Identifying a Ranking Method for Assessing the Potential Risk of Knee Musculoskeletal Disorders among Roofers in Shingle Installation

Amrita Dutta[1]; Scott P. Breloff[2]; Fei Dai[3]; Erik W. Sinsel[4]; Christopher M. Warren[5]; and John Z. Wu[6]

[1]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, West Virginia Univ., PO Box 6103, Morgantown, WV 26506. E-mail: amdutta@mix.wvu.edu
[2]Biomedical Research Engineer, National Institute for Occupational Safety and Health, 1095 Willowdale Rd., Morgantown, WV 26505. E-mail: sbreloff@cdc.gov
[3]Associate Professor, Dept. of Civil and Environmental Engineering, West Virginia Univ., PO Box 6103, Morgantown, WV 26506. E-mail: fei.dai@mail.wvu.edu
[4]Computer Scientist, National Institute for Occupational Safety and Health, 1095 Willowdale Rd., Morgantown, WV 26505. E-mail: ESinsel@cdc.gov
[5]Mechanical Engineer, National Institute for Occupational Safety and Health, 1095 Willowdale Rd., Morgantown, WV 26505. E-mail: cpw4@cdc.gov
[6]Senior Research Biomechanical Engineer, National Institute for Occupational Safety and Health, 1095 Willowdale Rd., Morgantown, WV 26505. E-mail: ozw8@cdc.gov

ABSTRACT

The objective of this study is to identify a ranking method for assessing the potential risk of knee musculoskeletal disorders (MSD) among construction roofers. On a slope-adjustable wooden platform, nine subjects performed the shingle installation, comprising seven phases: 1) reaching for shingles, 2) placing shingles, 3) grasping the nail gun, 4) moving to the first nailing position, 5) nailing shingles, 6) replacing the nail gun, and 7) retuning to upright position. Knee flexion, abduction, adduction, internal, and external rotational angles were measured using an optical motion analysis system. To analyze the relative level of risk at each phase, these angles were combined using multiplication and aggregation-based scoring models that generated ranks of phases at different roof slopes. The ranking results provide useful information for identifying the postures that might pose greater MSD risk, and may facilitate effective interventions development to reduce extreme knee positions which is a MSD risk factor.

INTRODUCTION

Awkward kneeling posture is a common source of knee musculoskeletal disorders (MSD) among construction roofers. However, the risk assessment of roofers' knee MSD for a specific roofing task that involves awkward kneeling is still missing. Shingle installation, a common repetitive and awkward task performed by the residential roofers, is a cause of work-related MSD among roofers in the construction community (Everett 1999). In a slanted roof setting, roofers are restricted to various awkward postures such as crawling, stooping and kneeling for more than 75% of their total working time. These awkward postures and repetitive motions are considered to be major contributing factors of MSD. As roofers encounter both of these factors, there is a high incident rate of MSD injuries among roofers (Wang et al. 2015). During shingle installation, roofers encounter awkward posture when their knees undergo significant amount of rotations beyond their tolerance limit. Knee awkward posture and repetitive motions have been proven to be associated with knee MSD (Hofer et al. 2011). However, identifying the individual phase of a shingle installation operation, during which the roofers experience the most awkward knee rotations, is not explored yet. The ranking of the phases based on the awkward postures that lead the knees to potential MSD risks would be useful for developing effective interventions.

BACKGROUND

Ergonomics practice for occupational kneeling: Although roofers have a high MSD injury incident rate, there are very few ergonomic guidelines to protect them. Some of the existing guidelines suggest using mechanical devices during roofing and knee pads while kneeling. General ergonomic practices to minimize the risk of MSD, promoted by safety and health organizations, such as the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH), are not specifically related to knee injury prevention for roofers working on a sloped surface. Most of these guidelines are focused on using knee protective measures to reduce stress on the knee during construction work on level surfaces (Albers and Estill 2007; OSHA 2018). There is still a lack of a detailed task-specific risk analysis that identifies roofers' riskier postures on sloped surfaces and suggests effective interventions.

Ergonomics research on MSD among roofers: Very few MSD risk assessment studies were previously done for the construction roofers. Choi and Fredericks (2008) investigated the impact of surface slope on roofers' shingling frequencies. Wang et al. (2017) assessed different work-related risk factors — roof slope, working technique, and working pace, during shingle installation for low back disorders among roofers. However, lower extremities were not systematically assessed. Breloff et al. (2019) examined the lower extremity kinematics of roofers and their associations to MSD while traverse walking across a sloped roof surface. But the potential MSD risk exposure of the knees while kneeling on a sloped roof surface was not explored.

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

A detailed ranking of the shingle installation phases and their relation to prospective knee MSD risk is missing in the literature. Such knowledge is important to promote knee interventions that can minimize the awkward knee rotations and prevent knee MSD among roofers. Therefore, the objective of this study is to identify a ranking method for evaluating the phases of a sloped shingle installation process with respect to awkward kneeling posture. A phase which places the roofer in a more awkward posture will be considered to be a greater risk for the development of knee MSD.

METHODOLOGY

Risk indicators: Frequent and high contact stress at knee joint is associated with knee osteoarthritis and damage of articular cartilage of the knee joint — two common forms of knee disorders. A previous study showed that, with an increase in knee flexion from 15.5° during walking to 90° during squatting posture, the contact stress in knee joint increased significantly by over 80% (Thambyah et al. 2005). Knee flexion beyond 90° generates larger moment and forces which results in high stress in the knee joint (Nagura et al. 2002). These indicate a strong association between knee rotational angle and knee joint contact stress which relates to knee MSD. Therefore, in this study, potential knee MSD risk is defined as an increase in knee rotations that creates high contact stress in the knee joint. Knee MSD risk is considered to increase as the knee rotational angles encounter larger awkward postures. Awkward posture is considered as a deep flexed posture of knee (>90°) with medial and lateral rotation leading to increased amount of stress in the knee joint. To assess the relative level of risk in each phase, five knee rotational angles — flexion, abduction, adduction, internal and external rotation — were measured. Three metrics — maximum, cumulative, and average of each knee rotational angle — were considered, resulting in a total of fifteen (15) risk indicators. Maximum value of the knee angles may reflect the risk of forceful exertion of knee during placing and installing shingles which is a risk factor of MSD. Cumulative angle can represent the risk due to prolonged kneeling, while the average knee angles can account for the extent of knee repetitive motions. In this study, the relative level of risk among the phases were compared using these fifteen (15) risk indicators. To determine the relative level of knee MSD risk, these risk indicators were combined to produce a risk score for each phase. The phase with the highest score was deemed to yield the largest potential risk for the development of knee MSD. The seven phases were ranked based on the scores computed.

Risk analysis framework: A comparative risk analysis of the seven phases was performed according to the following steps, depicted in Figure 1.

Step 1: Descriptive statistics (as risk indicators) calculation: The maximum, cumulative, and average knee angles were computed for each phase during each trial, and for each slope, using the knee kinematics data. The resulting maximum, cumulative, and average knee angles were then averaged for each phase. The phase averaged data were then used as risk indicators to compute the risk score for each phase for comparative risk analysis.

Step 2: Scoring and ranking the phases: The seven shingling phases were scored and ranked to compare their relative risks and identify the phase with the highest potential for knee MSD risk based on the knee exposure to the highest amount of rotation. To combine the risk indicators and compute the score for each shingling phase, two distinct scoring models were used: 1) aggregation-based scoring model, and 2) multiplication scoring model. Three different methodologies utilizing the aggregation-based scoring model were applied, which are explained in the next subsection. These models were previously employed in studies, such as decision making, university ranking, risk assessment and construction project management (El-Sayegh and Mansour 2015; Odeh and Battaineh 2002), and were found useful to generate ranks from multiple criteria. Since this study involved multiple knee injury risk indicators — phase averaged knee rotation angles, these models were applicable for this situation. The phase with the highest aggregated score was considered to display the most awkward knee posture and therefore identified as the phase with the most potential knee MSD risk and was ranked one.

(2a) Aggregation-based scoring model: The approach to construct a rank from multiple indicators using the aggregation-based model included three steps: (a) normalizing the data, (b) attaching weight to the indicators and, (c) aggregating the weighted values to produce an overall score. For step (a), three separate normalization approaches were tested: i) dividing the indicator values of each phase by the maximum among the phases, ii) dividing the indicator values of each phase by the sum across the phases, and iii) range normalization where each indicator value was scaled to fall within range [0,1] with respect to the maximum and minimum indicator values among the phases. As current literature lacks knowledge on the relative contribution of each knee rotational angle to knee MSD and there are biomechanical reasons of knees getting affected by these awkward rotations, in step (b), equal weights were assigned to all indicators. In step (c), for each normalization approach the weighted scores of all indicators were then combined to generate an overall score for each phase. The phases were then ranked in the descending order of scores.

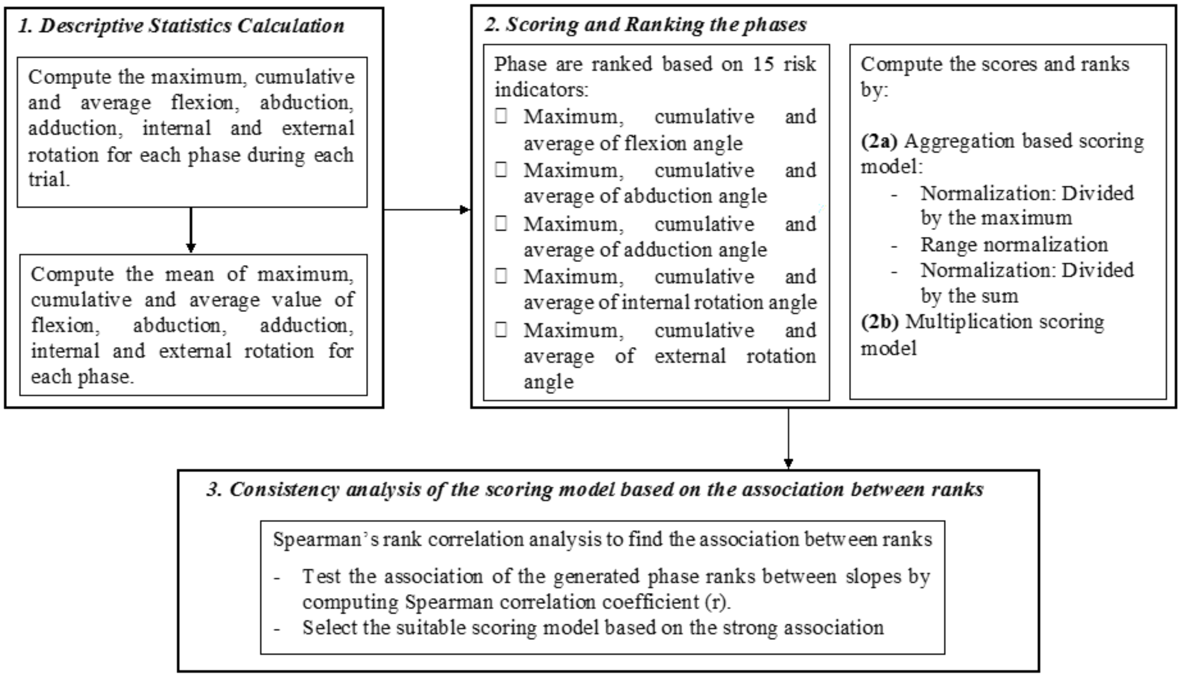

Figure 1. Risk analysis framework

Figure 2. Roof platform

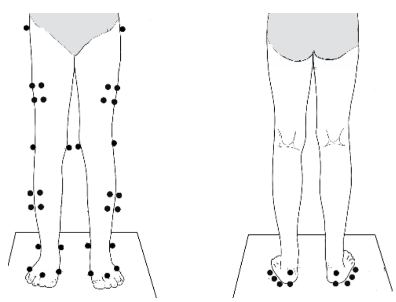

Figure 3. Marker set up in lower extremity

(2b) Multiplication scoring model: This study also used a multiplication based scoring model proposed by Tofallis (2014) to compute the phase scores. Using the phase averaged knee rotational angles as indicators, the multiplication score of a given phase was computed using the following equation:

$$\text{Multiplication score} = X_1^{w_1} \times X_2^{w_2} \times X_3^{w_3} \ldots\ldots\ldots X_n^{w_n}$$

$X_i\ (i=1,2,..n)$ were the risk indicators, and $w_i\ (i=1,2,..n)$ were the weights assigned to each indicator. In our study $w_i\left(i=1,2,..n\right)$ were set to 1 and $n=15$, representing 15 risk indicators.

Step 3: Comparative analysis of the consistencies of the scoring models. To ensure the generated ranks were consistent across the roof slopes, the Spearman correlation coefficient (r) (Rosso 1997) was used. The Spearman's test provided the association of the phase ranks between each pair of slopes generated by the two distinct scoring models (four total ranks: three from the aggregation-based scoring model and one from the multiplication scoring model). The Spearman's rank correlation coefficient is a statistical tool to test the strength of association between the ranks of two groups. A 'r' value close to 1 indicates a strong association between two ranks.

Table 1. Scores and ranks of the left knee

Phase	**Multiplication**		**Divide by max**		**Range normalization**		**Divide by sum**		**Slope**
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	
1	1.79×10^{36}	3	10.78	4	6.62	5	2.09	3	
2	5.67×10^{37}	1	13.04	1	7.99	2	2.83	1	
3	1.99×10^{34}	7	9.36	6	4.67	6	1.68	6	
4	4.12×10^{34}	6	9.00	7	3.24	7	1.66	7	0°
5	4.07×10^{37}	2	12.72	2	8.71	1	2.61	2	
6	8.35×10^{35}	5	10.96	3	6.63	4	2.06	4	
7	1.06×10^{36}	4	10.70	5	7.55	3	2.03	5	
1	2.07×10^{36}	4	10.47	4	7.28	2	2.04	4	
2	1.92×10^{38}	1	13.26	1	9.52	1	2.95	1	
3	1.59×10^{35}	6	9.84	6	6.71	3	1.83	6	
4	1.57×10^{35}	7	9.26	7	4.56	7	1.75	7	15°
5	1.56×10^{37}	2	11.37	2	5.89	5	2.39	2	
6	5.59×10^{35}	5	10.03	5	4.57	6	1.94	5	
7	3.09×10^{36}	3	10.52	3	6.60	4	2.08	3	
1	5.55×10^{36}	4	10.73	4	7.84	3	2.08	3	
2	7.22×10^{38}	1	13.46	1	9.60	1	3.11	1	
3	9.92×10^{34}	7	9.27	7	3.28	7	1.68	7	
4	2.90×10^{36}	5	10.44	5	6.06	5	1.98	5	30°
5	6.72×10^{37}	2	11.63	2	6.95	4	2.44	2	
6	2.30×10^{35}	6	9.31	6	3.47	6	1.72	6	
7	5.93×10^{36}	3	10.79	3	8.05	2	2.07	4	

EXPERIMENTAL SETUP AND PROCEDURE

Nine male volunteers [26.1 years (±5.6 years), 180.2 cm (±6.1 cm), and 99.7 kg (±27.6 kg)] with no history of MSD simulated shingle installation on a 1.2 ×1.6 m custom-made adjustable wood platform which was used as a rooftop (Figure 2). The research protocol was approved by both the Institutional Review Board (IRB) of NIOSH and West Virginia University. A VICON optical motion capture system with 14 MX VICON cameras (Oxford, U.K.) collected the lower extremity kinematic data (3D coordinate points) from 42 retroreflective motion capture markers placed bilaterally on the participant's shanks, thighs, feet and hip joints (Figure 3). These coordinate points were used to calculate the knee rotational angles. The experiment was performed in the NIOSH biomechanics laboratory. Each participant performed five trails of the task on the roof simulator for three slope angles —0^0, 15^0, and 30^0.

DATA PROCESSING

From the calibrated origin (x, y, z positons) of each marker, the local coordinates of thigh and shank were calculated and then transformed to a 3D (XYZ) coordinate system. Combining these local coordinate systems, a rotation transformation matrix was constructed to compute the five knee rotational angles according to the equations provided by Robertson et al. (2013). All kinematic data were processed in Visual 3D (C-Motion, Inc., Germantown, MD).

RESULTS

Tables 1 and 2 present the scores and ranks computed by multiplication and aggregation-based scoring models. Risks in both knees are presented separately.

Table 2. Scores and ranks of the right knee

Phase	Multiplication		Divide by max		Range normalization		Divide by sum		Slope
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	
1	4.76×10^{37}	3	11.58	2	9.44	2	2.37	2	
2	1.07×10^{39}	1	13.26	1	10.91	1	3.07	1	
3	4.17×10^{34}	7	8.47	7	4.19	6	1.58	7	
4	1.06×10^{36}	5	9.42	5	5.79	4	1.84	5	0°
5	4.86×10^{37}	2	10.86	3	5.39	5	2.34	3	
6	3.53×10^{35}	6	8.84	6	3.51	7	1.71	6	
7	6.52×1036	4	10.33	4	6.98	3	2.07	4	
1	1.70×10^{38}	2	12.22	2	10.28	1	2.48	2	
2	7.41×10^{38}	1	12.94	1	9.76	3	2.89	1	
3	1.28×10^{35}	7	8.66	7	3.86	5	1.62	7	
4	3.60×10^{35}	6	8.72	6	3.43	6	1.67	6	15°
5	4.11×10^{37}	4	10.64	4	5.21	4	2.25	4	
6	5.24×10^{35}	5	8.88	5	3.07	7	1.71	5	
7	1.08×10^{38}	3	11.75	3	10.22	2	2.37	3	
1	5.75×10^{37}	3	11.45	3	10.15	1	2.27	3	
2	5.29×10^{38}	1	12.57	1	7.60	3	2.93	1	
3	6.46×10^{34}	7	8.32	7	2.34	7	1.55	7	
4	1.08×10^{36}	6	9.13	6	3.66	6	1.77	6	30°
5	1.57×10^{38}	2	11.58	2	7.02	4	2.46	2	
6	1.68×10^{36}	5	9.87	5	5.38	5	1.89	5	
7	1.50×10^{37}	4	10.73	4	8.58	2	2.10	4	

Spearman correlation test result. The Spearman's correlation test result presented in Table 3 demonstrated that most of the strongest associations of ranks between each slope pair were obtained by multiplication scoring model [0°-15° (Left) with r =0.929; 0°-30° (Left & Right) with r = 0.929 and 0.964 respectively; 15°-30° (Left & Right) with r = 0.893]. Considering these strong associations, the results obtained by applying this model was used for subsequent risk analysis.

Table 3. Spearman correlation test result showing association of ranks across different slopes

Slope	Multiplication		Divide by max		Range normalization		Divide by sum	
	Left	Right	Left	Right	Left	Right	Left	Right
0°-15°	**0.929**	0.857	0.857	**0.929**	0.286	0.786	0.893	**0.929**
15°-30°	**0.893**	**0.893**	**0.893**	**0.893**	0.536	0.857	0.857	**0.893**
0°-30°	**0.929**	**0.964**	0.679	0.929	0.571	0.714	0.821	0.929

Risk analysis on left and right knee: From Tables 1 and 2, phase 2 was ranked first at all three slopes for both knees. Phase 5 was ranked second at all three slopes for left knee and at 0° and 30° slopes for right knee — which indicated that, overall, placing shingles was the riskiest phase followed by nailing shingles phase. The next risky phases were phase 1 (ranked third at 0° for both knees and second at 15° for right knee) and phase 7 (ranked third at 15° and 30° for left knee and at 15° for right knee). Based on the other ranks, the least risky phases were phases 4, 6 and 3.

DISCUSSION

A comparative ranking-based risk analysis of different phases that roofers undergo during shingle installation operation on a sloped surface was performed in this study. Based on the five knee rotational angles, risk scores were generated for each phase using two distinct scoring models. The multiplication scoring model generally performs better in ranking because it does not need any normalization of the indicators even if some indicators are numerically much greater than the other ones. The reason is that rescaling any indicator has no impact on the ranking result in this model. Therefore, although cumulative angles were much higher than the maximum and average angles, there was no possibility of the cumulative angles influencing the ranks.

A correlation analysis result also demonstrated higher consistency of the phase ranks across different roof slopes computed by the multiplication scoring model and hence was considered more appropriate for rank generation. The consistency of the ranks across different slope was computed for evaluating the performances of the scoring models, because the objective of this study was to identify the riskiest phases yielding the most awkward knee rotations at any roof setting and hence would be potentially critical for knee MSD. Although, at different roof slopes, roofers might require maintaining different posture which could yield different knee rotational angles, but the ranking results at different slopes demonstrated almost similar risk pattern. The possible reason could be that, at different slopes, individual knee rotation (e.g., flexion) might vary, but this variation did not impact the overall risk pattern of the phases. However, further assessment is necessary to confirm this causal relationship.

For both knees, at all slopes, the phase with the highest potential knee MSD risk was placing shingles. Except for the right knee at 15° slope, the next riskiest phase for both knees at all other slopes was nailing shingles. A possible reason is that, compared to other phases, the participants were more repetitively changing their knee angles encountering larger awkward posture during placing and nailing shingles on sloped roof surfaces for a longer duration. The cumulative effect of high repetition along with the awkward posture may induce additional stress and force on the knee joint ligaments and accelerate knee osteoarthritis among roofers. Interventions or strategies to minimize the extent of knee rotations during placing and nailing shingles may reduce knee MSD among roofers. However, further assessment is needed to identify which knee rotation contributes the most to the knee MSD so that proper interventions can be developed to minimize the extreme rotations commonly associated with knee MSD development.

CONCLUSION AND FUTURE WORK

This study identified a ranking based method for assessing the potential risk of knee MSD among roofers in shingle installation. The level of risk at different shingling phases was compared based on the risk scores generated by two distinct scoring models. Spearman correlation test result exhibited better consistency with multiplication scoring model. Based on the fifteen risk indicators, placing shingles and nailing shingles phases were identified as potentially imposing the greater risk for knee MSD development in terms of awkward postures and repetitive motions compared to the other phases. Further work is required to examine the contribution of each knee rotation to knee MSD among roofers, and to test different interventions with the participation of professional roofers with a large sample size in real-world construction work environment.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

REFERENCES

Albers, J., and Estill, C. F. (2007). "Simple solutions; ergonomics for construction workers."

Breloff, S. P., Wade, C., and Waddell, D. E. (2019). "Lower extremity kinematics of cross-slope roof walking." *Applied Ergonomics*, 75, 134-142.

Choi, S., and Fredericks, T. (2008). "Surface slope effects on shingling frequency and postural balance in a simulated roofing task." *Ergonomics*, 51(3), 330-344.

El-Sayegh, S. M., and Mansour, M. H. (2015). "Risk assessment and allocation in highway construction projects in the UAE." *Journal of Management in Engineering*, 31(6), 04015004.

Everett, J. G. (1999). "Overexertion injuries in construction." *Journal of construction engineering and management*, 125(2), 109-114.

Hofer, J. K., Gejo, R., McGarry, M. H., and Lee, T. Q. (2011). "Effects on tibiofemoral biomechanics from kneeling." *Clinical Biomechanics*, 26(6), 605-611.

Nagura, T., Dyrby, C. O., Alexander, E. J., and Andriacchi, T. P. (2002). "Mechanical loads at the knee joint during deep flexion." *Journal of Orthopaedic Research*, 20(4), 881-886.

Odeh, A. M., and Battaineh, H. T. (2002). "Causes of construction delay: traditional contracts." *International journal of project management*, 20(1), 67-73.

OSHA (2018). "(Occupational Safety and Health Administration), (https://www.osha.gov/SLTC/ergonomics/training.html)." (Aug 22, 2018).

Robertson, G., Caldwell, G., Hamill, J., Kamen, G., and Whittlesey, S. (2013). *Research methods in biomechanics, 2E*, Human Kinetics.

Rosso, R. (1997). *Statistics, probability and reliability for civil and environmental engineers*, Mc-Graw-Hill Publishing Company.

Thambyah, A., Goh, J. C., and De, S. D. (2005). "Contact stresses in the knee joint in deep flexion." *Medical engineering & physics*, 27(4), 329-335.

Tofallis, C. (2014). "Add or multiply? A tutorial on ranking and choosing with multiple criteria."

INFORMS Transactions on Education, 14(3), 109-119.
Wang, D., Dai, F., and Ning, X. (2015). "Risk assessment of work-related musculoskeletal disorders in construction: State-of-the-art review." *Journal of Construction Engineering and management*, 141(6), 04015008.
Wang, D., Dai, F., Ning, X., Dong, R. G., and Wu, J. Z. (2017). "Assessing Work-Related Risk Factors on Low Back Disorders among Roofing Workers." *Journal of Construction Engineering and Management*, 143(7), 0401702