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RESEARCH ARTICLE

Phase Level Assessment of Ergonomic Intervention Effectiveness in Reducing Knee Musculoskeletal Disorder Risks During Residential Roof Shingle Installation

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ABSTRACT

Background: This study aimed to assess how knee savers (KSs) and knee pads (KPs) alleviate risks of knee musculoskeletal disorders (MSDs) among roofers during various phases of shingle installation. These phases encompass (1) reaching for shingles, (2) placing shingles, (3) grabbing a nail gun, (4) moving to the first nailing position, (5) nailing shingles, (6) replacing the nail gun, and (7) returning to an upright position.

Methods: In a laboratory setting, nine male participants simulated the shingle installation task on a slope-adjustable roof platform (0°, 15°, and 30° slopes) under four intervention conditions: no intervention (NO); with KPs only (KP); with KSs only (KS); and with both KPs and KSs (BO). Knee flexion, abduction, adduction, and internal/external rotations were measured to assess intervention impact through statistical analysis.

Results: Phase 5 (nailing shingles), one of the riskiest phases, saw reduced knee rotations, with BO and KP interventions being the most effective. Phase 6 (replacing the nail gun) exhibited notable reductions in all knee rotations, primarily due to BO intervention. Significant improvements in certain knee angles for other phases were noted, particularly with BO intervention.

Conclusions: BO and KP can lower knee strain by minimizing extreme knee postures and thereby reducing the risk of MSDs during the installation of shingles, especially at critical periods and on steeper slopes. This study highlights the importance of applying focused ergonomic techniques in the roofing sector to improve workers' musculoskeletal health.

1 | Introduction

Residential roofers frequently perform tedious, time-consuming shingle installation at jobsites. This requires uncomfortable crawling, stooping, or kneeling postures and repetitive actions that cause knee MSDs such as osteoarthritis, bursitis, and persistent knee pain among roofers [1]. Roofers experience a high incidence rate of MSDs because they are forced to perform

Institution at which the work was performed: National Institute for Occupational Safety and Health (NIOSH) and West Virginia University (WVU).

[Correction added on 28 January 2025, after first online publication: Erik W. Sinsel has been added to the author byline and Author Contributions sections in this version.]

repetitive motions and awkward postures for more than 75% of their working time on sloped roofs [2].

Among all lower extremity injuries in the "Nonfatal Occupational Injuries and Illnesses Involving Days Away from Work" report in 2020 [3], the knees were involved in 35% of all cases. Roofers experience MSDs at a rate that is 30% greater than the average for all construction trades [4]. Based on the Washington State Department of Labor & Industries' 2018 report, roofers' insurance premium base rate is the highest of all the building construction trades in terms of cost. In the construction industry, knee injuries make up 7.8% of all days away from work due to nonfatal injuries [2].

In the prior studies of MSD risk and development among roofers, it was found that the installation of shingles on sloped roof surfaces would more likely cause the lower extremity injuries among roofers than working on flat surfaces [5]. Repetitive movements and uncomfortable knee postures would increase the risk of knee MSDs [6]. During the installation of residential roof shingles, roofers' knee joints may experience large, repeated rotations, close to their range of motion limits [6]. In addition to uncomfortable postures, the steep rooftop can also contribute to the loading to the knees, thereby increasing the MSDs among construction roofers [7, 8]. Some of the single installation phases would demand the extensive rotation, repetition, and exertion, which may increase the risk of knee MSDs among roofers [9].

Knee pads (KPs) and knee savers (KSs) serve distinct purposes in various occupational settings. KPs are commonly used by workers who need to kneel during their tasks. They come in various styles and designs, affecting knee joint contact forces [10] and knee flexion [11]. KPs also alleviate pressure on the patellar tendon and tibial tubercle [12]. KSs are placed on the shank's posterior aspect and contact the thigh's posterior aspect during squatting. The device can be used as an ergonomic aid to lessen the risk of knee injury during deep knee flexion and has been extensively used by catchers in baseball and softball [13]. The strain from the back side of the knee joint may lead to knee injuries, which might be reduced by using KSs. In a recent study [14], KPs and KSs were evaluated on their effects to reduce extreme lower extremity postures, thereby mitigating the knee MSD risk in the posture of deep kneeling. The findings supported the use of third-party KPs and KSs to reduce the extremity joint flexion angles on sloped surfaces, thereby reducing MSD risk [14]. Later, researchers [9] compared the knee joint angles of roofers performing shingle installation tasks at different phases to further examine the impact of roof work conditions on knee MSD risk development. Their study revealed that placing and nailing shingles are the phases when roofers sustain the most uncomfortable knee joint rotations, possibly posing the greatest risk for knee MSD development. Nevertheless, it remains unknown which phase of the roof shingle installation task will benefit from using the wearable devices of KPs and KSs.

2 | Materials and Methods

2.1 | Definition of Phases in Shingle Installation

During a typical process of roof shingle installation, roofers use a pneumatic nail gun to fasten the shingles. This process begins with roofers first reaching for the shingles and then positioning them, facing forward, on the rooftop surface. Subsequently, they take the nail gun from its designated location, preparing to secure the shingles. Afterward, they proceed to nail the shingles side by side. The shingle installation process is concluded by returning the nail gun to its original position and the roofer returning to the initial kneeling position. Figure 1 illustrates this process, which consists of seven phases.

2.2 | Variables

This study used two factors to assess the effectiveness of interventions in reducing knee MSD risks during shingle installation. They were roof slopes (0°, 15°, and 30°) and wearable devices - no

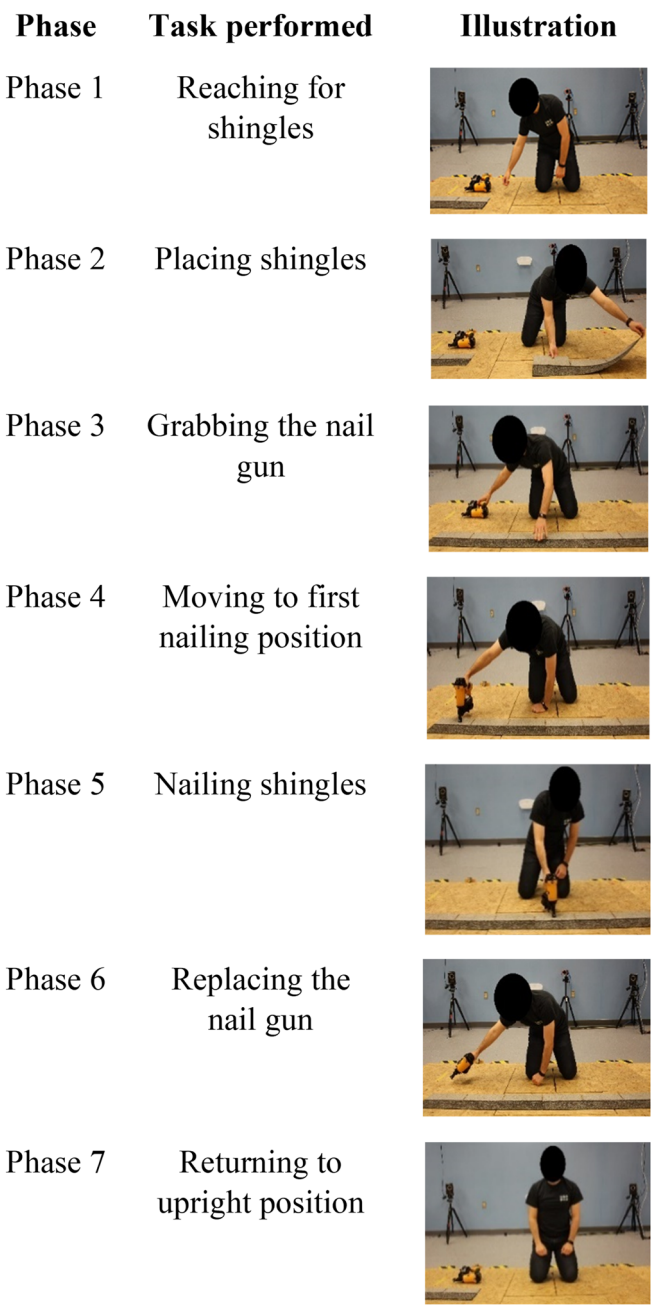

FIGURE 1 | Seven phases of shingle installation process.

wearable assist devices (NO), knee pads only (KP), knee savers only (KS), and both knee pads and knee savers (BO). These roof slope angles were selected according to typical roof pitches observed on building sites [15]. The KPs and KSs were chosen on accounts that many severe postures in the lower extremity during deep/full kneeling in the resting position of roof workers were reduced with the addition of these devices [14].

This study assumed that knee MSD risks are associated with knee rotations during the shingle installations. The knee rotation was considered a dependent variable that reflects the effectiveness of interventions in reducing knee MSDs.

Over the seven phases of shingle installation, this study measured five types of knee rotation angles (as illustrated in Figure 2): flexion (around the side-to-side axis), abduction and adduction (around the front-to-back axis), and internal and external rotations (around the lengthwise axis). Deep bending movements exert significant force and torque on the knee joint [16]. Elevated levels of knee movement toward and away from the body's midline subject the knee joint to stress, elevating the risk of developing knee osteoarthritis [17]. When the tibia undergoes internal and external rotations relative to the femur, it places additional strain on the knee joint's ligaments [6, 18].

2.3 | Participants

Nine male subjects [26.1 years (5.6 years), 180.2 cm (6.1 cm), and 99.7 kg (27.6 kg)] without any prior expertise in roofing participated in this study. No individual had any known neurological or MSD conditions. The research protocol was approved by the Institutional Review Board (IRB) of the National Institute for Occupational Safety and Health (NIOSH). Before participating in the research, the participants read and filled out an informed consent document.

2.4 | Instruments

This study used an optical motion capture system featuring 14 MX cameras – VICON (Oxford, UK) to collect endpoint data of the participants. A total of 42 retroreflective markers were affixed to the lower extremities of the participants, including their feet, heels, toes, ankles, shanks, knee joints, thighs, and hip joints. The three-dimensional (3D) coordinates acquired from these markers were utilized for computing knee angles. The kinematic data were recorded at a rate of 100 Hz.

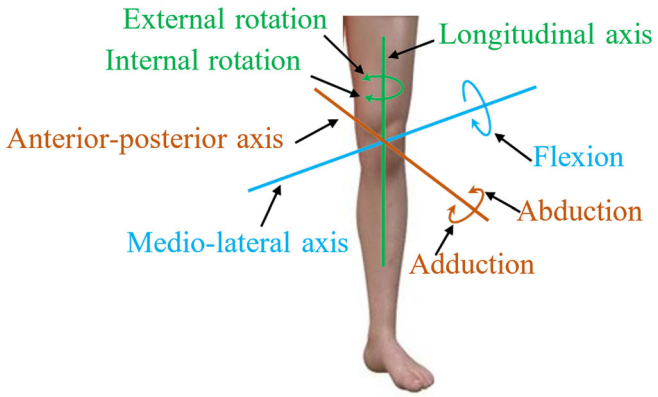

FIGURE 2 | Knee motion measured in rotations in three axes.

A custom-built wooden platform (as illustrated in Figure 3) measuring 1.2 by 1.6 m was employed to replicate the surface of a roof during shingle installation. This platform could be adjusted using a battery-powered lift, allowing for slope angles to be set anywhere between 0° and over 30° with the assistance of two sets of wooden support legs.

2.5 | Procedure

The experiment was performed in NIOSH's biomechanics lab. Participants were fitted with motion markers for kinematic calibration and data collection when they arrived at the lab. Before data collection began, participants were positioned to kneel on the roof simulator in an upright position. When told to start, participants first reached for two shingles and placed them in front of themselves. Then, they took up the nail gun from their right side and acted out inserting six nails—three into each of the two shingles—one on each side, starting from the left and working their way to the right. The participants then placed the nail gun at its starting location and returned to their starting/resting positions. The participants completed the shingle installation assignment in seven phases as a single continuous action. Each participant completed the simulated shingle installation task on the roof simulator at three different slope angles (Figure 3)—0°, 15°, and 30° under four different intervention conditions—no wearable assist device (NO), knee pads only (KP), knee savers only (KS), and both knee pads and knee savers (BO), leading to 12 combinations. For each combination, five trials were recorded.

2.6 | Data Processing

The knee motions in three axial rotations (i.e., flex/extension, ad/abduction, and in/external rotation) were obtained in Visual 3D version 6 by applying the method described using the coordinates of the recorded markers [19]. Using these data, the maximum values of knee rotation angles were computed, resulting in 315 (9 subjects × 5 trials × 7 phases) data points for each knee rotation angle in a specific knee under each combination of slope and intervention conditions.

2.7 | Data Analysis

A descriptive analysis was performed to determine to what extent the interventions led to the MSD risk reduction. A two-way repeated measure analysis of variance (ANOVA) was used to examine the kinematics: 4 (intervention) × 3 (slope). The Mauchly's test of Sphericity was utilized to find out the sphericity of the data. There was no need for a correction if Mauchly's test revealed that the data were spheric. In cases that sphericity was violated as indicated by Mauchly's Test, significance was assessed using the Greenhouse–Geisser correction if epsilon was less than 0.75 and the Huynh–Feldt correction if epsilon was larger than 0.75. To identify

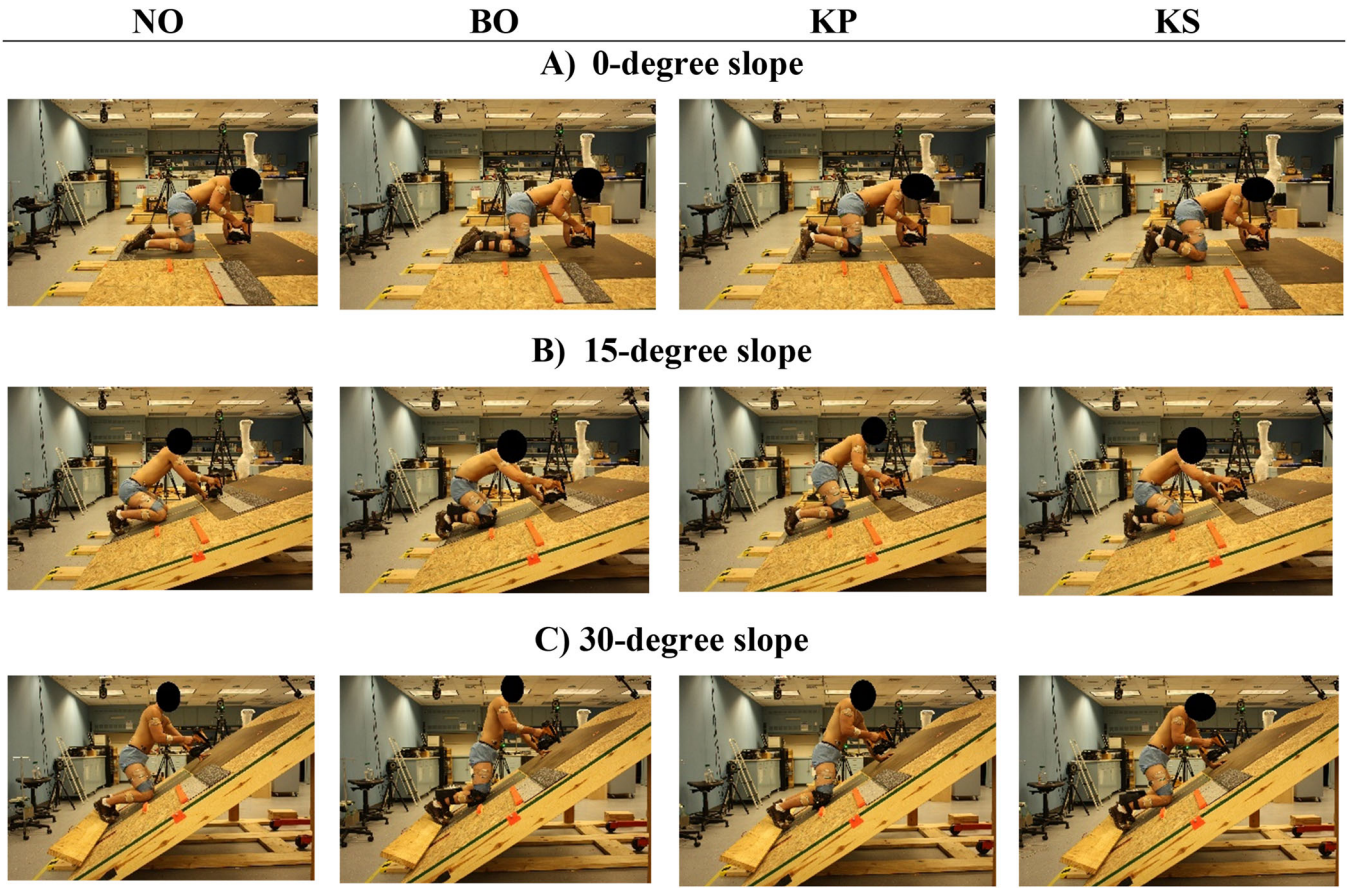

FIGURE 3 | Illustration of roof simulator and a subject moving to first nailing position under four intervention conditions (NO, BO, KP, KS) on each of three slopes of (A) 0°, (B) 15°, and (C) 30°.

particular changes between conditions, post hoc pairwise comparisons were employed. Data analysis was completed using SPSS v22 (IBM Corp. Armonk, NY), and *p*-values were set to 0.05.

3 | Results

3.1 | Relative Effects of Interventions Across Phases

Mean and standard deviation values of each knee rotational angle under all intervention conditions across seven phases at each roof slope for both knees were plotted in Figures 4–8. The colors of the bars represent different intervention conditions as labeled. The error bars represent standard deviations. The percentage number shows the effect of each intervention relative to the NO (no intervention) condition, as calculated by (mean maximum angle of NO – mean maximum angle of intervention)/mean maximum angle of NO. The "*" symbol indicates statistical significance in comparing an intervention with the NO condition based on the two-sample *t*-test.

For both knees at 0° slope, the analysis indicates that the KS intervention achieved statistical significance in P7. The BO intervention reached a maximal effect of 5% in P6 in left knee when compared with NO condition.

For both knees at 15° slope, the KP intervention showed a statistical difference in P3 and P4 compared to the NO condition. The maximum effect compared to NO condition was observed in the KP condition in P6 for the left knee which is 13%.

For both knees at 30° slope, all three intervention conditions showed a statistical difference in P1 compared to the NO condition. The KP intervention conditions in P3 and P4 were statistically significant for both knees. Under the KP condition in P6 for both knees, it was observed a highest value of 20% as compared to the NO condition across seven phases.

Across all three slope conditions, P6 (replacing nail gun) received the maximum effects in comparison to other phases under the intervention conditions.

3.1.1 | Maximum Ext/Flexion

Figure 4 shows relative effects of the interventions across seven phases at each slope for both knees, as indicated by the maximum flexion angles.

3.1.2 | Maximum Ab/Adduction

Figure 5 shows the relative effects of the interventions across seven phases at each slope for both knees, as indicated by the maximum abduction angles.

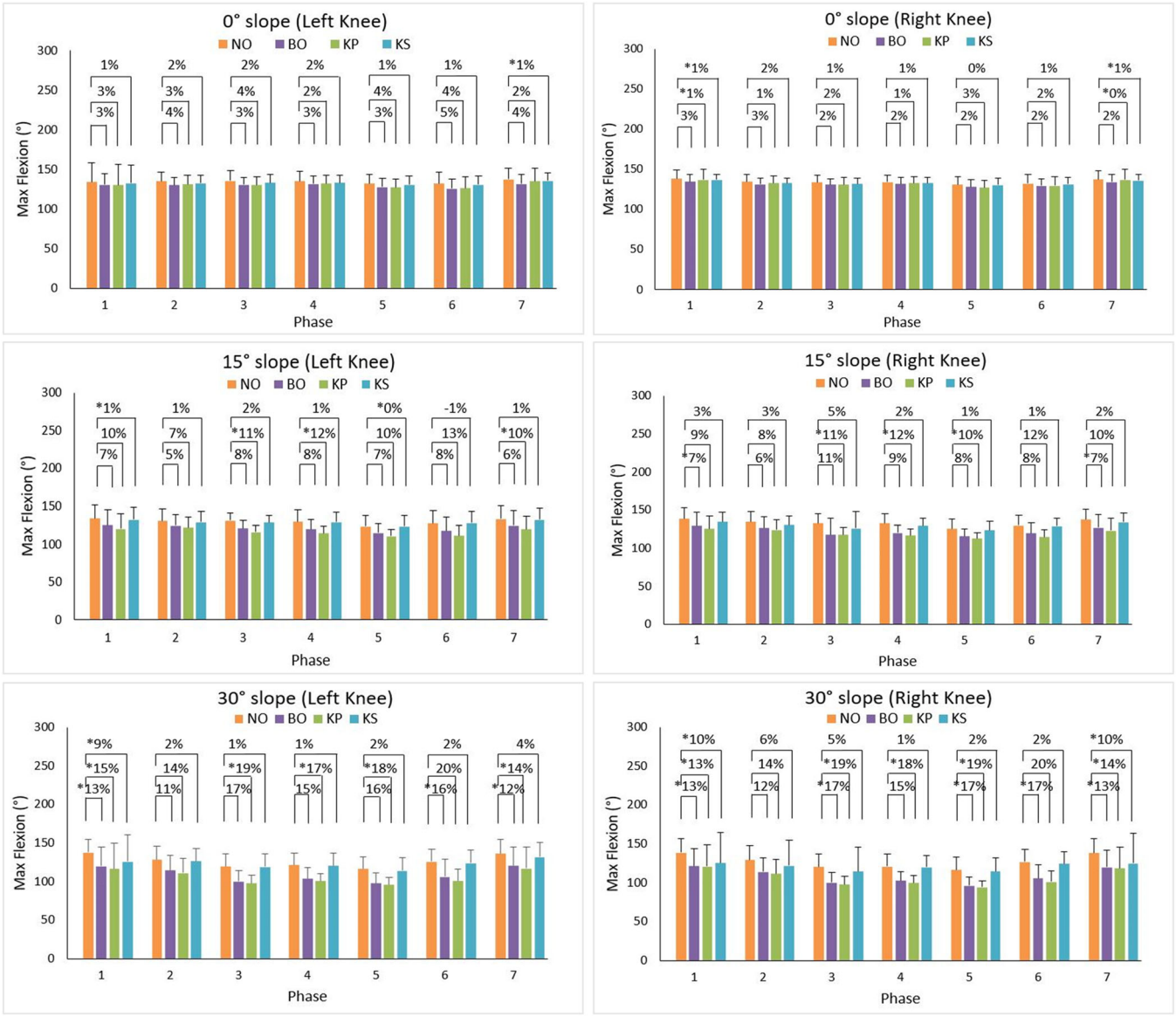

FIGURE 4 | Relative effects of interventions indicated by maximum flexion angles.

For the left knee at 0° slope, the analysis indicates that BO and KP interventions achieved statistical significance in P1 and P6. For the right knee at 0° slope, the analysis indicates that KP and KS interventions achieved statistical significance in P3 and P4. Additionally, the BO and KP interventions reached a maximal value of 100% in P5 in the right knee when compared with NO condition.

For right knee at 15° slope, all three interventions showed a statistical difference from P1 to P7 compared to NO condition. A maximum value was observed in P4 for right knee in KS intervention condition compared to NO condition which is 38%.

For both knees at 30° slope, the KP intervention showed a statistical difference in P1, P3 and P7 compared to the NO condition. The KP intervention in P5 of the right knee shows a peak value of 97% compared to the NO condition.

Figure 6 shows the relative effects of the interventions across seven phases at each slope for both knees, as indicated by the maximum adduction angles.

For the right knee at 0° slope, the analysis indicates that all three interventions achieved statistical significance in P1, P3, and P4. The KS intervention reached a maximal value of 60% in P7 in the right knee when compared with NO condition.

For the left knee at 15° slope, all three interventions showed a statistical difference in P2, P3, P4, and P7 compared to NO condition. For right knee at 15° slope, all three interventions showed a statistical difference in P1, P3, P4, P5, and P7 compared to NO condition. A maximum value of 114% was observed in P1 for the left knee in BO intervention condition compared to NO condition.

For the left knee at 30° slope, all three interventions showed a statistical difference in all phases except P1 compared to the NO condition. For the right knee at a 30° slope, all three interventions showed a statistical difference in P1, P4, P5, and P7 compared to the NO condition. The BO condition in P6 of the right knee shows a peak value of 168% compared to the NO condition.

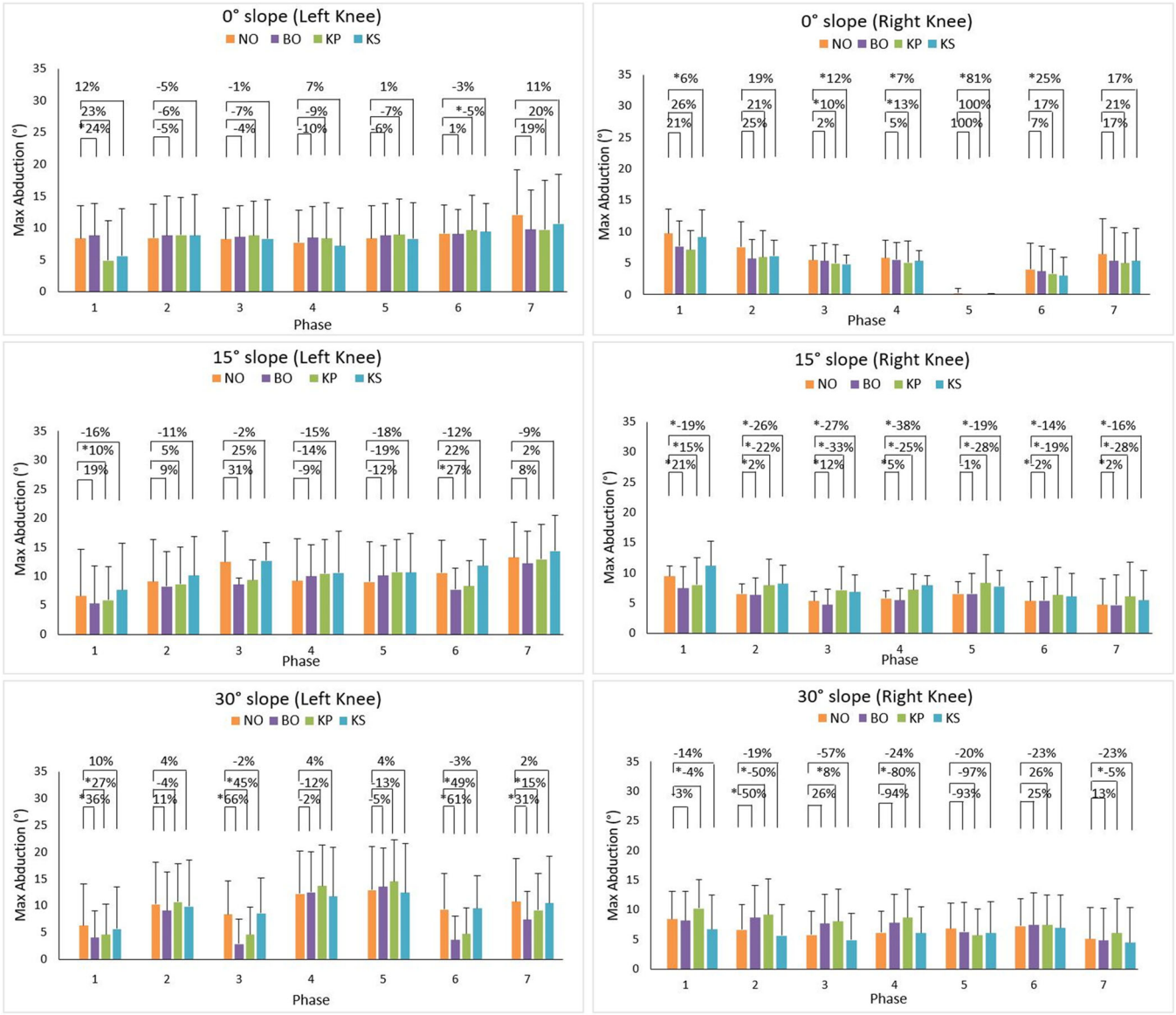

FIGURE 5 | Relative effects of interventions indicated by maximum abduction angles.

3.1.3 | Maximum Int/External Rotation

Figure 7 shows the relative effects of the interventions across seven phases at each slope for both knees, as indicated by the maximum internal rotation angles.

For left knee at 0° slope, the analysis indicates that all three intervention conditions achieved statistical significance in P1. The BO and KS interventions exhibits a maximal value of 73% in P1 and P3 in left knee when compared with NO condition.

For left knee at 15° slope, all three intervention conditions showed a statistical difference in P1, P2, P4, and P5 compared to the NO condition. The KP intervention exhibits a maximum value of 68% in P6 in both knees compared to NO condition.

For left knee at 30° slope, all three intervention conditions showed a statistical difference in P1 to P7 except P2 compared with the NO condition. For the right knee at 30° slope, all three intervention conditions showed a statistical difference in P2, P3, and P4. The BO condition in P3 of both knees showed a peak value of 96% compared to the NO condition.

Figure 8 shows the relative effects of the interventions across seven phases at each slope for both knees, as indicated by the maximum external rotation angles.

For both knees at 0° slope, the analysis indicates that the BO intervention condition achieved statistical significance in P4. The BO intervention yielded a maximal value of 108% in P4 in the right knee when compared with NO condition.

For left knee at 15° slope, all three intervention conditions showed a statistical difference in P3 compared to the NO condition. The KP intervention condition exhibited a maximal

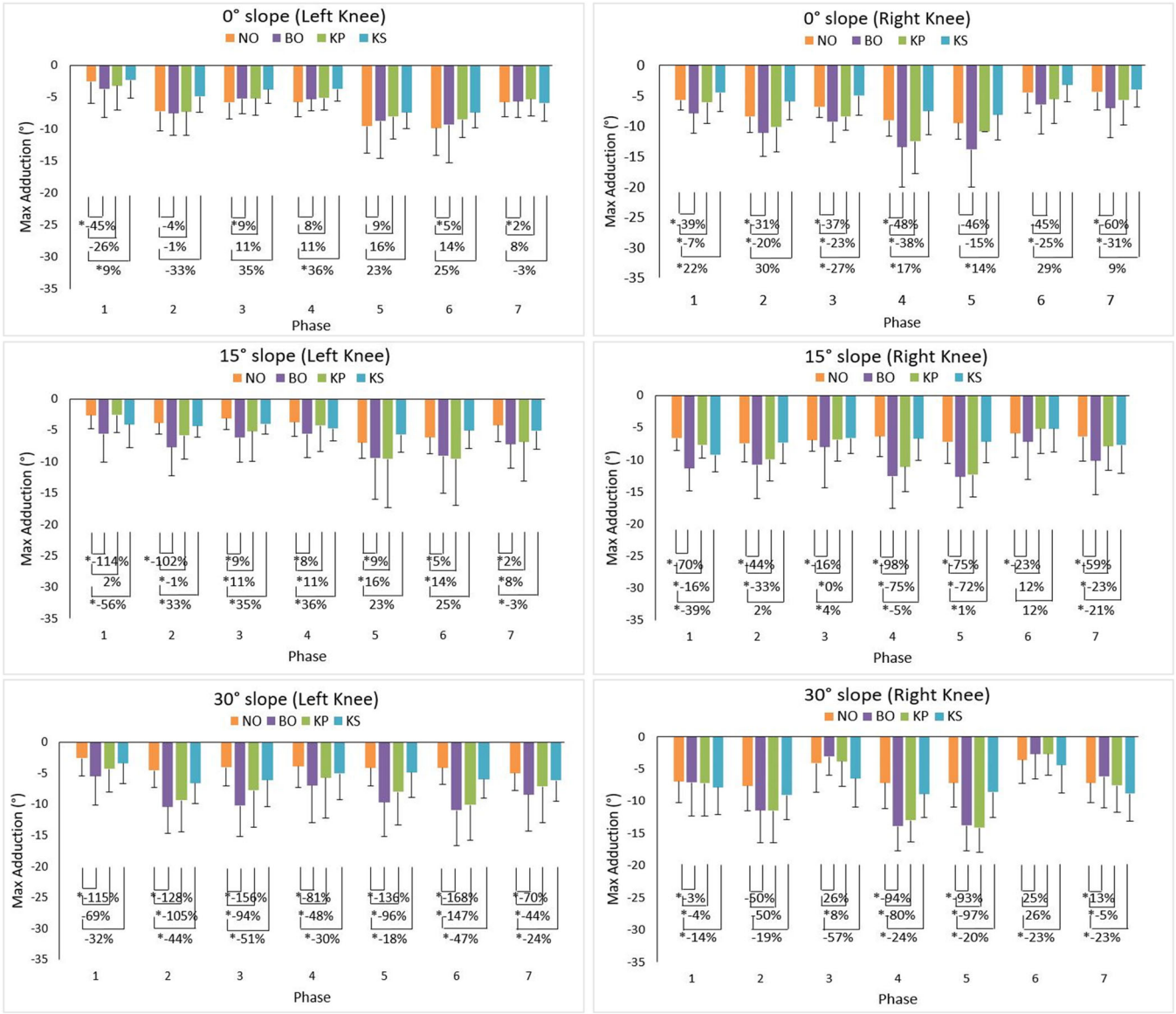

FIGURE 6 | Relative effects of interventions indicated by maximum adduction angles.

value of 86% in P3 in both knees when compared to NO condition.

For right knee at 30° slope, all three intervention conditions showed a statistical difference in P4, P5 and P7 compared with the NO condition. The BO condition in P7 for both knees showed a peak value of 87% compared to the NO condition.

3.2 | Statistical Effects of Slope, Intervention, and Their Interaction

Tables 1 and 2 show the *p*-values obtained from the repeated measure ANOVA test, which indicate the statistically significant effects of the roof slope, intervention, and their interaction on five knee rotation angles in seven phases for the left knee and right knee, respectively. A *p*-value less than 0.05 is considered statistically significant and bolded in Tables 1 and 2.

3.2.1 | Effects of Roof Slope

The analysis of knee rotation angles in relation to roof slope from Tables 1 and 2 reveals significant trends in most conditions. In particular, a consistent and significant slope effect was observed for the flexion angle across all phases for both knees.

Table 3 shows the result of pairwise comparisons by post hoc test to determine significant differences between slope groups. In Table 3, there are significant differences in maximum knee flexion angles between three slopes in all phases, except P1 and 15°–30° in P7 for the left knee and slope 0°–15° in P1 and P2, and 15°–30° in P7 for the right knee. There are significant differences observed for other angles (maximum abduction, maximum adduction, maximum internal rotation, and maximum external rotation) in comparing three slopes. Insignificant differences were observed between three slopes

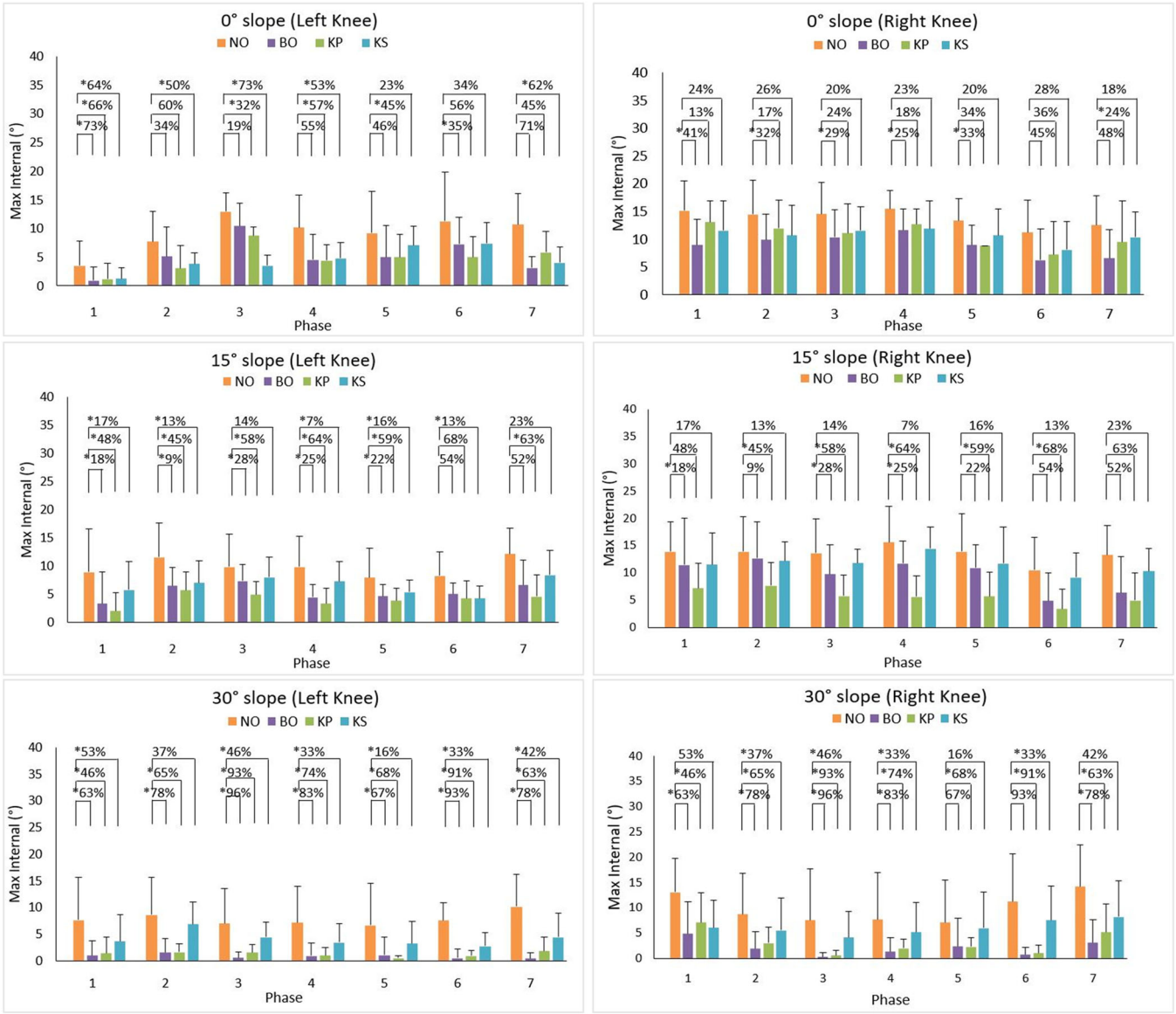

FIGURE 7 | Relative effects of interventions indicated by maximum internal rotation angles.

in P1's maximum abduction angle, P7's maximum adduction angle, and P2's and P6's maximum external rotation angle for both knees.

3.2.2 | Effects of Intervention

Based on the results in Tables 1 and 2, when knee rotation angles were analyzed in relation to intervention, significant trends were seen in most cases. In particular, a consistent and significant effect was observed for the flexion and external rotation angles across all phases for both knees.

Table 4 shows the result of pairwise comparisons by post hoc test to determine specific differences between intervention groups. The analysis revealed significant differences for most intervention comparisons across all knee rotation angles in all phases for the right knee. However, for the left knee, P1's, P2's, P4's, and P5's the maximum abduction angle and P3's maximum internal rotation showed no statistical difference between intervention conditions.

3.2.3 | Interaction Effects of Roof Slope and Intervention

In Tables 1 and 2, significant interaction effects were noted in seven phases for flexion for both knees. From Table 1, for abduction, interaction effects are significant in P4, P5, and P7, but not in other phases. Adduction and internal rotation exhibit significant interaction efforts in certain phases, while external rotation demonstrates a significant interaction effect only in P2. These findings suggest that the combined effects of slope and intervention are not uniformly distributed across all angles and phases. From Table 2, except P2, all phases showed significant interaction effects. Adduction and external rotation exhibit significant

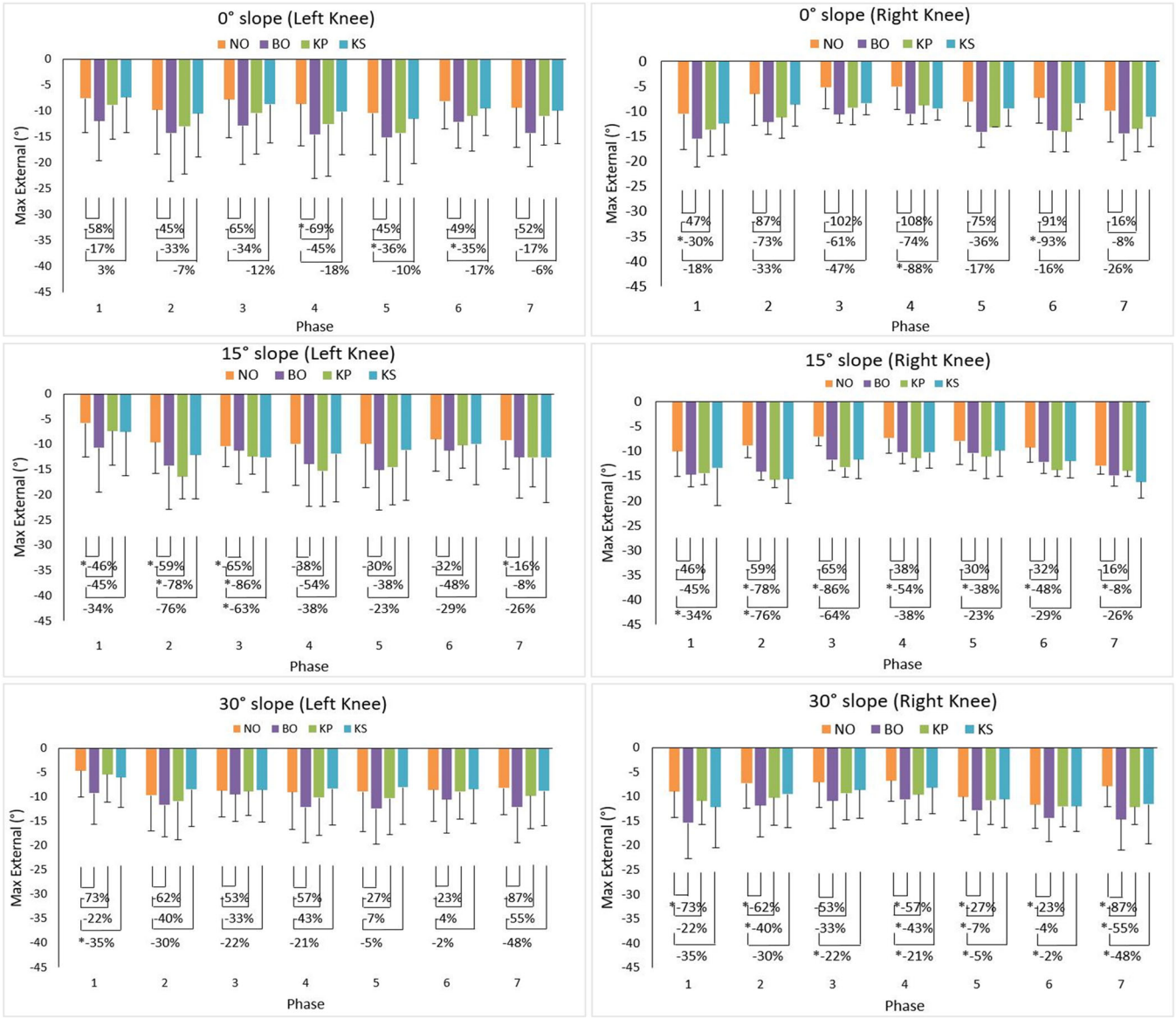

FIGURE 8 | Relative effects of interventions indicated by maximum external rotation angles.

interaction efforts in certain phases, while internal rotation demonstrates no significant interaction effect in any phase.

4 | Discussion

This study conducted a phase-level assessment under various slope conditions and interventions. The knee angle variations that occurred during the shingle installation task are illustrated in Figures 4–8. The highest value with statistically significant differences was observed in several slopes and phases when the relative effects of the intervention were tested. For example, for the maximum adduction angle at 30° slope in P6 under BO condition for the right knee, a statistically significant peak value of 168% was observed. However, a few conditions associated with peak values did not show a statistical significance (e.g., abduction at 30° slope in P5 under KP condition for right knee: 97%). This might be because the high fluctuations of standard deviation exist in two samples so even with high mean difference, two samples may not be significantly different. Overall, with the aid of interventions, knee angles were significantly altered in most of the phases, especially in P5 (nailing shingles) and P6 (replacing the nail gun). The result also suggested the positive impacts of the interventions across the phases.

To assess the impact of interventions on roofers' dynamic postures during the shingle installation, two factors—slope and intervention—were examined. From the result of the repeated measure ANOVA, it was observed that for both knees, slope has impact on maximum flexion angles across all the phases. For abduction, adduction, internal rotation, and external rotation, slope did not show consistent effects. From the pairwise comparisons between slopes, across all the phases for both knees, the maximum flexion angles showed the most significant differences, whereas the maximum external rotation angles

TABLE 1 | The resulting *p*-values for the left knee.

Angle	Independent variable	P1	P2	P3	P4	P5	P6	P7
Flexion	Slope	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
	Intervention	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
	Interaction	**0.025**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Abduction	Slope	0.343	**< 0.001**	0.486	**< 0.001**	**< 0.001**	0.73	**0.228**
	Intervention	**< 0.001**	0.233	**< 0.001**	**0.02**	**0.011**	**< 0.001**	**< 0.001**
	Interaction	0.197	0.166	**< 0.001**	**0.045**	**0.024**	**< 0.001**	**< 0.001**
Adduction	Slope	0.056	**0.031**	0.328	0.45	0.315	0.302	**0.031**
	Intervention	**< 0.001**	**0.009**	0.262	0.493	0.158	**0.042**	0.221
	Interaction	0.158	**0.009**	**0.03**	0.178	**< 0.001**	**< 0.001**	0.357
Internal Rotation	Slope	**0.001**	**0.005**	**0.015**	0.799	0.13	0.071	**0.012**
	Intervention	**< 0.001**	**0.012**	0.056	**0.039**	**0.012**	**0.011**	0.061
	Interaction	**0.016**	0.16	0.093	0.19	0.081	0.181	0.346
External Rotation	Slope	**< 0.001**	**0.03**	**0.013**	**0.014**	0.054	0.289	**0.004**
	Intervention	**< 0.001**	**< 0.001**	**0.003**	**< 0.001**	**< 0.001**	**0.003**	**0.003**
	Interaction	0.351	0.169	**0.006**	**0.036**	0.763	0.257	0.351

TABLE 2 | The resulting *p*-values for the right knee.

Angle	Independent variable	P1	P2	P3	P4	P5	P6	P7
Flexion	Slope	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
	Intervention	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
	Interaction	**0.03**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**0.018**
Abduction	Slope	0.97	**0.003**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**0.005**
	Intervention	**< 0.001**	0.077	**0.013**	**0.042**	0.153	**0.002**	0.073
	Interaction	**0.009**	0.06	**0.019**	**0.047**	**0.002**	**< 0.001**	**0.015**
Adduction	Slope	**0.013**	**0.045**	**< 0.001**	0.165	0.084	**0.297**	**< 0.001**
	Intervention	**< 0.001**	**< 0.001**	0.322	**< 0.001**	**< 0.001**	0.114	**0.001**
	Interaction	**0.004**	**0.042**	**0.003**	0.429	0.303	**0.047**	**0.003**
Internal Rotation	Slope	**0.009**	**0.006**	**< 0.001**	**0.015**	0.149	**< 0.001**	**0.003**
	Intervention	**< 0.001**	**0.032**	0.043	**0.042**	0.09	0.09	**0.027**
	Interaction	0.155	0.163	0.194	0.142	0.198	0.212	0.3
External Rotation	Slope	**< 0.001**	**0.004**	**< 0.001**	**< 0.001**	**0.013**	**< 0.001**	**< 0.001**
	Intervention	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**0.001**	**0.003**
	Interaction	0.075	**0.015**	0.07	0.254	**0.035**	**< 0.001**	**0.002**

showed the least significant differences. The assessment results of intervention showed a distinct and substantial influence on the maximum flexion and external rotation angles for both knees across all the phases. Slope and intervention were also found to have an interaction effect on knee flexion across all the phases for both knees.

According to the results in several earlier studies, the addition of a KS intervention lowered the risk of MSDs induced by extreme posture by reducing the peak angle during that condition [13, 20, 21]. This study also showed that inclusion of interventions (KP and KS) reduced the maximum knee angles in all of the sloping conditions in comparison to NO condition, which confirms a positive impact of these interventions for awkward postures encountered by roofers during shingle installation task.

Dutta et al. [9] indicated that both knees were exposed to the highest possible risk of knee MSDs in P2 (placing shingles) and P5 (nailing shingles). Based on the findings of this study, P2 and P5 in the shingle installation process include greater repetition of severe knee movements than other phases. In these phases, the participants had to sustain larger, uncomfortable knee rotations as they leaned forward to pick up the shingles and backward to place and nail them. The findings of this study

TABLE 3 | Pairwise comparisons between slope groups at each phase.

Phase	Slope	Flexion		Abduction		Adduction		Internal rotation		External rotation	
		Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
1	0°–15°							†		†	
	0°–30°		†			†		†		†	†
	15°–30°					†					
2	0°–15°	†			†	†		†			
	0°–30°	†	†	†	†				†		
	15°–30°	†	†	†		†		†	†		
3	0°–15°	†	†				†	†			
	0°–30°	†	†		†	†	†		†	†	
	15°–30°	†	†			†	†	†	†	†	
4	0°–15°	†	†				†	†			
	0°–30°	†	†	†	†				†		
	15°–30°	†	†	†				†	†		
5	0°–15°	†	†	†			†		†		
	0°–30°	†	†	†		†		†	†	†	†
	15°–30°	†	†	†				†	†		
6	0°–15°	†	†		†						
	0°–30°	†	†		†		†	†	†		
	15°–30°	†	†	†			†	†	†		
7	0°–15°	†	†					†			
	0°–30°	†	†		†					†	†
	15°–30°							†			†

†Indicates statistical significance.

confirmed that the inclusion of the interventions would positively impact knee angles in P5.

5 | Limitations

This study has several limitations, which may deserve future extension. First, this study was performed with non-roofers, which is one possible limitation. From the biomechanics standpoint, a distinction between novice and professional roofers are expected. However, this study specifically selected novice roofers to ascertain the risks that individuals with no previous roofing experience faced when encountering a sloped rooftop while installing shingles. Second, this study was carried out in a controlled laboratory setting, potentially limiting generalizability to real-world roofing conditions at workplaces to minimize the possible risk of injury to participants. Third, this study only focused on the risks of lower extremities associated with knees, excluding the effects on the other body parts, such as ankles, arms, and spine, during shingle installation for knee MSD risks. Fourth, roofers' perceptions of using these types of personal protective equipment (PPE) were not studied. As end users and final beneficiaries, roofers' opinions may play a key role in PPE adoption and implementation. Last, the potential unintended consequences of using knee pads and/or knee savers for increasing the risk of falls were not studied.

6 | Conclusions

The study aimed to assess how knee pads/savers interventions and roof slopes influence the severity of knee MSD risks among roofers. By analyzing the specific phases of work, the study revealed the potential of these interventions in reducing knee rotation angles. This reduction is necessary, as it leads to a lower strain on the knees, potentially decreasing the risk of long-term musculoskeletal damage, particularly when roofers are engaged in awkward postures. The phases involving nailing shingles (P5) and replacing the nail gun (P6) were found to benefit the most from these interventions across all roof slopes.

Future work will include professional roofers to study knee MSD risk in shingle installation, and the study will be performed in real work settings. Other body parts such as ankles will also be investigated. The sustained impact of the interventions on MSDs over time will be assessed to provide insights of these interventions' long-term benefits or potential drawbacks. Moreover, understanding roofers' perceptions of using knee pads and knee savers and the potential unintended consequences of using these types of PPE for increasing the risk of falls will be a focal point of future study, as these are two important components for future research-to-practice success of getting companies and workers to consistently and properly use these types of interventions.

TABLE 4 | Pairwise comparisons between intervention groups at each phase.

Phase	Intervention	Flexion		Abduction		Adduction		Internal rotation		External rotation	
		Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
1	NO-BO	†	†			†	†	†	†	†	
	NO-KP	†	†		†		†	†	†		†
	NO-KS		†		†			†	†		
	BO-KP				†	†	†		†	†	†
	BO-KS					†	†	†		†	†
	KP-KS							†	†		
2	NO-BO	†	†			†		†	†		†
	NO-KP	†	†		†			†	†		
	NO-KS		†					†	†		
	BO-KP				†	†	†	†	†		†
	BO-KS	†			†	†	†			†	†
	KP-KS	†						†	†		
3	NO-BO	†	†	†		†		†	†		†
	NO-KP	†	†	†	†		†	†	†		
	NO-KS						†	†	†		
	BO-KP				†	†	†	†	†		†
	BO-KS	†	†			†					†
	KP-KS	†	†	†				†	†		
4	NO-BO	†	†				†	†	†	†	†
	NO-KP	†	†		†			†	†		
	NO-KS							†			
	BO-KP	†			†	†	†	†	†		†
	BO-KS	†	†			†	†			†	†
	KP-KS	†	†				†	†	†		
5	NO-BO	†	†			†	†	†	†	†	†
	NO-KP	†	†		†			†	†		
	NO-KS							†	†		
	BO-KP					†	†	†	†		†
	BO-KS	†	†			†	†			†	†
	KP-KS	†	†					†	†		
6	NO-BO	†	†			†		†	†	†	†
	NO-KP	†	†	†	†		†	†	†		
	NO-KS							†	†		
	BO-KP				†	†	†	†	†	†	†
	BO-KS	†	†			†				†	†
	KP-KS	†	†	†	†			†	†		
7	NO-BO	†	†		†	†		†	†	†	
	NO-KP	†	†	†	†			†	†		
	NO-KS		†		†			†	†		
	BO-KP					†	†			†	†
	BO-KS	†				†	†	†		†	†
	KP-KS	†						†	†		

† Indicates statistical significance.

Author Contributions

Nazia Zerin: methodology, data analysis, writing–original draft preparation. S**cott P. Breloff, Fei Dai, John Z. Wu:** conceptualization, methodology, writing–review and editing. **Robert E. Carey, Christopher M. Warren, Kevin D. Moore, Ashley L. Hawke, Erik W. Sinsel:** data acquisition and cleaning. All authors have read and agreed to the published version of the manuscript.

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Disclosure

The authors have nothing to report.

Ethics Statement

NIOSH's Institutional Review Board (IRB) approved the research protocol.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request.

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