	[c]	[d]
Frequency	[b]	[c]	[c]	[b]
Slope × frequency	[c]	[c]	[c]	[c]

[a] $p < 0.001$.

[b] $p < 0.01$.

[c] $p >= 0.05$.

[d] $p < 0.05$.