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## Effects of working posture and roof slope on activation of lower limb muscles during shingle installation

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### Abstract

Awkward and extreme kneeling during roofing generates high muscular tension which can lead to knee musculoskeletal disorders (MSDs) among roofers. However, the combined impact of roof slope and kneeling posture on the activation of the knee postural muscles and their association to potential knee MSD risks among roofers have not been studied. The current study evaluated the effects of kneeling posture and roof slope on the activation of major knee postural muscles during shingle installation via a laboratory assessment. Maximum normalized electromyography (EMG) data were collected from knee flexor and extensor muscles of seven subjects, who mimicked the shingle installation process on a slope-configurable wooden platform. The results revealed a significant increase in knee muscle activation during simulated shingle installation on sloped rooftops. Given the fact that increased muscle activation of knee postural muscles has been associated with knee MSDs, roof slope and awkward kneeling posture can be considered as potential knee MSD risk factors.

### Practitioner Summary:

This study demonstrated significant effects of roof slope and kneeling posture on the peak activation of knee postural muscles. The findings of this study suggested that residential roofers could be exposed to a greater risk of developing knee MSDs with the increase of roof slope during shingle installation due to increased muscle loading.

### Keywords

Ergonomics; knee injury; risk assessment; construction safety

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## 1. Introduction

Awkward kneeling posture is considered as a primary risk factor for musculoskeletal disorders (MSDs) among occupations that require frequent kneeling (Xu et al. 2017). Due to the unique work condition of slanted rooftops, residential roofers spend more than 75% of their working time in crawling, squatting, stooping and kneeling postures. The cumulative effects of these awkward postures combined with repetitive motions have, in large part, led to a high incident rate of MSDs among residential roofers (Dulay, Cooper, and Dennison 2015; Wang, Dai, and Ning 2015). Awkward postures during a task can lead to less efficient force production in skeletal muscle. This decrease in muscle efficiency may result in higher muscle activation and muscle overloading compared to a neutral posture (Kaushik and Charpe 2008). Cumulative muscle overloading coupled with repetitive motions without adequate recovery time may cause MSDs due to overexertion or imbalance (Kumar 2001; Hofer et al. 2011). According to Marras and Karwowski (2003), the incident rate of knee MSDs is the highest among residential roofers in comparison to other workers in construction.

Studies have been conducted on assessments of MSD risk factors for roofers. Lu et al. (2015) investigated the effects of roof slope, visual cue, muscular fatigue, and task performance on the lower limb postural muscle activation associated with balance maintenance. Wang et al. (2017) examined the influences of roof slope, working technique, and working pace in kneeling and stooped postures on the development of low back disorders to roofers. The effects of roof slope and kneeling posture on the knee kinematics of roofers were investigated by Breloff et al. (2019a). The impacts of traverse walking across a sloped roof surface on lower extremity kinematics of roofers were examined by Breloff, Wade, and Waddell (2019b). Risky phases in terms of awkward knee rotations and repetitive motions during shingle installation were assessed by Dutta et al. (2020). These studies have greatly advanced understanding of MSD risks in roofing by examining the association of the roofing work-related factors to the potential MSD development among roofers.

Working posture has been identified as a vital mechanical variable to account for occupational safety and used to compute muscle activation and joint loads (Tennant et al. 2014; Tennant, Chong, and Acker 2018). Residential roofers typically kneel on the sloped rooftop during roofing work. These awkward kneeling postures are associated with an increased risk of knee MSDs such as meniscal disorders and knee osteoarthritis (Gallagher, Pollard, and Porter 2011; Canetti et al. 2020). However, the effect of such constrained awkward kneeling postures on the peak muscle activation of lower extremities in residential roofing and their association to knee MSDs has not been studied. Furthermore, increasing the inclination of working surface has been identified as a contributing factor for muscular loading in the lower limb muscles (Lu et al. 2015). In a kneeling posture, while it was revealed that lumbar spine-muscle activation increases at a higher-pitched roof surface during roofing (Wang et al. 2017), the impact of roof slope on the activation of knee postural muscles during roofing is still unknown. Despite the advances in the previous studies on MSDs in the residential roofing work-related factors, there is limited knowledge regarding the activation of associated muscles of the lower limbs during kneeling in residential roofing on a sloped surface, which are associated to the osteoarthritis of knee joints.

The objective of the current study was to assess the impact of two residential roofing work-related factors—roof slope and awkward kneeling posture—on the activation of knee flexor and extensor muscles during the repetitive shingle installation task. This study hypothesised that roof slope, kneeling posture, and their interaction would significantly impact the activation of the knee postural muscles during performance of roofing, which may lead to knee MSDs among construction roofers.

## 2. Methods

### 2.1. Participants

Seven healthy male volunteers [26.1 years (mean) 5.6 years (standard deviation), 180.2 cm (mean)  $\pm$  6.1 cm (standard deviation), and 99.7 kg (mean)  $\pm$  27.6 kg (standard deviation)] participated in this study. As over 97% of roofers are male (BLS 2019), females were excluded from this study. All participants were physically active, right-handed, and had experience in home remodelling work. No participant had any history of musculoskeletal or neurological disorders. The protocol was approved by both the Institutional Review Boards (IRBs) of West Virginia University (WVU) and National Institute for Occupational Safety and Health (NIOSH).

### 2.2. Instruments

Muscle activation signals were recorded using a surface electromyography (EMG) system (Noraxon Desktop Direct Transmission System with myoMUSCLE Master software, Arizona, USA). According to the instructions outlined in Reichert and Stelzenmueller (2011), surface EMG Ag/AgCl electrodes were placed bilaterally on the palpated muscle bellies of each of three extensor muscles [rectus femoris (RF), vastus lateralis (VL) and vastus medialis (VM)] and two flexor muscles [biceps femoris (BF) and semitendinosus (S)]. The EMG data were collected at a rate of 1000 Hz.

Knee kinematics data (segment endpoints) were also collected using the VICON optical motion analysis system with 14 MX Vicon cameras (Oxford, UK). Retroreflective motion capture markers were placed in participants' hip and knee joints, thighs and lower legs to capture their three-dimensional (3 D) coordinates and derive knee flexion angles (Brelhoff et al. 2019a).

Simulated shingle installation was conducted on a  $1.2 \times 1.6$  m custom-made adjustable wood platform to mimic a residential rooftop. With the help of a battery powered lift and two sets of wooden legs, the slope of the platform could be adjusted. Anti-skidding tape was attached to the platform surface to increase the friction and avoid slips or falls. A wooden plank was also attached to the platform when the roofing simulator was set to a high-pitched slope, so that the participants could have their feet supported on it. Figure 1 depicts the wooden platform along with a participant nailing shingles while kneeling on it at 0°, 15° and 30° slopes.

### 2.3. Experimental design

The experimental design was comprised of two independent variables: roof slope and kneeling posture. The roof slope included three levels: 0°, 15° and 30°. The kneeling posture included two levels: static posture and dynamic posture.

The static posture is a deep-flexed kneeling position where the roofers flex their knees and trunk, place their non-nailing hand on the rooftop, and hold the nail gun with the opposite hand with negligible movement in their lower limbs. This posture represents the general body orientation of the roofers during shingle installation. It can be considered as a non-working condition considering that they neither place nor nail shingles in this posture.

The dynamic posture is a working technique that involves generating cyclic muscle contraction and relaxation as the residential roofers perform the entire shingle installation task. First the residential roofers reach for and grasp the shingles by lifting the trunk slightly upward. Then they place the shingles on the rooftop. Next, they pick up the nail gun from the side and begin nailing the shingles side by side. Following nailing, the nail gun is returned to its starting position; and finally, the roofers return to the upright position resting on their knees.

The dependent variables were peak normalized EMG of the aforementioned ten muscles.

### 2.4. Procedures

The experiment was performed at the biomechanics laboratory, NIOSH (Morgantown, WV). The experiment procedure was introduced to the participants upon their arrival and they read and signed the informed consent forms. The EMG electrodes and motion markers were then placed on the designated locations of the participants. The skin areas for the EMG electrodes were shaved and cleaned before the placement of the electrodes. After that, the participants mimicked the shingling task on the wooden platform using different combinations of postures and slopes (2 postures  $\times$  3 slopes = 6 scenarios). In the static kneeling, all participants placed their left hand on the wooden platform and held the nail gun with their right hand. In the dynamic kneeling, they secured six nails (three in each) into two shingles side by side on the roof segment with a pneumatic nail gun (weight 5.8 pounds). The six scenarios were randomised by slope and then posture for each participant. For each combination of the randomised slope and posture, each participant performed five repeated trials.

### 2.5. Data processing

Collected EMG signals were preprocessed using Visual 3 D (C-Motion, Inc). First, the raw EMG signals were filtered using a second order Butterworth high-pass filter with a cut-off frequency of 20 Hz and a low-pass filter with a cut-off frequency of 500 Hz. Then, the signals were rectified by a full-wave rectifier. Next, short-term fluctuations were removed from the signals with a moving average filter that had a three data point window. The value of the resulting signal at each point was the average of the values in the window of three data points.

Following these, the preprocessed EMG signals were normalized with respect to a reference EMG measurement for each participant to ensure fair comparison. This was done using the method suggested by Chapman et al. (2010) and described as below.

Let the EMG signal of certain muscle of the left or right knee observed for participant  $i$  at slope  $s$ , posture  $p$ , trial  $j$ , and time  $t$  be represented as  $E_{i, s, p, j}(t)$ ,

where  $i \in \{1, 2, 3, 4, 5, 6, 7\}$  representing each one of the participants,

$p \in \{1, 2\}$  with 1 and 2 representing the static and dynamic postures, respectively,

$s \in \{1, 2, 3\}$  with 1, 2 and 3 representing  $0^\circ$ ,  $15^\circ$  and  $30^\circ$  slopes, respectively, and

$j \in \{1, 2, 3, 4, 5\}$  representing each one of the trials.

For participant  $i$ , the reference EMG measurement was calculated using the following equation:

$$R_i = \frac{\sum_{s=1}^3 \sum_{p=1}^2 \sum_{j=1}^5 \max_t(E_{i, s, p, j}(t))}{N} \quad (1)$$

where  $N$  is the total number of trials for each participant. In this study,  $N=30$  for the three slopes and two kneeling postures with five repeated trials for each combination.

Consequently, the normalized EMG signal of certain muscle for participant  $i$  at slope  $s$ , posture  $p$ , trial  $j$ , and time  $t$  was computed using the following equation:

$$N E_{i, s, p, j}(t) = \frac{E_{i, s, p, j}(t)}{R_i} \quad (2)$$

For each participant, the maximum value of the normalized EMG signal within each trial was selected as the dependent variable.

## 2.6. Data analysis

The assumptions of analysis of variance (ANOVA) (i.e. constant variance of residuals, normality of residuals, and independence of observations) were examined before analyses using a graphical approach (Freund, Mohr, and Wilson 2010). Multivariate ANOVA (MANOVA) was then applied to evaluate the effects of the two independent variables (i.e. roof slope and posture) and their interaction on all the dependent variables. The independent variables that demonstrated significant effects were further analysed using univariate ANOVA. Tukey post-hoc analysis was performed for any independent variable with three or more levels (i.e. slope) to explore the effect differences between levels. The  $p$ -value was set as 0.05 for all tests. All tests were performed in Minitab 19 (Minitab, Inc.).

## 3. Results

Tables 1 and 2 show the  $p$ -values illustrating the bilateral effects of the working conditions on the muscle activation. As the effects of the working conditions were different for both

knees, the results were presented and discussed separately. Here, LBF, LRF, LS, LVL and LVM denoted the BF, RF, S, VL and VM muscles of the left knee, respectively. RBF, RRF, RS, RVL and RVM denoted the BF, RF, S, VL and VM muscles of the right knee, respectively.

### 3.1. Main effects of roof slope

The *p*-values obtained from the ANOVA test implied that slope had a significant impact on the maximum normalized activation of the LRF, LS, LVL and LVM muscles and the RBF, RVL and RVM muscles (Tables 1 and 2). Tukey post-hoc analysis results plotted in Figure 2 illustrates that for the LRF muscle, the 0° slope was categorised in one group (denoted as group A) and the 15° and 30° slopes were categorised in another group (denoted as group B). This meant that the effect at 0° roof slope (group A) on the maximum normalized muscle activation (MNMA) was significantly different from the effect at 15° and 30° slopes (group B). From the trend of the graph for the LRF muscle, the MNMA at 15° and 30° slopes was significantly higher than that at 0° slope. The levels of the independent variable sharing a common group (e.g. 15° and 30° slopes in group B for LRF) indicated that there was no significant difference in their effects on the dependent variables (i.e. MNMA). For the RBF muscle, the only significant difference that existed was between 15° (group A) and 30° slopes (group B) where the MNMA at 30° slope was significantly higher than that at 15° slope. Slope did not have any significant effect on the MNMA of the LBF and RRF muscles.

For the LVM and RVL muscles, the MNMA at 30° slope (group B) was significantly higher than that at 0° slope (group A) (Figure 3). For the LVL muscle, the MNMA at 30° slope (group B) was significantly higher than that at 0° and 15° slopes (group A). For the RVM muscle, the MNMA at 15° and 30° slopes (group B) was significantly higher than that at 0° slope (group A).

For the LS muscle, the MNMA at 30° slope (group B) was significantly lower than that at 15° slope (group A). For the RS muscle, no significant difference was observed between any two of the roof slopes (all in group A) (Figure 4).

### 3.2. Main effects of posture

For both knees, the MNMA of all muscles but RVM was significantly associated with posture. For all muscles, the MNMA was significantly higher in the dynamic posture than in the static posture. It indicates that higher muscle recruitment was required during shingle installation than what was required to maintain a static flexed kneeling posture. The effect of posture on different postural muscles are depicted in Figures 5, 6, and 7.

### 3.3. Interaction effects of roof slope and posture

As indicated in Tables 1 and 2, there was significant interaction effects between slope and posture on the MNMA of the LVM, RBF and RS muscles. Due to these results, at each slope, the maximum normalized EMG signals in the static and dynamic postures were compared for these muscles. For each posture, differences between any two of the three slopes were compared as well.

In Figure 8, at 0°, 15° and 30° slopes, the MNMA in the dynamic posture was significantly higher than that in the static posture for the RBF muscle. In the dynamic posture, the MNMA at 30° slope was significantly higher than that at 0° and 15° slopes. No significant difference was observed between any two slopes in the static posture.

In Figure 9, for the RS muscle, at 15° and 30° slopes, the MNMA in the dynamic posture was significantly higher than that in the static posture. In the dynamic posture, the MNMA at 30° slope was significantly higher than that at 0° slope. No significant difference was observed between any two slopes in the static posture.

In Figure 10, for the LVM muscle, at each slope, the MNMA in the dynamic posture was significantly higher than that in the static posture. During shingle installation in the dynamic posture, the MNMA at 30° slope was significantly higher than that at 0° and 15° slopes. No significant difference was observed between any two slopes in the static posture.

## 4. Discussions

The current study assessed the effects of roof slope and kneeling posture on the maximum normalized activation of knee postural muscles in sloped residential roof shingle installation. Both the static and dynamic kneeling postures were studied as potential knee MSD risk factors because the peak activation of the muscle can be obtained in either of these scenarios (Andriacchi and Favre 2014). The five bilateral muscles were included in the current study, as they are responsible for the flexion and extension of each knee joint during kneeling and the increased activation of these muscles is potentially associated with MSD developments (Kingston et al. 2016).

### 4.1. Effects of roof slope

In general, at a high-pitched roof (30°), the knee extensor muscles of the left knee (LRF, LVL, LVM) and the right knee (RVL and RVM) exhibited a statistically significant increase in the maximum normalized activation. The possible reason for higher muscle activation during shingle installation on a sloped surface could be explained by the muscle length-tension relationship (Gordon, Huxley, and Julian 1966), which relates the isometric contraction force to the muscle length, at which the contraction occurs. According to this relationship, muscles operate with high active tension when close to the optimal resting length (or a posture around 90° of knee flexion). But when the muscle is lengthened too much (e.g. flexion greater than 140°) or shortened too much (e.g. flexion less than 80°), the isometric active tension generated in the muscle decreases because the less than optimal force is produced due to the insufficiency of the actinmyosin filament overlap and binding site availability within the muscle. When residential roofers knelt on the sloped surface during shingle installation, it was observed that the knee flexion angle, on average, ranged from ~110° to 125°, and with the increase in roof slope (between 0° and 30°), the flexion angle decreased by 12°–15°. Due to the decrease in knee flexion, the knee extensor muscles might contract concentrically and the flexor muscles might contract eccentrically as residential roofers tended to incline a bit to the roof surface to maintain balance (Kennedy and Cresswell 2001). As the length of the muscles deviated from the optimal resting length during shingle installation on the sloped roof surface, the ability of producing the maximum

active tension in the muscles decreased. In this situation, the muscle activation was triggered by the nerve simulation, which promoted the recruitment of more motor neurons that, in turn, stimulated the muscle fibres and resulted in the generation of the required muscle force to perform the shingle installation task.

For the knee flexor muscles, although the maximum normalized activation of the RBF muscle significantly increased at high-pitched roof, the maximum normalized activation of the LS muscle decreased. According to the length-tension relationship, tension development in a muscle increases as the resting length of the muscle increases up to an optimal length. Tension development then decreases with further increase in the muscle length. Although the length of the knee flexor muscle LS increased at high-pitched roof due to decrease in knee flexion, it might be possible that the muscle was still within the range of optimal resting length when the active tension generation capability of the muscle increased and hence the activation decreased (since the muscle had the required active tension available to perform the task). Another possible reason was that all the participants were right-handed and they used their right hands for grasping the nail gun, reaching for shingles, placing and nailing them. This might have caused more repetitive lateral movement of the right knee compared to the left knee and contributed to higher cyclic muscle contraction and elongation of the right knee flexor muscle (RBF). Onishi et al. (2002) studied the differences in activities among three flexor muscles during maximum voluntary isometric and isokinetic knee flexion and reported that the activation of the S muscle decreased and the BF muscle increased as flexion decreased, which corroborated our findings. However, further investigation is needed to substantiate the explanation.

#### 4.2. Effects of posture

For most of the muscles tested in this study, higher muscle recruitment was required during shingle installation than what was required to maintain a static flexed kneeling posture. The possible reason could be explained by the knee flexion angles generated in the static and dynamic postures. It was observed that the knee flexion in the dynamic posture was higher ( $\sim 132^\circ$ ) than that in the static posture ( $\sim 106^\circ$ ). This might cause concentric contractions to the flexor muscles as the muscles were shortened due to increased flexion during shingle installation. Meanwhile, eccentric contractions were generated to the extensor muscles as they were lengthened. Thanks to this deviation from the ideal or optimal resting length, the ability to produce the maximum active tension by these muscles decreased leading to possible requirement for more muscle recruitment during shingle installation. Our findings matched with the findings from Kingston et al. (2016), who measured the peak activation of lower limb muscles during high flexion static kneeling and trowelling movements in kneeling postures, and reported significant increase in muscle activation during the movement task.

#### 4.3. Interaction effects of roof slope and posture

For low to high-pitched rooftops ( $0^\circ$ ,  $15^\circ$  and  $30^\circ$ ), the maximum normalized activation of the LVM, RBF and RS muscles was significantly higher in the dynamic kneeling posture than in the static kneeling posture. In addition, the maximum normalized activation of these muscles was significantly higher at high-pitched roof slope ( $30^\circ$ ) compared to two other roof



slopes (0° and 15°) at the dynamic kneeling posture. The possible reason for the higher muscle activation during shingle installation on high-pitched rooftop could be the extra effort required to maintain balance on the high-pitched rooftop by accounting for the postural variances involved in the dynamic posture. Also, the instability caused by the dynamic posture and the reduction of the base of support with increase of roof slope might be a potential reason for heightened muscle activation, because more work by the muscles was required to stabilise the trunk. In addition, simultaneous contraction of knee flexor and extensor muscles to help with knee joint instability on sloped-surface might contribute to the heightened muscle activation during sloped-shingle installation. Nevertheless, further studies are required to investigate the exact muscle physiology and their association to heightened muscle activation during sloped-shingle installation.

## 5. Limitation of study

As with all laboratory studies, there are limitations which are important to note. First, the experiment was conducted with seven participants. Typically, muscle activation is associated with the generation of joint contact forces, and thereby is relatable to MSDs. There are biomechanical reasons behind the association between muscle activation and the musculoskeletal loadings. Based on this reasonable association, seven subjects are appropriate for this study and it is not necessary to have a large sample size to draw the conclusion like those from random variables. Historically, biomechanical models have been validated using less than ten subjects in literature (Lay et al. 2007; Ha and Han 2017; Li et al. 2017).

Second, all the shingles were initially placed at the right side of the participants. They reached for those shingles first and then placed them in the front. Next, they grabbed the nail gun from their right side and nailed shingles. Once done, they replaced the nail gun to their right side. Therefore, it could be expected that the right knee muscles did more work. Since there is no standard procedure for shingle placement, and most people tend to be right hand dominant, shingles were placed on the dominant side on an account that it is what most roofers would do in the workplace.

Third, the participants were not professional roofers. It is possible that there would be variation in the working techniques and installation procedures that the novices and professional roofers adopt on sloped rooftop. The professional roofers can adopt their postures based on their working experience which might reduce the risk of knee injuries. Also, from the perspective of biomechanics, there should be differences in the kinematics between professional roofers and non-professional roofers that can impact the muscle activation. In this study, all subjects involved were physically active and had experience in tasks such as home remodelling. It is presumed that in a controlled experimental setting, the biomechanical reactions of novice roofers are similar to those of professional roofers to a large extent. Despite this, further biomechanical studies are still needed to justify this statement. While differences exist, knee MSD incident rates are the highest among construction roofers. Novice individuals were chosen in this study because roofers suffer most of the MSDs at the age range of 18–24 although working roofers have higher age range (BLS 2019). Besides, this study intended to observe the initial muscular demand to which

people with less experience in roofing can be exposed, when they first encounter a sloped-rooftop shingle installation. Because a roofer without experience usually undertakes the technique that works best for him. In fact, several biomechanical studies were found in the literature where non-professional and novice participants were employed for risk assessments. In the future, this experimental framework might be used to develop investigations for training new roofers and/or interventions, so that the heightened muscle activation can be minimised and MSD risks can be reduced in roofing activities. For example, knee flexion has impacts on the muscle contraction and thereby on the muscle activation. So, roofers should adjust their knee flexion (not less than 80° and not greater than 140°) during shingle installation on sloped roof surfaces. Using knee savers and knee pads might be helpful in this regard because they can reduce the peak lower extremity kinematics during sloped shingle installation (Breloff et al. 2019c). Moreover, knee savers can reduce cumulative muscular effort and fatigue during prolonged kneeling (Pejhan et al. 2019). A known level of knee-muscle activation at different work settings and kneeling postures will also help understand the mechanism related to the onset of knee MSDs (Nagura et al. 2006) and develop knee joint biomechanical models for computing in-vivo muscle and contact forces in different occupational tasks (Lin et al. 2010).

## 6. Conclusions and future research

This study examined the impact of roof slope and awkward kneeling posture—two common residential roofing work-related factors—on the peak normalized activation of knee flexor and extensor muscles as potential risk factors of knee MSDs among construction roofers. The findings suggested that roof slope, awkward kneeling posture, and their interaction all have an association with the peak normalized activation of the knee postural (flexor and extensor) muscles, implying that they are potential risk factors of knee MSDs. The findings also suggested that roofers become exposed to a greater risk of developing knee MSDs with the increase of roof slope during shingle installation as the dynamic kneeling posture during shingle installation on high-pitched rooftops requires significantly higher muscle loading for task performance compared to a static flexed kneeling posture. Therefore, the heightened muscle activation while kneeling during shingle installation on high-pitched rooftop should be given particular attention.

In the future, to provide more comprehensive understanding of knee MSD risks among construction roofers, assessments of roofing-related factors will be performed by observing the knee joint contact force and the ground reaction force captured by force plate. Future studies will also include testing of potential interventions such as knee pads and roofing footwear on the muscle activation with the participation of professional roofers in a real construction site.

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## Abbreviations:

<b>MSDs</b>	musculoskeletal disorders
<b>EMG</b>	electromyography
<b>ANOVA</b>	analysis of variance
<b>MNMA</b>	maximum normalized muscle activation
<b>RF</b>	rectus femoris
<b>VL</b>	vastus lateralis
<b>VM</b>	vastus medialis
<b>BF</b>	biceps femoris
<b>S</b>	semitendinosus

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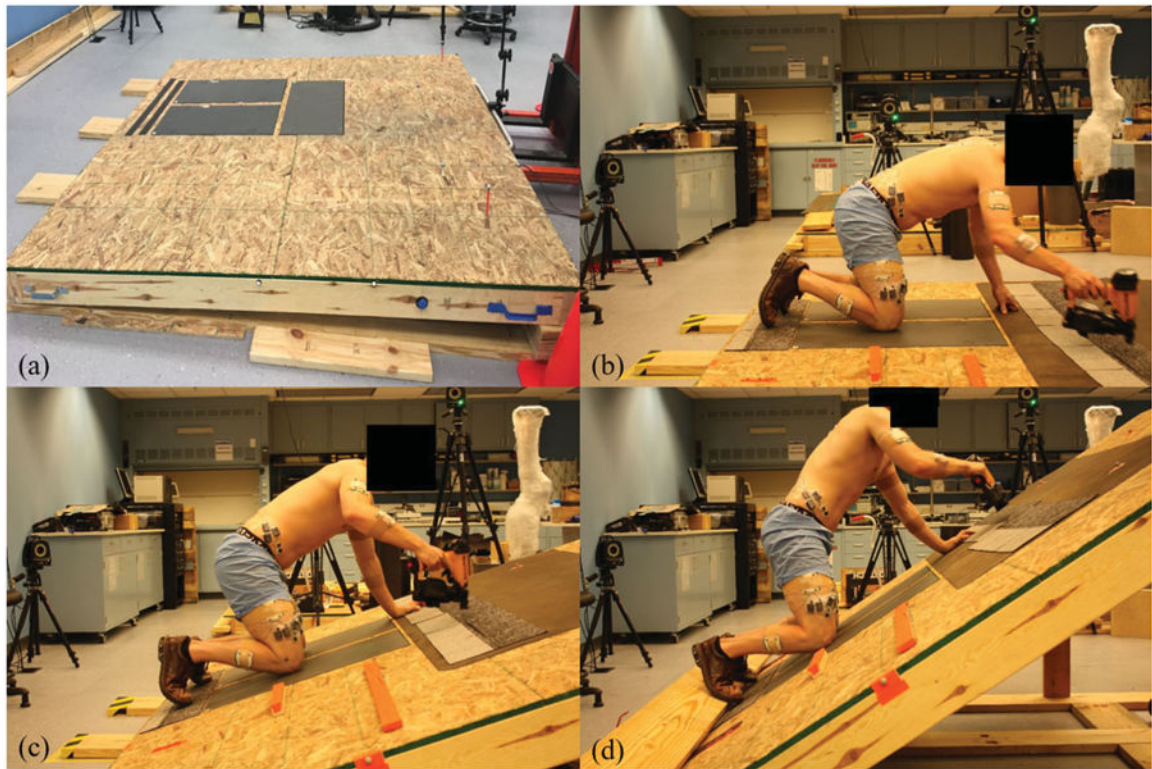
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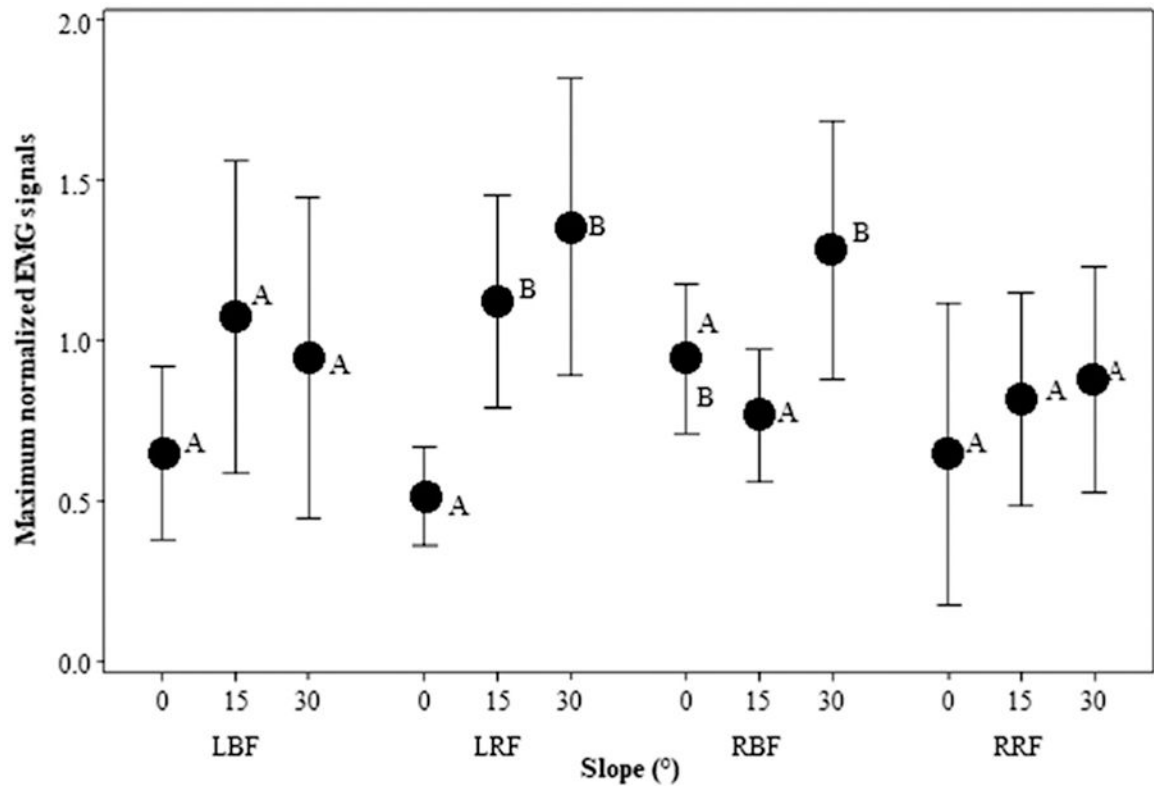
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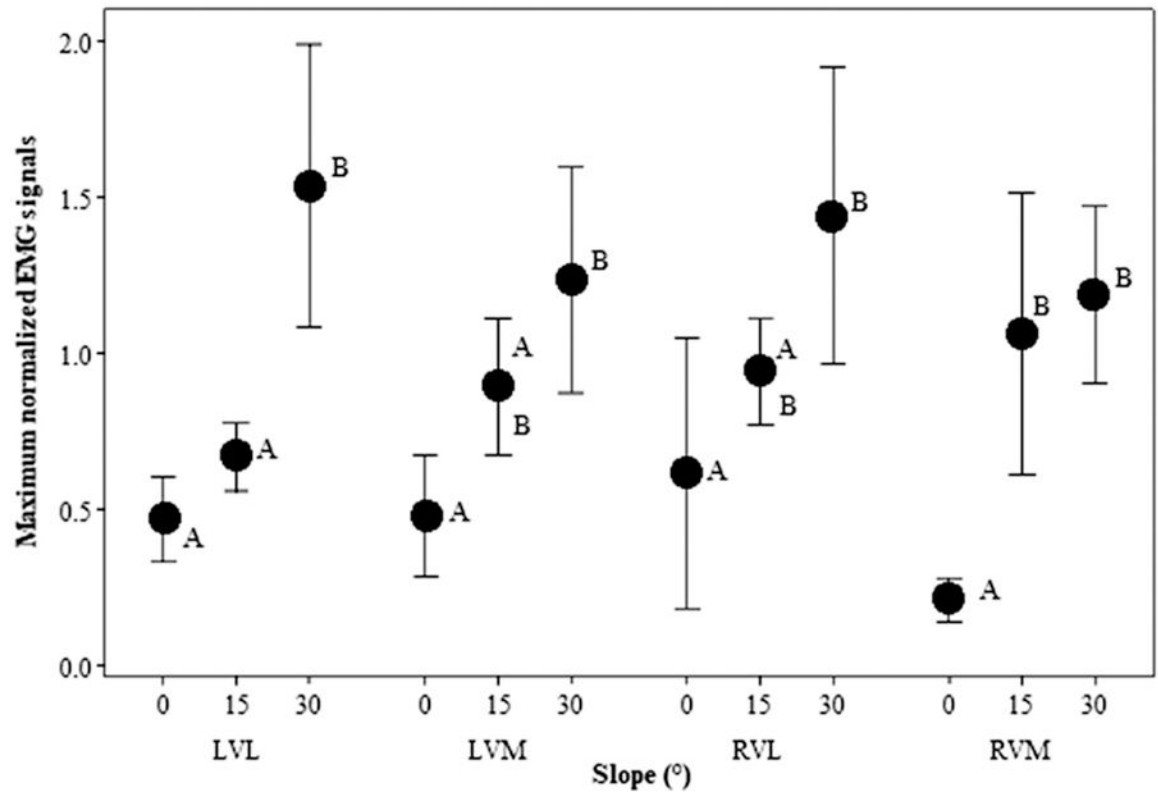


**Figure 1.** Experimental setting for the shingle installation simulation (a) wooden platform, (b) at 0° slope, (c) at 15° slope, and (d) at 30° slope.



**Figure 2.**

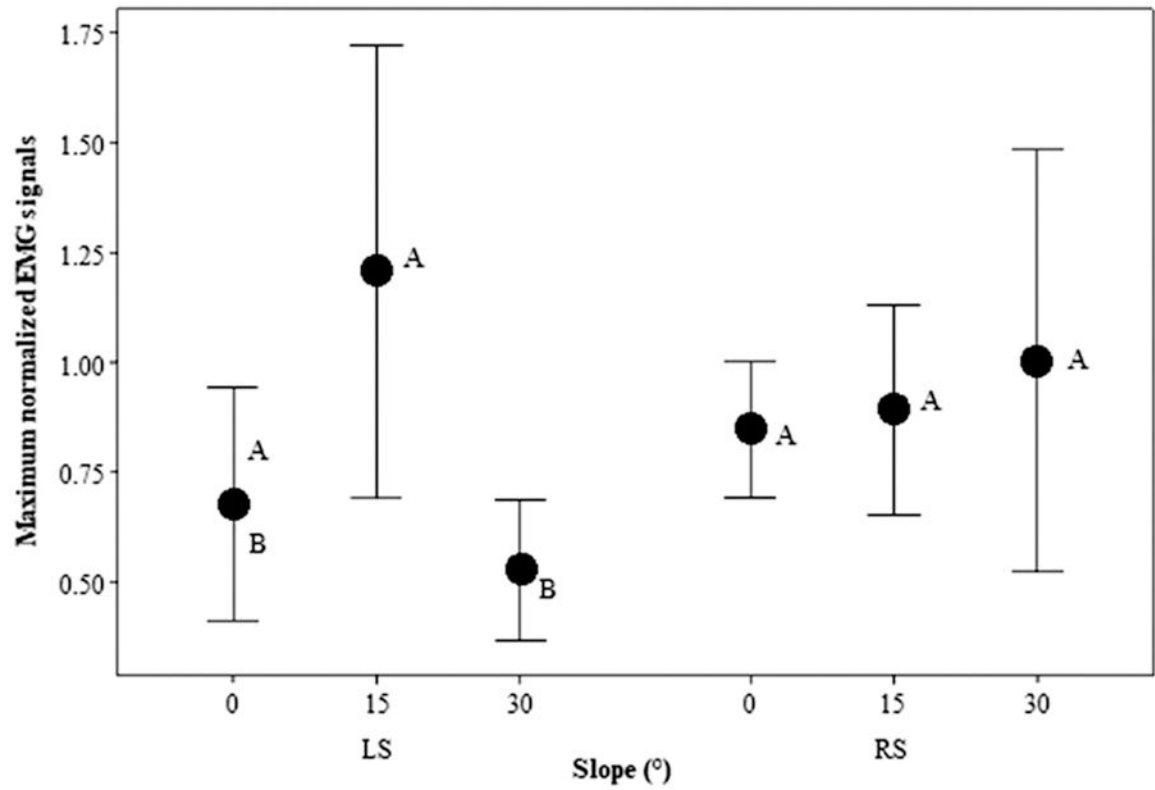
Average maximum normalized EMG signals of the LBF, LRF, RBF and RRF muscles with 95% confidence intervals. Results were averaged by the three roof slopes. Here, 'A' and 'B' illustrate significant and non-significant effect differences between levels of slope.



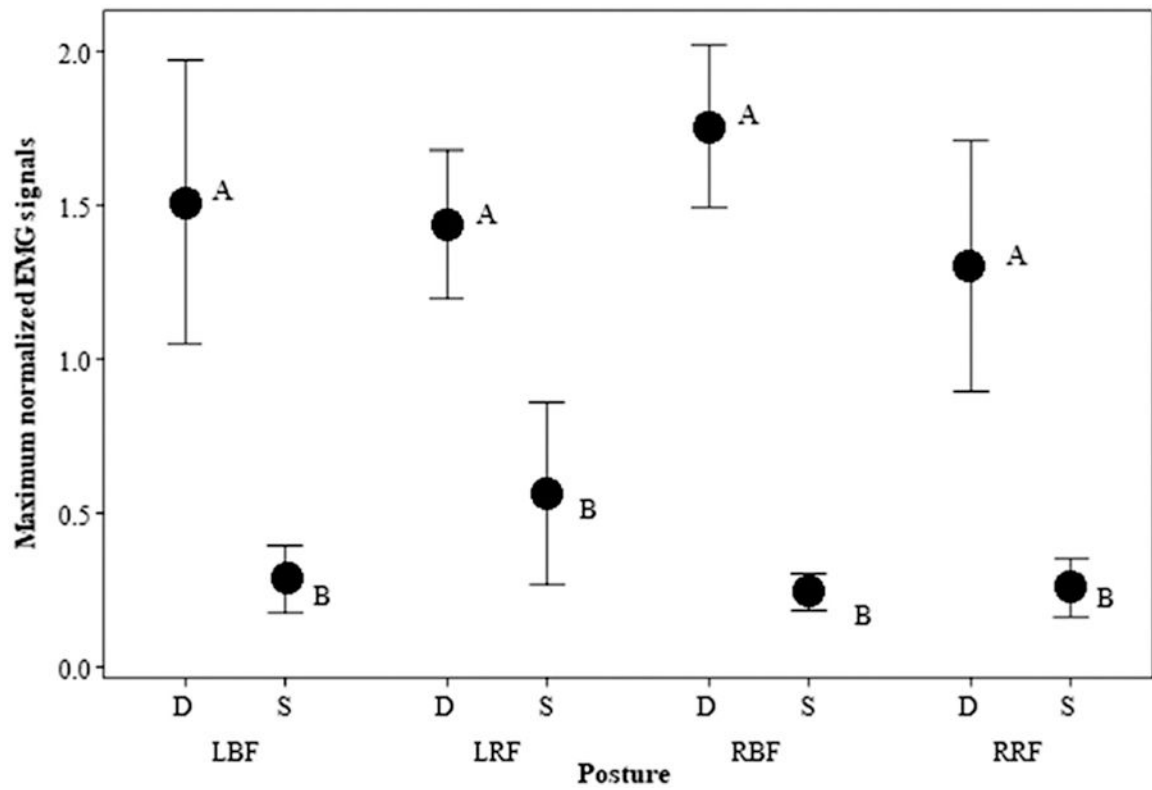
**Figure 3.**

Average maximum normalized EMG signals of the LVL, LVM, RVL and RVM muscles with 95% confidence intervals. Results were averaged by the three roof slopes. Here, 'A' and 'B' illustrate significant and non-significant effect differences between levels of slope.

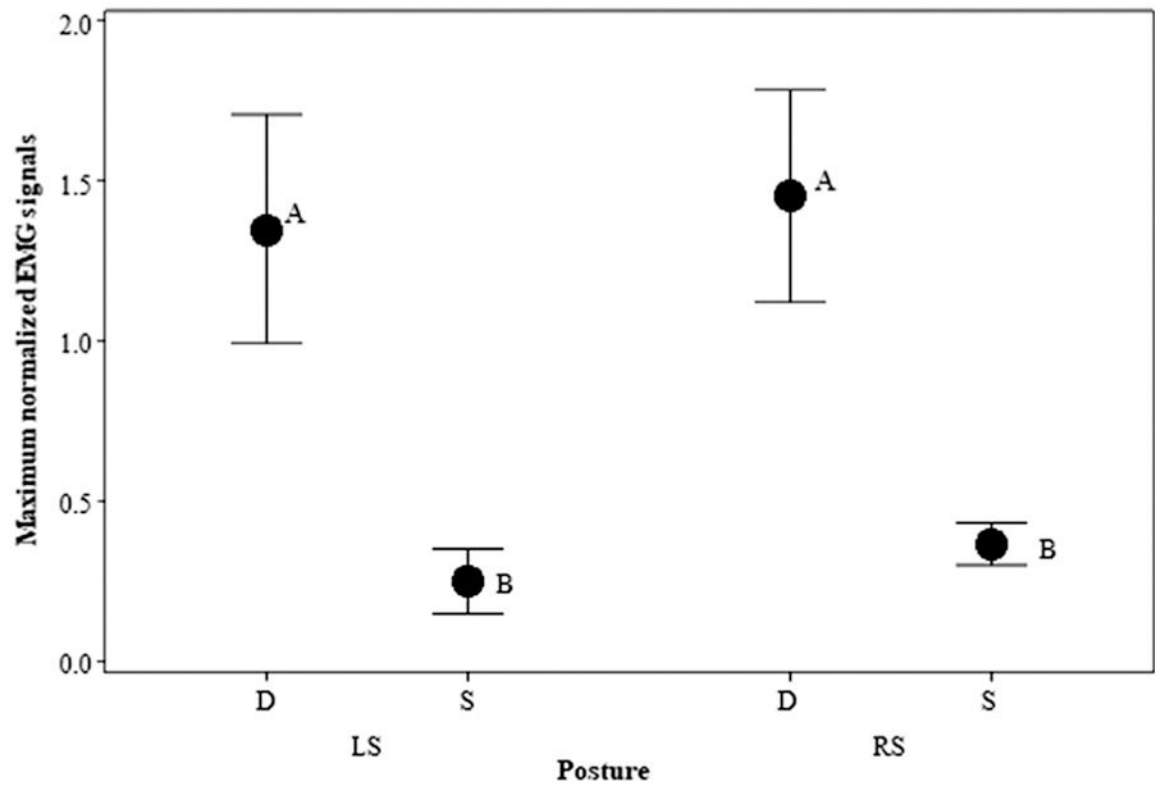




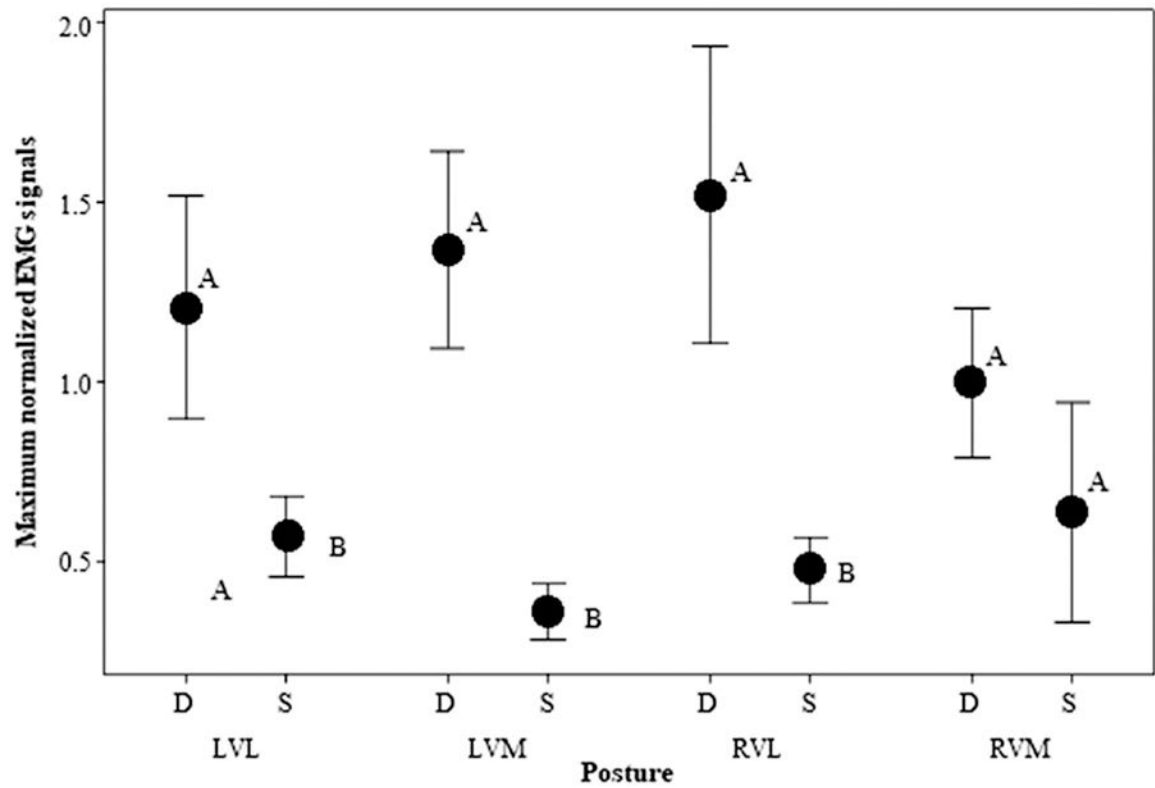
**Figure 4.** Average maximum normalized EMG signals of the LS and RS muscles with 95% confidence intervals. Results were averaged by the three roof slopes. Here, 'A' and 'B' illustrate significant and non-significant effect differences between levels of slope.



**Figure 5.** Average maximum normalized EMG signals of the LBF, LRF, RBF and RRF muscles with 95% confidence intervals. Results were averaged by the two kneeling postures. Here, 'A' and 'B' illustrate significant and non-significant effect differences between levels of posture. 'D' and 'S' denote dynamic and static postures, respectively.

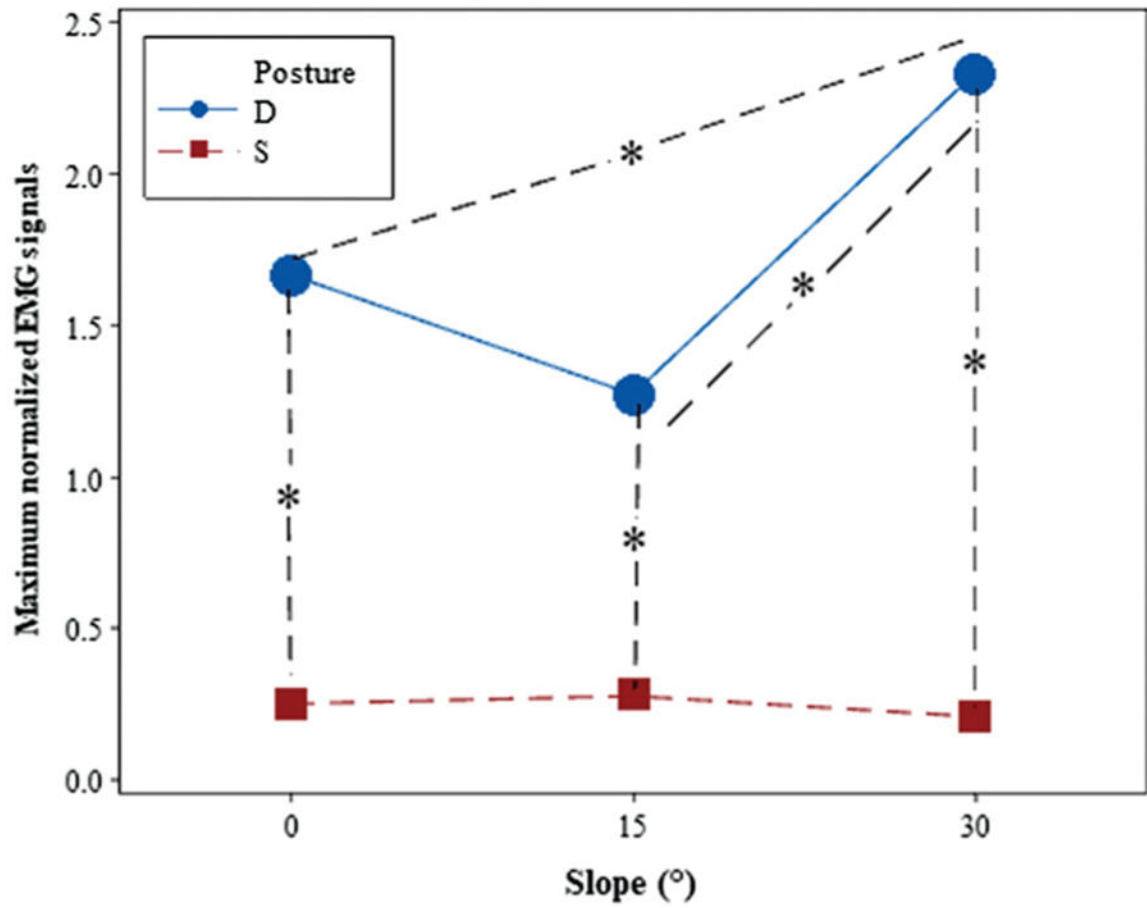


**Figure 6.** Average maximum normalized EMG signals of the LS and RS muscles with 95% confidence intervals. Results were averaged by the two kneeling postures. Here, 'A' and 'B' illustrate significant and non-significant effect differences between levels of posture. 'D' and 'S' denote dynamic and static postures, respectively.

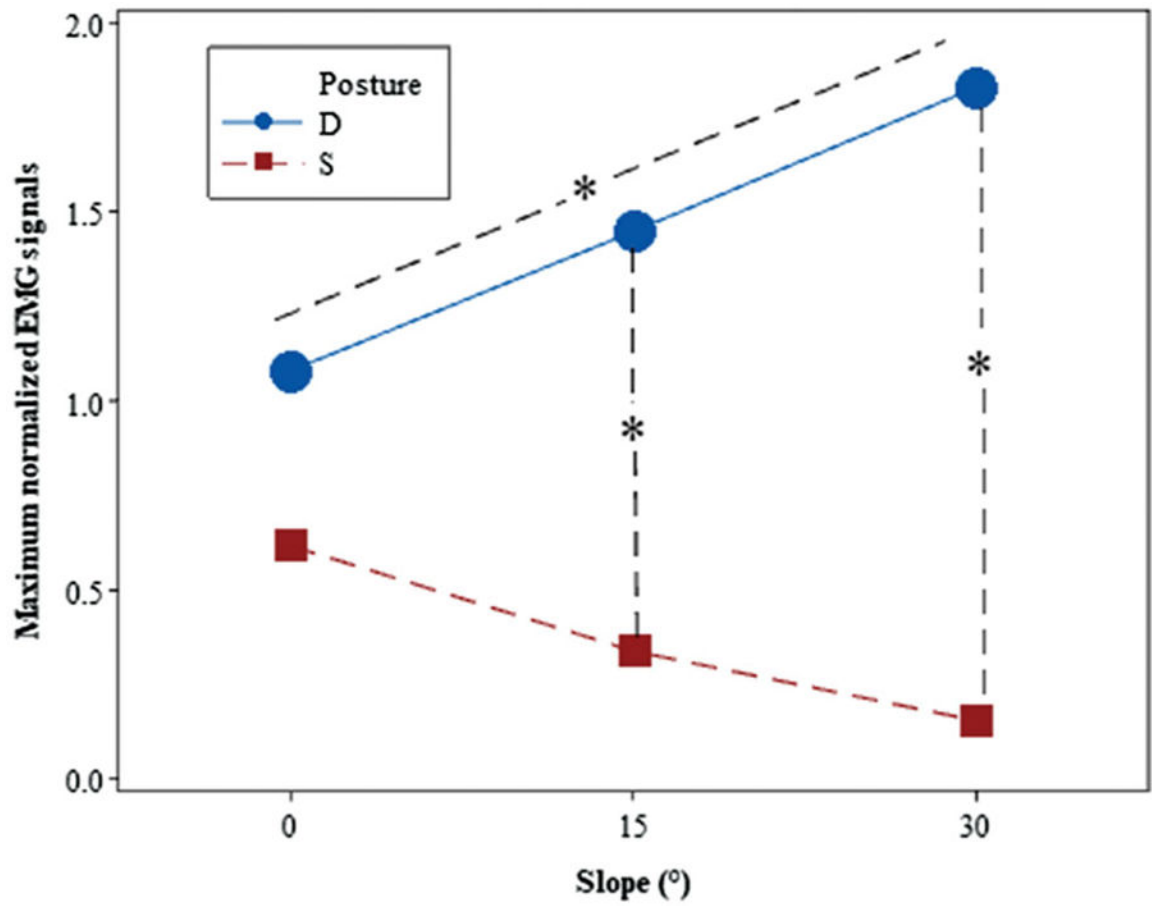


**Figure 7.**

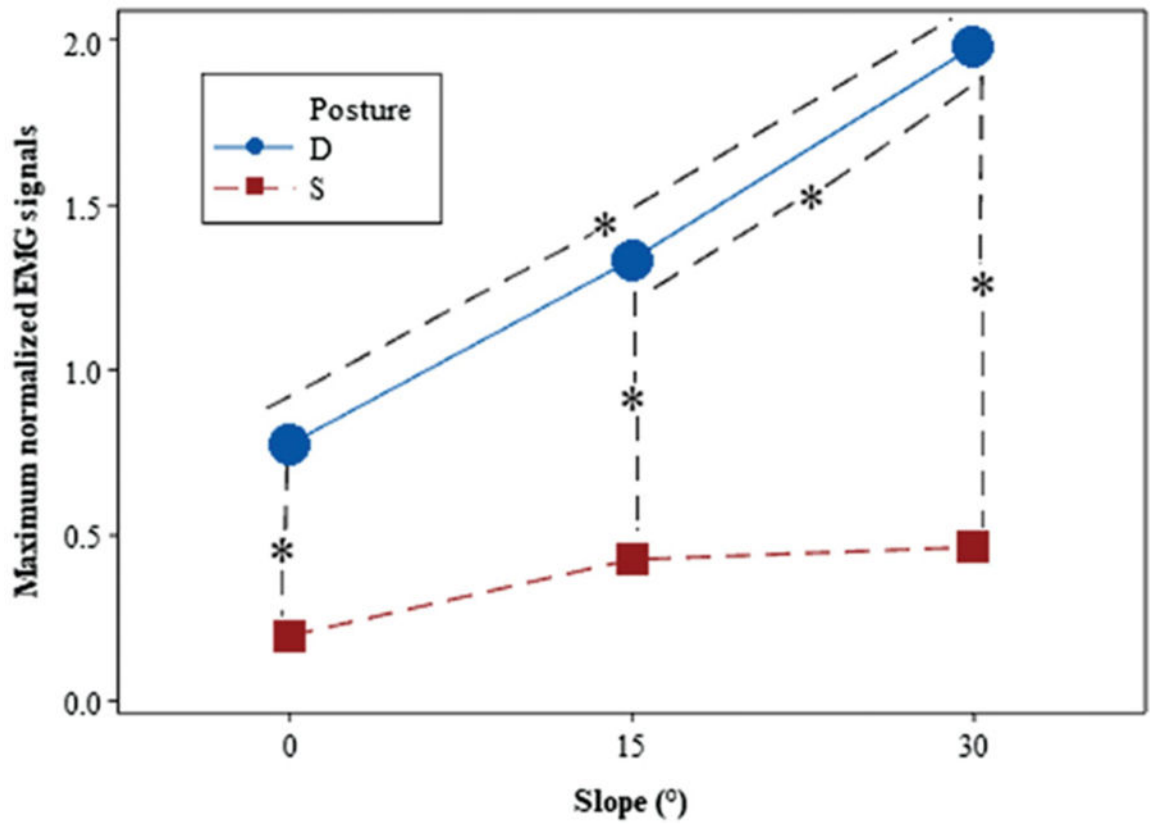
Average maximum normalized EMG signals of the LVL, LVM, RVL and RVM muscles with 95% confidence intervals. Results were averaged by the two kneeling postures. Here, 'A' and 'B' illustrate significant and non-significant effect differences between levels of posture. 'D' and 'S' denote dynamic and static postures, respectively.



**Figure 8.** Interaction effect of slope and posture on the maximum normalized activation of the RBF muscle. Here, 'D' and 'S' denote dynamic and static postures, respectively. '\*' indicates statistical significance.



**Figure 9.** Interaction effect of slope and posture on the maximum normalized activation of the RS muscle. Here, 'D' and 'S' denote dynamic and static postures, respectively. '\*' indicates statistical significance.



**Figure 10.** Interaction effect of slope and posture on the maximum normalized activation of the LVM muscle. Here, 'D' and 'S' denote dynamic and static postures, respectively. '\*' indicates statistical significance.

**Table 1.**

The resulting  $p$ -values for the left knee.

Independent variables	MANOVA	ANOVA				
		LBF	LRF	LS	LVL	LVM
Slope	<0.001	0.343	0.001	0.011	<0.001	<0.001
Posture	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Slope*Posture	<0.001	0.121	0.676	0.091	0.118	0.019

*Note.* Bold font indicates a significant effect.



**Table 2.**

The resulting  $p$ -values for the right knee.

Independent variables	MANOVA	ANOVA				
		RBF	RRF	RS	RVL	RVM
Slope	<0.001	0.007	0.684	0.776	0.007	<0.001
Posture	<0.001	<0.001	<0.001	<0.001	<0.001	0.056
Slope*Posture	<0.001	0.002	0.718	0.015	0.107	0.160

*Note.* Bold font indicates a significant effect.