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Evaluating Muscle Activation and Joint Angle Correlation During Stooping Tasks on Sloped Surfaces

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Roofers are more susceptible to work-related musculoskeletal disorders (WMSDs) because they often adopt awkward postures. The purpose of this study is to assess how muscle activation patterns and knee joint angles relate to stooping on a 30-degree slope. Stooping posture was selected for this study as it is one of the most performed postures in sloped surface. The researchers collected kinematic and surface electromyography (sEMG) data of six healthy participants using Inertial Measurement Unit (IMU) and sEMG sensors. Significant relationships between knee flexion angles and biceps femoris muscle activation was identified using Analysis of Variance (ANOVA). Additionally, a combined examination of the rectus and biceps femoris also revealed statistical significance with the knee flexion angles. The results show that higher muscular activation of biceps femoris is correlated with increased knee flexion, suggesting a larger muscle load and possible risk of WMSDs. The study provides insights for developing ergonomic interventions, such as exoskeletons, to reduce muscle strain during stooping tasks on inclined surfaces. Additionally, this research can work as a model to check the correlation between muscle activation and joint angles for other construction traits.

Keywords: Roofing, Musculoskeletal Disorders, Muscle Activation, Joint Angles, Stooping

Introduction

Studies portray 41% of the construction workforce is retiring by 2031 (NCCER, 2023) and 88% of the construction firms have hard time hiring workers (AGC & Autodesk, 2023). The perception of the construction industry as unsafe is indeed a critical barrier to recruitment of new workers. The industry's safety climate, characterized by poor safety awareness and inadequate commitment to safety makes the construction industry less attractive to new entrants (Buniya et al., 2024). The physical demands of construction work pose additional WMSDs risks (Karthick et al., 2023).

In the construction industry, awkward working postures are a primary risk factor for WMSD. It is the leading cause of non-fatal occupational injuries (Antwi-Afari et al., 2018). As per Bureau of Labor Statistics report, 2022, the total recordable non-fatal injuries are 2.4 per 100 full time workers with 1.5 per 100 reporting cases with days away from work (BLS, 2023). Roofers spend over 75% of their working time squatting, stooping, kneeling or crawling have a high incident rate of WMSDs (Kaushik & Charpe, 2008). Moreover, the unique nature of working on sloped surfaces when combined with awkward postures and repetitive motions only add to the cause (Dulay et al., 2015).

Roofers experience greater discomfort and pain in their lower extremities with increase in slope (Choi, 2008). They have 30% more WMSDs incident reported rate as compared to all other construction traits (Wang et Al., 2015). As roofers encounter awkward postures during their day-to-day activities, their body parts experience significant twists and turns, which can be beyond the ergonomically safe limit (Dutta et al, 2020). Common biomechanical risks associated with stooping tasks include increased peak lateral shear forces and average anterior-posterior shear forces on the lumbar spine, which can elevate the risk of injury (Gallager et Al., 1994), while the flexion-relaxation phenomenon can lead to instability and increase the risk of fall (Miller & Fathallah, 2006).

A lot of sensor technologies and biomechanical models have been used to assess WMSDs (Lee et al., 2017) but lack the direct application in construction tasks. Additionally, while construction automation has high-tech solutions to address real-world construction challenges (Gautam et al., 2024), their adoption in the industry is still in the early stages, and further research is needed to fully understand their impact on reducing WMSDs (Halder et al., 2024). The ergonomic practices and guidelines provided by Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH) help reduce the risk of developing WMSDs in construction workers (Albers & Estill, 2007). These guidelines are generic and do not address the unique nature of working on sloped surface (Dutta et al., 2020). The need of specific guidelines to develop proper intervention methods for roofers during stooping provides distinctive research opportunities.

Previous research has focused on roofing tasks by assessing low back disorders during different roof slopes and working techniques (Wang et al., 2017, Dutta et al., 2020), evaluating balance maintenance during roofing based on visual cues and muscle fatigue (Lu et al., 2015), and examining lower extremity kinematics during cross-slope roof walking (Breloff et al., 2019a). These studies primarily concentrated on kneeling postures and their impact on knee musculoskeletal disorders. However, there is a gap in research specifically investigating stooping tasks, which are crucial for understanding one of the most performed postures by roofers (Breloff et al., 2019b). Hence, this research aims to understand different types of joint movements and find out the which movement occurs the most. Additionally, this research aims to assess the relationship between knee joint angle changes with its corresponding flexor/extensor muscles activation while in stooping posture. The researchers use the one-way ANOVA test to determine statistical significance of their relationship. This research would help in understanding ergonomically safe stooping posture and contribute to intervention strategies while performing stooping tasks on a sloped surface. Additionally, this research can aid training of new employees in construction by providing information on usage of knee muscles in relation to their knee flexion and reduce the risk of WMSDs.

Methodology

The researchers collected kinematic and EMG data of six participants while in stooping posture using IMU and sEMG sensors respectively. The researchers analyzed the data to check how biceps femoris and combined activation of biceps and rectus femoris muscles react against the knee flexion angle changes to determine the relationship between the knee flexion angle changes and the muscle activation patterns.

Based on scientific concepts and information obtained from informal conversations with roofers from two different companies, the experimental roof configuration was designed. The experimental design has been modified to better mimic real-world conditions thanks to the valuable recommendations made during these talks. Following IRB authorization, participants were questioned about their history of injuries, WMSDs, allergies and sleep quality. Participants with no history of WMSDs, major injuries, allergies and adequate sleep quality were recruited.

Data Collection

Participants were asked to perform stooping posture on a 30-degree sloped surface for four minutes with four repetitions. The participants were provided a minute rest in between of each repetition to avoid any cumulative fatigue effect. Prior to starting, they signed a consent form to perform the experiment after being informed of the study's goals and safety protocols.

Participants were attached with Cometa sEMG on twelve muscle groups on both left and right sides of erectus spinae, rectus femoris, rectus abdominis, biceps femoris, tibialis anterior, and gastrocnemius following the guidelines outlined by Barbero et al. (2012). The participants were demonstrated how lumbar extension exercise, sit-ups, isometric knee- extensions, isometric prone leg curl, foot dorsiflexion and plantarflexion are performed such that they were able to replicate it in order to calculate Maximum Voluntary Contraction (MVC) values for erector spinae, rectus abdominal, biceps femoris, tibialis anterior and gastrocnemius muscles respectively (Ambrose et al., 1997; Murley et al., 2010; Muyor et al., 2018; Noorkoiv et al., 2014; Vera-Garcia et al., 2000). The participants replicated the exercises three times for each muscle to calculate MVC. and were asked to relax for five minutes to ensure that they have adequate rest and fatigue doesn’t play a part in the data collection process.

The participants were then equipped with 17 sensors and a suit which helps in placement of the sensor on the upper body. Sensors on the lower extremities were fitted using strap-on. The participants were then asked to calibrate the sensors. The complete experimental setup for the participant is shown in Figure 1a (side view) and Figure 1b (front view). The experimental setup utilized Cometa sEMG sensor and Xsens IMU sensors due to their high signal-to-noise ratio and sensitivity. Also, these sensors facilitate the use of multiple channels whenever required and are highly compatible with each other.

Figure 1a. Experimental setup (side view)

Figure 1b. Experimental setup (front view)

Data Analysis

The researchers processed data from six participants performing roofing tasks on a 30-degree sloped surface. Each participant had four repetitions providing 24 data sets. One of the datasets was discarded as the dataset had missing data points likely due to data transmission issues of the sensors. The analysis integrated EMG and kinematic measurements to examine muscle activation patterns and joint angles during stooping postures.

EMG Data Processing

The EMG and Motion Tools software exported raw EMG data from C3D to CSV format. Python scripts using NumPy and Pandas libraries processed these files. The processing pipeline included bandpass filtering (0.5-250 Hz) with a 60 Hz notch filter to remove electrical noise interference (De Luca et al., 2010). The filtered signals underwent normalization to MVC values for each muscle group, following standard EMG analysis protocols (Burden, 2010).

Kinematic Analysis

The IMU data were processed using the XSens Movella Analyze PRO software, where High Definition (HD) processing was applied before exporting the results to Excel. The exported data were further analyzed using Python scripts, which facilitated several critical processing steps. The researchers used Python scripts synchronized the IMU timestamps with the corresponding EMG event markers, ensuring accurate temporal alignment. Following this, bilateral hips, knee, and ankle joint angles were extracted in the ZXY plane. The scripts then calculated the average joint angles for each session and computed the cumulative absolute changes in joint angles to quantify overall movement patterns.

For statistical analysis, Python scripts were employed to organize and prepare the dataset for further testing. ANOVA tests were conducted to evaluate the relationships between knee flexion/extension angles and muscle activation levels. Specifically, the analysis examined the correlation between knee flexion/extension angle changes in a session and the activation of the biceps femoris, as well as the combined activation of the biceps femoris and rectus femoris muscles. The significance level was set at $\alpha = 0.05$, with an assumption of equal variances. The joint angle change values were classified as "High" or "Low" based on participant's median angle change in each session. Finally, Minitab software was used to perform the final statistical computations. The research analyzed more than two variables in an ANOVA test, however, due to limitations of the data points, the tables present only the significant variables in this study.

Results

Six healthy volunteers of age 27.5 years (±12.5), of height 172.42 cm (±12.56)], weighing 152.16 lbs. (± 65.83) and with no history of MSDs, adequate sleep and having no allergies related to hydrogel were recruited. These participants had a rest day before the experiment was performed and had adequate sleep (7.5 hours ± 0.5hrs) recommended for adults for optimal functioning (Tai et al., 2022).

Each of participants data for flexion (+) / extension (-), abduction (+) / adduction (-), and internal (+)/external (-) rotation was plotted. Figure 2 shows the time series plot of joint angles for one of the participants performing the stooping tasks on 30-degree sloped surface for Left and Right Knee. The graph shows Knee Flexion for both Left and Right Knee is higher compared to Abduction/ Adduction or Internal/External Rotation values.

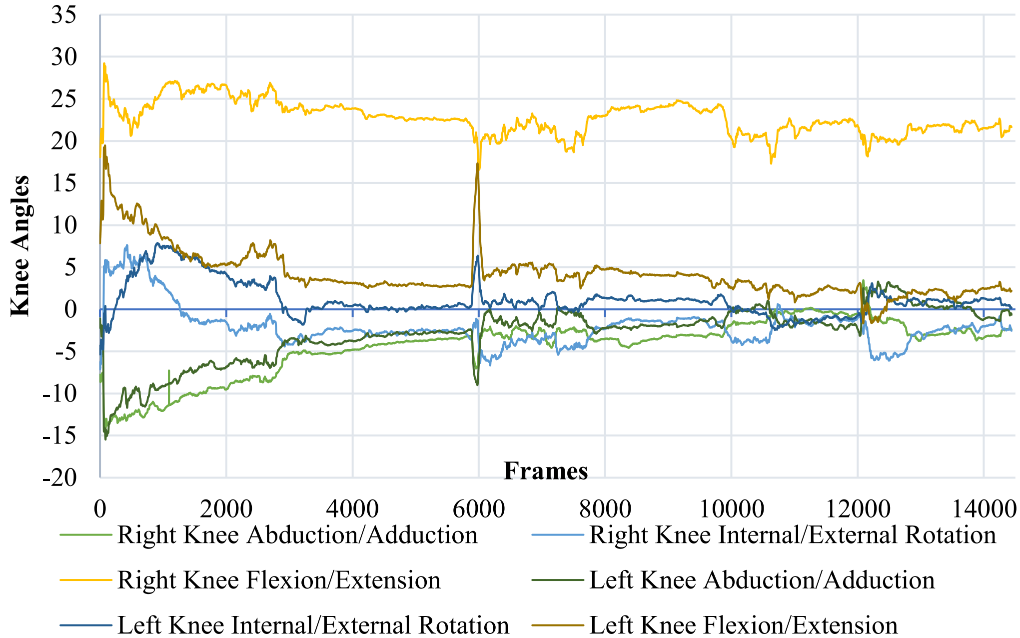

Figure 2. Time series plot of joint angles for left & right knee

Next, the researchers assessed the relationship between changes in knee joint flexion and muscle activation patterns. ANOVA tests between biceps femoris and their corresponding knee joint flexion demonstrated significant relationship between them. ANOVA results showed a significant effect of knee flexion on biceps femoris activation ($F(1,21) = 4.56$, $p = 0.045$) as seen in Table 1.

Table 1: ANOVA test for cumulative right knee flexion angle change vs right biceps femoris

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Joint Angle Change	1	158047754	158047754	4.56	0.045
Error	21	727262850	34631564		
Total	22	885310603			

Participants displayed higher mean EMG activation (25,754 ± 5,279) during high knee flexion compared to low knee flexion conditions (20,506 ± 6,486). The left biceps femoris showed similar activation patterns ($F(1,21) = 6.22$, $p = 0.021$), with higher activation during increased knee flexion (28,793 ± 6,022) versus lower knee flexion (21,338 ± 8,237) as shown in Table 2.

Table 2: ANOVA test for cumulative left knee flexion angle change vs left biceps femoris

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Joint Angle Change	1	319010980	319010980	6.22	0.021
Error	21	1077373267	51303489		
Total	22	1396384247			

The researchers combined biceps femoris and rectus femoris activation to determine their relationship with changing knee flexion. ANOVA tests between combined biceps femoris and rectus femoris with its corresponding knee joint flexion changes demonstrated stronger statistical significance. Table 3 shows the right leg combined activation showed meaningful differences between high and low knee flexion ($F(1,21) = 4.50$, $p = 0.046$).

Table 3: ANOVA test for cumulative right knee flexion angle change vs cumulative EMG for combined right rectus femoris and biceps femoris

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Joint Angle Change	1	211563615	211563615	4.50	0.046
Error	21	987517083	47024623		
Total	22	1199080697			

The left leg exhibited the strongest relationship ($F(1,21) = 7.68$, $p = 0.011$) as shown in Table 4, with mean of cumulative EMG values of 35,964 ± 6,069 for high flexion and 26,772 ± 9,592 for low flexion conditions.

Table 4: ANOVA test for cumulative left knee flexion angle change vs cumulative EMG for combined left rectus femoris and biceps femoris

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Joint Angle Change	1	484919807	484919807	7.68	0.011
Error	21	1325137095	63101766		
Total	22	1810056902			

Figure 3 and 4 shows the box plot that highlights key differences in muscle activation patterns during stooping posture. The biceps femoris activation shows clear differences between high and low knee flexion positions as shown in figure 3, with higher activation in higher knee flexion angle changes. The left knee displays notably higher activation levels compared to the right, suggesting potential dominance patterns or compensatory mechanisms during the stooping task.

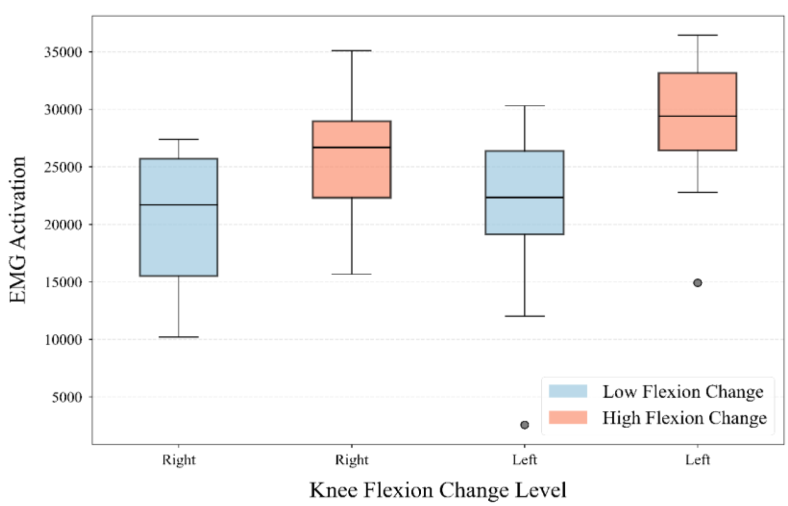

Figure 3. Biceps femoris EMG Activation

When examining the combined muscle activation (rectus femoris + biceps femoris) as in Figure 4, the distinction between high and low flexion becomes more distinct. The wider spread of data in high flexion conditions suggests more varied muscle recruitment strategies when participants adopt more demanding postures. The left leg's higher overall activation and greater variability might indicate increased stabilization demands or uneven load distribution during roofing tasks.

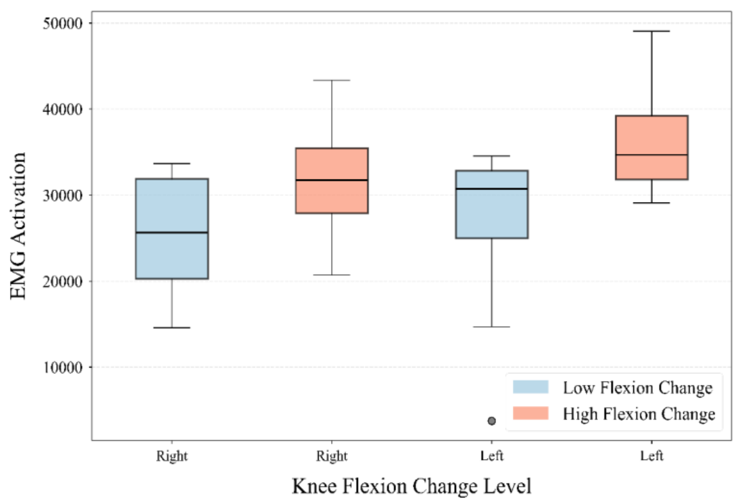

Figure 4. Combined EMG Activation Distribution

The overall trends in muscle activation and knee flexion suggest that stooping postures place substantially greater demands on the lower limb muscles, especially the biceps femoris. Notably, the elevated and more variable activation of the left leg indicates a possible dominance factor or compensatory behavior which should be further explored as uneven muscle recruitment over time can increase the likelihood of long-term musculoskeletal issues. Additionally, the broader range of EMG values under high-flexion conditions points to individualized stabilization strategies: participants may shift their weight distribution differently to manage the biomechanical load.

Limitation

The participants were not experienced roofers, the experiment was done in a controlled environment, and the experimental setup was set to 30-degree slope only. These factors may not fully replicate real-life roofing scenarios, as professional roofers often encounter varying slopes and adapt to specific circumstances differently to optimize muscle activation and joint angles. Lastly, the study only analyses flexion of knee while other joint movements (abduction/adduction, internal/external rotation) of other body parts (hip, ankle) also needs to be studied. These limitations may affect the muscle activation patterns and the body's posture adjustments, potentially influencing the results and their interpretation. So, it may affect the generalizability of the findings, not fully capturing the complexity of real-world roofing tasks or interactions between multiple joints. Nonetheless, the study was designed to explore the relationship between muscle activation and joint angles, aiming to raise awareness among roofers about potential injuries and guide them toward ergonomically safe working postures on sloped surfaces.

Conclusion and Further Research

The initial results of the study established that knee flexion was the dominant movement compared to abduction/adduction or rotation during stooping posture. The time series analysis of joint angles demonstrated that participants consistently showed higher knee flexion values while maintaining relatively minimal movement in other planes, indicating that the stooping posture primarily challenges the knee joint in the sagittal plane.

This study then examined muscle activation patterns during stooping posture on sloped surfaces, revealing significant relationships between knee flexion angles and muscle activity. Analysis showed that higher changes in knee flexion consistently led to increased biceps femoris activation in both legs. This relationship strengthened when examining the combined activation of biceps femoris and rectus femoris muscles, indicating coordinated muscle engagement during slope work.

The findings are consistent with prior studies. For example, Dutta et al. (2020) found that steeper roof slopes led to increased lower limb muscle activation, similar to our observation of higher biceps femoris activation with greater knee flexion. Additionally, Breloff et al. (2019b) reported asymmetrical muscle activation patterns during cross-slope walking, which aligns with our finding of higher left-leg activation, suggesting compensatory mechanisms or dominance.

The findings point to several practical implications for roofing work. First, the increased muscle activation when knee flexion changes is high which suggests that roofers may face elevated risks of muscle fatigue during prolonged stooping tasks. Second, the left leg's higher activation patterns indicate possible asymmetrical loading, which could lead to uneven muscle development or compensatory movements over time. Third, the strong relationship between changes in knee angles and muscle activation suggests that monitoring working postures could help identify high-risk situations.

These results support the need for workplace interventions in roofing operations. Task rotation, regular breaks, or supportive equipment might help reduce sustained muscle loading. The findings also suggest that training programs focusing on balanced posture and movement patterns could benefit roofers' long-term musculoskeletal health.

Future research should enhance EMG and IMU sensor integration to reduce data loss and interference, while expanding beyond knee flexion to include abduction/adduction, rotation, and the roles of hip and ankle joints in stooping tasks. Research on professional roofers working under real-world conditions could provide valuable insights into how experience influences muscle activation and joint angles across various roof pitches. Examining a range of slopes and common roofing tasks, such as shingling, carrying materials, and installing underlayment, deepen our understanding of roofing biomechanics. This knowledge could inform the development of targeted injury prevention strategies and more effective workplace interventions tailored to the demands of the job. The team plans to address these areas in future studies while incorporating comparisons with similar research.

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