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Electromyography Signal Analysis of Knee Flexor and Extensor Muscles in Potential Knee Musculoskeletal Disorders during Roofing

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ABSTRACT

Awkward and extreme kneeling postures required during shingle installation on sloped rooftops generates large muscular tension on lower extremities of residential roofers. This study assessed the effects of kneeling posture and roof slope on the peak activations of knee flexor (biceps femoris and semitendinosus) and extensor (rectus femoris, vastus lateralis, and vastus medialis) muscles that are potential risk indicators of knee musculoskeletal disorders (MSD) in shingle installation. Using surface electromyography (EMG), the authors collected maximum normalized EMG signals from the above-mentioned muscles of seven subjects who mimicked a shingle installation task with kneeling on a slope-configurable wooden platform. The results suggested a significant association of the roof slope, kneeling posture, and their interaction with the peak muscle activation. Except for the vastus medialis muscle of the right knee, significant increase in the peak normalized EMG was observed for all flexor and extensor muscles during shingle installation on the sloped roof surface. Significant interaction between the slope and posture was observed for the flexor muscles of the right knee and vastus medialis muscle of the left knee. Therefore, the large muscle activations during kneeling in shingle installation on high-pitched rooftops should be given particular attention as it might lead to development of the knee MSD among residential roofers.

INTRODUCTION

Residential roofers spend a large amount of time in awkward kneeling postures while performing shingling activities on sloped rooftops. The large muscular tension generated by awkward and extreme kneeling postures is commonly associated with knee musculoskeletal disorders (MSD) (Kaushik and Charpe 2008). Although knee joint kinematics and compressive loads in kneeling have been previously studied in arthroplasty and ergonomics research (Kingston et al. 2016), limited information is available on the activation of lower limb muscles during kneeling in shingle installation on a sloped surface. Specifically, it is unclear if the combined effect of an awkward kneeling posture and a sloped roof surface on the peak activation of lower limb muscles contributes to the development of lower extremity MSDs during the performance of kneeling shingle installation. This knowledge is important as these muscles are the greatest contributors to peak knee joint contact forces and thus are major factors in knee joint degeneration or osteoarthritis (Andriacchi and Favre 2014). This study examined the impact of the extreme kneeling posture and sloped roof surface—two residential roofing work-related factors—on the peak activation of knee flexor and extensor muscles as a potential that leads to knee MSD during shingle installation.

BACKGROUND

State of practice

Awkward kneeling and repetitive motion have been proven to be risk factors of knee MSD (Hofer et al. 2011). As roofers encounter both of these factors, there is a high incident rate of MSD injuries among roofers (Wang et al 2015). According to the *2018 base rates by business type and classification code* published by the Washington State Department of Labor and Industries, the insurance premium composite base rate for roofers is the highest ($7.03) among all building construction trades (Washington DOL & I 2018). In spite of this, there are very few ergonomic guidelines to protect residential roofers. In the United States, safety and health organizations such as the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) have promoted some general ergonomic practices to minimize the MSD risk among construction roofers. For example, NIOSH has suggested using simple and inexpensive tools, such as an auto-feed screw gun with an extension arm, a kneeling creeper and knee pads to minimize the stress on knees during construction tasks (Albers and Estill 2007). OSHA has marketed training programs (10-hour and 30-hour) and provided educational tools (eTools, eMatrix, v-Tools) (OSHA 2019). However, these guidelines are generic. They are neither specific for knee injury prevention nor designed for the tasks performed on sloped roof surfaces and hence may not be applicable for the work setting of the residential roofing industry.

State of research

Although abundant research has been conducted on fatal injuries among roofers caused by falls from height, few studies assessed the MSD risk factors to suggest interventions. Among the few studies, Choi and Fredericks (2008) investigated the impact of surface slope on roofers' shingling frequency. Kingston et al. (2016) assessed the peak activation of eight bilateral lower limb muscles during high flexion kneeling and transitional movement tasks performed on a level surface. Wang et al. (2017) examined the influence of roof slope, working technique, and working pace in kneeling and stooped postures on the development of low back disorders among roofers. Lee et al. (2017) assessed wearable sensors to facilitate data collection of roofers' heart rate, energy expenditure, metabolic equivalents, and sleep efficiency that might be associated with MSD developments. Wearable EMG sensors have been used to evaluate construction workers' muscle fatigue (Jebelli and Lee 2019). Despite these efforts, lower extremities have not been systematically evaluated and the to-date findings were not necessarily related to the lower extremity MSD risk associated with kneeling on a sloped roof surface. Until now, the knowledge regarding the peak muscular activity of knee postural muscles during shingle installation on a sloped roof surface is still missing in literature. The activation of the knee postural muscles is anatomically responsible for the flexion and extension of the legs during kneeling and repetitive motion in a dynamic task. These muscles become highly activated as they produce force that is greater than their normal force generation capability, which is associated with MSD (Kingston et al. 2016).

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

Awkward kneeling postures may overload the muscle tissues of the lower extremity. Repetitive and cumulative muscle overloading without enough recovery time can cause muscle strains. These factors by themselves or combined may cause MSD such as knee joint degeneration, knee osteoarthritis and anterior cruciate ligament (ACL) injuries (Andriacchi and Favre 2014). On sloped roof surfaces, larger activation of the lower extremity muscles is required to maintain the body balance than that on a level work condition. However, a systematic evaluation of the activation of knee postural muscles during shingle installation while kneeling on sloped roof surfaces is still lacking. This knowledge is vital to develop effective interventions so that muscle overloading might be reduced for the prevention of knee MSD among roofers. Therefore, the objective of this research is to assess the effects of kneeling posture and roof slope on the peak activation of knee flexor and extensor muscles in a shingle installation task for the purpose of suggesting if kneeling while shingling on a sloped roof surface may lead to development of the knee MSD among residential roofers due to overloading of the muscles.

Figure 1. Static kneeling

EXPERIMENT AND IMPLEMENTATION

Variables

Two roofing work-related factors that may potentially cause the increased knee postural muscle activity were considered: roof slope and kneeling posture. Three roof slopes—0°, 15° and 30°—were chosen as these roof angles are commonly used residential roofing (National Contractors 2019). Two kneeling postures—static and dynamic—were considered to represent typical kneeling techniques residential roofers utilize during a shingle installation task. The static condition represented a highly flexed kneeling position when roofers flex their knees and trunk and put their non-nailing hand on the roof surface while holding the nail gun with negligible movement in the lower limb, as illustrated in Figure 1. Dynamic kneeling—involved rigorous lateral movement—required the roofers to perform the entire shingle installation task including placing and nailing shingles, as shown in Figure 2. To identify the potential knee MSD risk, peak normalized activations of the knee muscles were recorded with surface EMG and compared between the different combinations of slope and kneeling posture. Five bilateral (10 total) knee postural muscles—biceps femoris (BF), semitendinosus (ST), rectus femoris (RF), vastus lateralis (VL) and vastus medialis (VM)—were selected as they are the primary flexor and extensor muscles of the knee. Peak activations of these muscles collected with wearable surface EMG system have been considered as risk indicators in this study, as activations of these muscles can contribute to peak knee joint contact force and high knee joint contact force is associated with knee MSD (Andriacchi and Favre 2014).

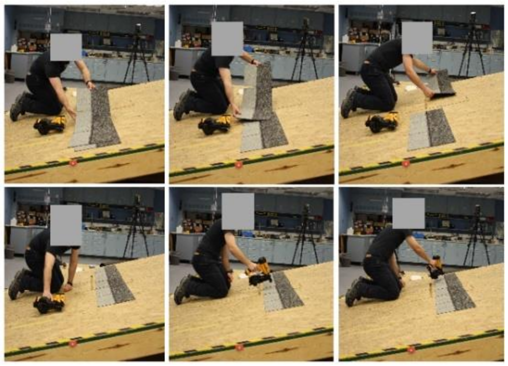

Figure 2. Dynamic kneeling

Participants

Seven subjects [26.1 years (±5.6 years), 180.2 cm (±6.1 cm), and 99.7 kg (±27.6 kg)] with no history of MSD participated in the study. The protocol was approved by the Institutional Review Board (IRB) of NIOSH and West Virginia University.

Instruments and data collection

All the subjects simulated a kneeling shingle installation on a 1.2m×1.6m custom-made adjustable wood platform (Figure 3). The platform was connected to a hydraulic lift that could adjust the wood platform between slope angles ranging from 0° to 30°. A surface EMG system (Noraxon Desktop Direct Transmission System with myoMUSCLE Master software, Arizona, USA) was used to record the muscular activation from surface EMG Ag/AgCl electrodes placed on the palpated muscle bellies at a rate of 1,000 Hz.

Figure 3. Roof platform

During the experiment session, the subjects performed the aforementioned simulation of kneeling static and dynamic shingle installation tasks. The kneeling static and dynamic shingle installation trials were completed on the wood platform at three slopes—0°, 15°, and 30°—which resulted in a total of 6 (2 posture×3 slope) tasks. The subjects performed 5 trials of each condition. The experiment was performed in the NIOSH (Morgantown, WV) biomechanics laboratory.

Data processing

To remove the DC bias, the EMG signals were filtered using a 2nd order Butterworth high pass filter with a cut off frequency of 20 Hz and then low pass filtered with cutoff frequency 500 Hz. The EMG signals were then rectified and further smoothed using a moving average filter with a window of 3 data points approach. As the maximum voluntary contraction (MVC) data of the muscles were not available, for each subject, the EMG signal of each muscle was normalized to the average of the maximum EMG signals of all trials to ensure fair comparison.

Data analysis

To measure the impact of the factors (slope and posture) on the peak normalized knee muscle activation, a univariate ANOVA technique was employed. Normality of residuals, constant variance of residuals and independence of observations were evaluated for all response variables using a graphical approach (Freund et al. 2010). Tukey Post-hoc analysis was performed on the factors (slope and posture) to further analyze where the significant difference existed among different levels of the factors. The *p*-value was set at 0.05 and all tests were performed in Minitab 19 (Minitab, Inc.).

RESULTS

The effects of the factors were different for both knees. Therefore, the results were presented and discussed separately: Table 1 (left knee) and Table 2 (right knee). Bold texts indicate significant effects of the factors (slope and posture) on the response variables (EMG values of the muscles).

Table 1. Effects of the Factors for the Left Knee

Factors	ANOVA				
	BF	**RF**	**ST**	**VL**	**VM**
Slope	0.343 (0.3)	0.001 (0.5)	0.011 (0.4)	<0.001(0.6)	<0.001 (0.6)
Posture	<0.001(0.6)	<0.001 (0.6)	<0.001 (0.7)	<0.001 (0.5)	<0.001 (0.7)
Slope*Posture	0.121(0.4)	0.676 (0.9)	0.091 (0.4)	0.118 (0.9)	0.019 (0.8)

Note: Bold numbers indicate significant p values. Effect sizes are provided in the parenthesis.

Analysis of the left knee

Effect of Slope-Posture Interaction

For the left knee, Table 1 indicated a statistically significant interaction between slope and posture for only the VM muscle. For both of the static and dynamic kneeling postures, as roof slope increased, the peak normalized muscle activation increased (Figure 4). Post-hoc analysis revealed that, during the dynamic kneeling posture (D), the peak normalized muscle activation at

30° slope [1.98 (mean)±1.80 (standard deviation)] was significantly larger than that at 0° (0.77±1.02) and 15° (1.33±1.01) slopes. For the static kneeling (S), there was no significant difference among the slopes. These results suggested a potentially larger MSD risk at sloped roof surfaces during the dynamic shingle installation compared to the deep flexed static kneeling.

Table 2. Effects of the Factors for the Right Knee

Factors	ANOVA				
	BF	RF	ST	VL	VM
Slope	0.007 (0.4)	0.684 (0.2)	0.776 (0.2)	0.007 (0.4)	<0.001 (0.5)
Posture	<0.001 (0.9)	<0.001 (0.5)	<0.001 (0.7)	<0.001 (0.5)	0.056 (0.3)
Slope*Posture	0.002 (0.4)	0.718 (0.2)	0.015 (0.7)	0.107 (0.5)	.0160 (0.7)

Note: Bold numbers indicate significant p values. Effect sizes are provided in the parenthesis.

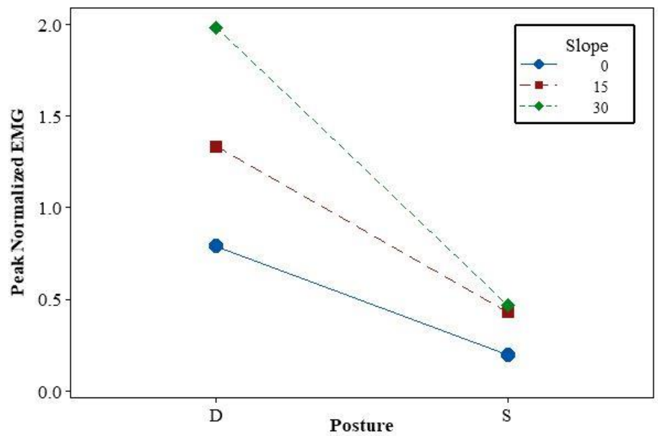

Figure 4. Interaction effect of slope and posture on the peak normalized muscle activation of the vastus medialis

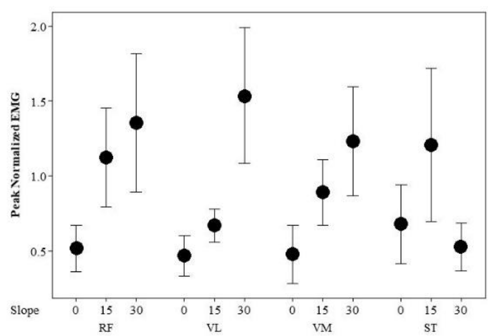

Figure 5. Effect of slope on the peak normalized muscle activation (Left)

Effect of Slope

Statistically significant effect of slope was observed for all muscles except the BF (Table 1). For all muscles except ST, larger muscle activation was observed as roof slope increased. Post hoc analysis suggested that the peak normalized muscle activation of RF muscle at 15° and 30° slopes (1.13±1.30 and 1.36±1.90 respectively) were significantly larger than that at 0° slope (0.52±0.60). For the VL muscles, the peak normalized muscle activation at 30° slope (1.54±1.80) was significantly larger than that at 0° (0.47±0.50) and 15° (0.67±0.40) slopes. For the VM muscle, the peak normalized muscle activation at 30° slope (1.23±1.50) was significantly higher than that at 0° (0.49±0.80) slope. But for the ST muscle, the peak normalized muscle activation at 30° slope (0.53±0.60) was significantly lower than that at 15° slope (1.20±2.10) (Figure 5).

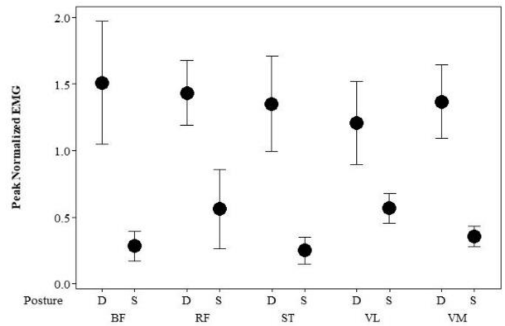

Figure 6. Effect of posture on the peak normalized muscle activation (Left)

Effect of Posture

Statistically significant effect of posture was observed for all flexor and extensor muscles (Table 1). Post hoc examination revealed that the peak normalized muscle activation of all knee postural muscles was significantly higher in the dynamic kneeling (D) than the static kneeling (S) condition (Figure 6).

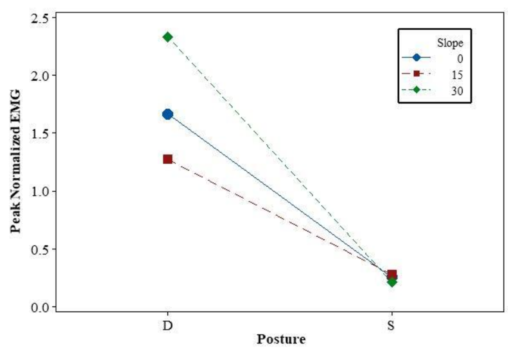

Figure 7. Interaction effect of slope and posture on the peak normalized muscle activation of biceps femoris (Right)

Analysis of the right knee

Effect of Slope- Posture Interaction

Statistically significant interaction effect of slope and posture was observed for the BF and ST muscles of the right knee (Table 2). During the dynamic kneeling posture (D), for the BF muscle, the peak normalized muscle activation at 30° slope (2.33±1.80) was significantly larger than that at 0° (1.67±0.85) and 15° (1.28±0.90) slopes (Figure 7). For the ST muscle, the peak normalized muscle activation at 30° slope (1.83±2.50) was significantly larger than that at 0°slope (1.09±0.70) (Figure 8). In general, for all roof slopes, the peak normalized muscle activation was significantly larger in the dynamic kneeling posture (D) than that in the static kneeling (S) for these two muscles.

Effect of Slope

Statistically significant effect of slope was observed for all muscles except the RF and ST muscles (Table 2). In general, as roof slope increased, the peak normalized muscle activation increased. Post hoc analysis revealed that for the BF and VL muscles, the peak normalized muscle activation at 30° slope (BF=1.30±1.60, VL= 1.45±1.90) were significantly larger than at 15° (BF=0.78±0.80) and 0° slopes (VL=0.62±1.80). For the VM muscle, the peak normalized muscle activation at 15° (1.06±1.80) and 30° (1.20±1.10) slopes were significantly larger than at 0° (0.21±0.20) slope (Figure 9).

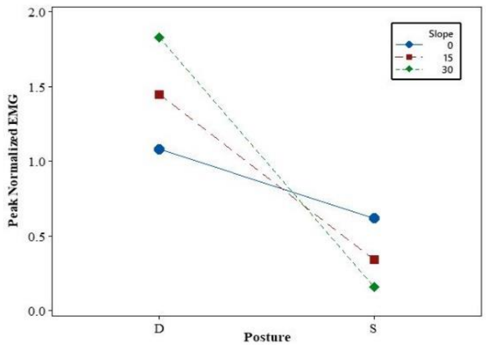

Figure 8. Interaction effect of slope and posture on the peak normalized muscle activation of semitendinosus (Right)

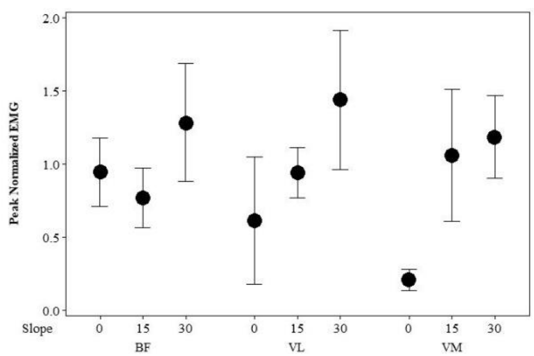

Figure 9. Effect of slope on peak normalized muscle activation (Right)

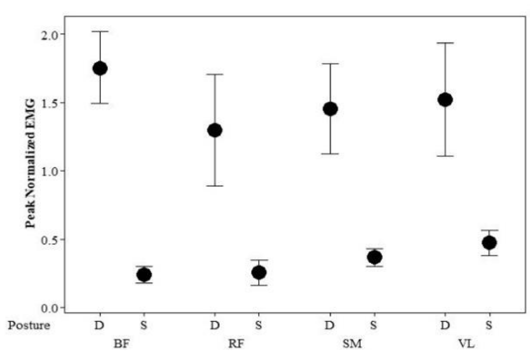

Figure 10. Effect of posture on peak normalized muscle activation (Right)

Effect of Posture

Statistically significant effect of posture was observed for all muscles except VM (Table 2).

Post hoc analysis suggested that the peak normalized muscle activation of all knee postural muscles was significantly larger in the dynamic kneeling than in the static kneeling condition (Figure 10).

DISCUSSION

The current study examined the peak activation of the knee flexor and extensor muscles to understand the effect of two residential roofing work-related factors—slope and kneeling posture—as potential risk factors of knee MSD during a kneeling shingle installation task. The experimental results suggested that, roof slope, kneeling posture and their interaction significantly affect the peak activation of knee flexor muscles (Tables 1 and 2). Based on these findings, it is understood that roofers become exposed to potential knee MSD risks when they perform a kneeling shingle installation task on a sloped roof surface. One possible reason might be that, as the roof slope increases, a larger force is needed to raise the body's center of mass for maintaining its balance. Also, due to the repetitive lateral movement of the lower limbs during kneeling shingle installation, the knee joint angle changes frequently. The repetitive change in the joint angle also alters the muscle length and affects the force generation capacity of the muscles (Ha and Han 2017). During the performance of a kneeling sloped shingle installation task, as the roof slope increases, the knee flexion decreases because the participants need to adjust their thighs to incline more towards the rooftop surface. As the knee flexion decreases, the length of the muscles increases (Lieber and Boakes 1988). According to the force-length relationship, when the muscle is stretched or shortened beyond its resting length due to an action of the muscle, the ability to produce the maximum active tension generated in the muscle decreases (Kuriki et al. 2012). This might be the reason of the larger peak muscle activation on a sloped surface during a kneeling shingle installation.

In the static kneeing posture, the participants had negligible movement in the lower limbs. However, in the dynamic kneeing posture, the participants were placing and nailing shingles which involved greater awkward rotation and a large range of motion among the lower limbs. For this reason, the length of the muscles also deviated from the ideal resting length which could affect the force generation capability of the muscle. Thereby the knee muscles would need to recruit more motor units by the means of an increased muscular activation to generate the required amount of force to complete the kneeling shingle installation process. The increased muscle activation can lead to muscle overloading, and the repetitive and cumulative overloading of the muscles can be associated with MSD—such as knee joint degeneration, patellofemoral pain and osteoarthritis—if the knee muscles are not given enough recovery time. Hence, proper interventions need be developed to minimize and possibility prevent the awkward knee rotations and cumulative muscle overloading. Possible solutions might be using knee pads, wearable assist devices and knee savers specifically designed for residential roofers during the performance of sloped shingle installation task. However, further experimental studies are required to determine if the inclusion of these interventions can in fact reduce the awkward knee rotations and cumulative muscle overloading that is commonly associated with knee MSD.

CONCLUSION AND FUTURE WORK

This study assessed the effects of roof slope and kneeling posture as potential risk factors of knee MSD development among residential roofers during a kneeling shingle installation task. From the experimental kneeling shingle installation tasks performed in a laboratory setting, the peak normalized muscle activation of ten knee postural muscles were collected and analyzed as risk indicators. Overall, this study confirmed that the potential knee MSD risk of awkward postures and repetitive motions encountered during residential roofing do indeed increase knee postural muscular demand compared to a level surface. The awkward knee rotations involved in the dynamic kneeling on a sloped surface influence the muscle length which alters the ability to generate the required muscle force to complete the task. The change in the length of the knee muscles due to the extreme posture incites a larger muscle activation, which may cause knee MSD. The findings provided useful information to understand the knee MSD risk in kneeling sloped shingle installation roofing task, which can be helpful to promote interventions for preventing knee MSD among roofers. By statistically measuring the knee muscles exposures to roofing work-related risk factors, this study will also contribute to developing biomechanical models for risk analysis of knee joint. Future work will explore the effect of slope and kneeling posture on the combined activation of all knee postural muscles that will facilitate in-depth understanding of the knee MSD risk. Interventions (knee pad, assistive device) will be tested in a real construction site with the participation of real roofers of a large sample size.

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." *The National Institute for Occupational Safety and Health (NIOSH)*.

Andriacchi, T. P., and Favre, J. (2014). "The nature of in vivo mechanical signals that influence cartilage health and progression to knee osteoarthritis." *Current rheumatology reports*, 16(11), 463.

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.

Freund, J., Rudolf, Mohr, L., Donna, and Wilson, J., William (2010). "Statistical Methods, 3rd edition." ELSEVIER.

Ha, M., and Han, D. (2017). "The relationship between knee joint angle and knee flexor and extensor muscle strength." *Journal of physical therapy science*, 29(4), 662-664.

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.

Jebelli, H., and Lee, S. (2019). "Feasibility of Wearable Electromyography (EMG) to Assess Construction Workers' Muscle Fatigue." *Advances in Informatics and Computing in Civil and Construction Engineering*, Springer, 181-187.

Kaushik, V., and Charpe, N. A. (2008). "Effect of body posture on stress experienced by worker." *Studies on Home and Community Science*, 2(1), 1-5.

Kingston, D. C., Tennant, L. M., Chong, H. C., and Acker, S. M. (2016). "Peak activation of lower limb musculature during high flexion kneeling and transitional movements." *Ergonomics*, 59(9), 1215-1223.

Kuriki, H. U., De Azevedo, F. M., Takahashi, L. S. O., Mello, E. M., de Faria Negrão Filho, R., and Alves, N. (2012). "The relationship between electromyography and muscle force." *EMG Methods for evaluating muscle and nerve function*, Intechopen.

Lee, W., Lin, K.-Y., Seto, E., and Migliaccio, G. C. (2017). "Wearable sensors for monitoring

on-duty and off-duty worker physiological status and activities in construction." *Automation in Construction*, 83, 341-353.
Lieber, R. L., and Boakes, J. L. (1988). "Sarcomere length and joint kinematics during torque production in frog hindlimb." *American Journal of Physiology-Cell Physiology*, 254(6), C759-C768.
National Contractors, I., (NCINC). (2019). "http://www.nationalcontractors.net/specialty-services-roof-low-slope.html." (7/8/2019).
OSHA (2019). "(Occupational Safety and Health Administration), (https://www.osha.gov/SLTC/ergonomics/training.html)." (7/8/2019).
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), 04017026.
Washington DOL & I (2018). "Rates for Worker's Compensation: 2018 base rates by business type and classification code." <http://www.lni.wa.gov/ClaimsIns/Files/Rates/2018RatesBusTypeClassCode.pdf>. (7/10/2019)

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Preface

The Construction Research Congress (CRC) 2020 Organizing Committee, Arizona State University (ASU), the Construction Research Council, and the Construction Institute of the American Society of Civil Engineers (ASCE) are all pleased to present the CRC 2020 Proceedings. CRC is one of the prime international conferences in the area of construction engineering and management; it is held every two years, providing one university the privilege to serve and host our peers from around the globe to facilitate an interactive exchange of ideas and research findings. CRC 2020 was hosted by Arizona State University (ASU) and its Del E. Webb School of Construction, in Tempe, Arizona, on March 8-10, 2020. Tempe is in the Phoenix metropolitan area, the fifth most populous city in the United States. It is home to the flagship campus of ASU, the nation's largest university by enrolment.

The theme for this conference is "*Construction Research and Innovation to Transform Society*." As the built environment, including civil, industrial, building, and cyber infrastructure, evolves to support sustainable and resilient communities of the future, the construction industry will need to evolve. New infrastructure system developments are already transforming society in terms of safety, health, economics, and quality of life. A global network of construction stakeholders gathered at this event to share the state-of-the-art in research and practice for tackling the challenges of the 21st-century construction industry. This premier conference also provided an opportunity to inspire the next generation of construction leaders, emphasizing an interdisciplinary approach to research and innovation.

The Conference Proceedings contain a record number of 481 peer-reviewed technical papers, which stemmed from almost 900 abstract submissions. All submissions went through a two-step review process with a minimum of two external reviewers per paper, by a scientific committee of more than 500 international construction experts. The work was presented at the conference in a variety of formats including short talks and posters. The resulting proceedings are divided into four volumes according to the following areas:

- Volume 1: Infrastructure Systems and Sustainability (101 papers)
- Volume 2: Computer Applications in Construction (143 papers)
- Volume 3: Safety, Workforce, and Education (90 papers)
- Volume 4: Project Management and Controls, Materials, and Contracts (147 papers)

On behalf of the Organizing Committee, ASU, the Construction Research Council and the ASCE Construction Institute, I hope you enjoy these CRC 2020 proceedings documenting our intellectually-stimulating conference.

Mounir El Asmar, Ph.D.
Conference Chair
Arizona State University

Acknowledgments

The editors would like to thank and recognize each and every person who volunteered their time, effort, and expertise to make CRC 2020 a successful conference. CRC 2020 could not have happened without the leadership and support of the following individuals:

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