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Kneeling trunk kinematics during simulated sloped roof shingle installation

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Abstract

Trunk musculoskeletal disorders are common among residential roofers. Addressing this problem requires a better understanding of the movements required to complete working tasks, such as affixing shingles on a sloped residential roof. We analyzed the extent to which the trunk kinematics during a shingling process are altered due to different angles of roof slope. Eight male subjects completed a kneeling shingle installation process on three differently sloped roof surfaces. The magnitude of the trunk kinematics was significantly influenced by both slope and task phase of the shingling process, depending on the metric. The results unequivocally point to roof slope and task phase as significant factors altering trunk kinematics. However, extension of the results to roofing workers should be done carefully, depending on the degree to which the study protocol represents the natural setting. Future studies on shingle installation in residential roofing should absolutely consider capturing a wider array of shingling procedures in order to encapsulate all the possible methods that are used due to the lack of a standardized procedure.

Keywords

Roofing; Trunk kinematics; Kneeling; Musculoskeletal disorders

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CRediT authorship contribution statement

Scott P. Breloff: Conceptualization, Methodology, Validation, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Robert E. Carey:** Data curation, Investigation, Writing - review & editing, Visualization, Software. **Amrita Dutta:** Writing - review & editing. **Erik W. Sinsel:** Data curation, Writing - review & editing, Software, Investigation, Validation. **Christopher M. Warren:** Investigation, Writing - review & editing. **Fei Dai:** Writing - review & editing, Conceptualization. **John Z. Wu:** Investigation, Conceptualization, Writing - review & editing, Supervision.

Declaration of competing interest

Myself or my co-authors do not have a conflict of interest with the data presented in this manuscript.

1. Introduction

Residential roofers have a particularly high injury rate, at 280.2 per 10,000 workers (BLS, 2017); in some years up to 27% of those injuries are classified as musculoskeletal disorders (MSDs) leading to the roofing trade having the 2nd highest incident rate of work-related MSDs among all construction sectors (BLS, 2013). The Bureau of Labor Statistics (BLS) stated there were roughly 128,000 roofing contractors in 2018 (BLS, 2019). The BLS also estimates that the job growth will be around 11% between 2016 and 2026, suggesting that by 2026 there could be over 209,000 roofing contractors (BLS, 2019). From 2013 to 2016, the occurrence of MSDs in the roofing industry has more than doubled from 340 to 850 reported cases per year (CPWR, 2018), resulting in a median of 10 days away from work in 2016 (BLS, 2017). According to Liberty Mutual (Mutual, 2018), the costs for repetitive motion related injuries reached as high as $1.81 billion in 2017. As a result, the cost of injury and illness for roofers is extremely high (Leigh et al., 2004; Welch et al., 2010). For example, the insurance rates for roof work are nearly three times as high as the average rate of all construction trades in the state of Washington (Washington_DL&I 2015) and more than three times of the average rate of all trades in the state of Ohio (Ohio_BWC, 2015). With the expected increases in risks and costs associated with predicted roofing industry growth, reducing MSD injury risk in roofing workers is increasingly important.

Over 90% of roofers work on residential projects, which usually have pitched roof surfaces that typically range from 10° to 26°, but can be as steep as 45° (BLS, 2015). Additionally, roofers are required to bend and twist their bodies frequently in a kneeling, crouching, stooping or crawling position for up to 75% of their work time. When combined with excessive loading, these postures may contribute to the development of MSDs (CPWR, 2018). Due to the sloped surface and awkward posture job requirements during roofing, there is an abundance of low back and lower extremity disorders among roofers and floorers (Holmstrom and Engholm, 2003). This is further evidenced by the CPWR report that the back injury rate among roofers is greater than the construction sector average (CPWR, 2018). Workers who experienced back pain in more physically demanding work settings and in awkward postures were 300% more likely to retire prematurely than those involved in less physically challenging work (Welch et al., 2010).

Kneeling trunk kinematics and their association with back pain have been studied in various occupations such as airport/aircraft baggage handlers (Koblauch, 1996; Splittstoesser et al., 2007; Wahlstrom et al., 2016), floor layers (Jensen et al., 2010), coal miners (Moore et al., 2012) and in general restricted conditions (Gallagher and Unger, 1990). Often manual material handling (MMH) is associated with several jobs that require kneeling: e.g., airport/aircraft baggage handlers (Splittstoesser et al., 2007) and roofers (Zhou et al., 2015). In single installation operations, roofers are required not only to perform physically demanding MMH, but also operate a pneumatic nail gun, which can weigh approximately 6 pounds (2.72 kg). External forces are expected to influence the biomechanical response in the spine (Council, 2001). Although MMH of heavier objects is considered a main factor affecting the spine (Splittstoesser et al., 2007; Zhou et al., 2015), the use of a relatively light tools may also effectively influence the trunk biomechanical response, particularly in a kneeling posture when the tool is far away from the body, creating a large moment arm. Though trunk and lumbar responses on a roofing surface have been reported to alter due to the slope (Hu et al. 2013, 2016), these were in standing postures. No studies have focused on the kinematics of the trunk during a shingle installation process on a sloped surface.

With the projected growth in roofer jobs over the next 10 years and the accompanying increase in medical and insurance costs, it is paramount to make an effort to reduce MSD injury risk in this population. The current study evaluated the variations in trunk kinematics due to different surface pitches during a shingle installation process. It is hypothesized that shingling on a sloped surface, compared to a level surface, will induce substantial changes in trunk kinematics.

2. Methods

Eight male healthy subjects (age: 27.6 ± 5.9 years, height: 181.0 ± 6.6 cm, weight: 89.5 ± 9.8 kg) with no roofing experience participated in the study. Given that 97% of roofers are male (BLS, 2018), all subjects tested were male. Subjects did not have diagnosed musculoskeletal or neurological disorders—such as stroke or head trauma, Parkinson’s disease, diabetic neuropathy, dementia, or visual impairment uncorrectable by lenses—which would influence the outcome of the study. The protocol was approved by the National Institute for Occupational Safety & Health’s (NIOSH) Institutional Review Board (IRB), and subjects read and completed informed consent.

Subjects came to the NIOSH biomechanics laboratory for one testing day and were outfitted with eighty-two 9 mm diameter retro-reflective motion capture markers (Fig. 1A). Kinematic data were collected using 14 Vicon MX cameras (Vicon Inc., Oxford, England) at a sampling rate of 100 Hz. Trajectory data were filtered in Visual 3D (C-Motion, Germantown, Maryland), using a lowpass 4th order Butterworth filter with a 6 Hz cut off. Recorded kinematic marker data were then modeled using Visual3D to obtain three degrees of freedom trunk joint angles (flexion/extension, left/right lateral bending, left/right axial rotation). Trunk joint angles (Fig. 1B & 1C) were defined as the changes relative to the position between the two joint segments: back (created with the left and right shoulder and S1markers) and pelvis (created using the left and right anterior and posterior iliac spine markers). The trunk joint was meant to represent the 5th lumbar and 1st sacral (L5/S1) joint which has been commonly associated as a problem area for back pain (Schwarzer et al., 1995a,b; Kalichman et al., 2008).

No standard operating procedure exists for shingle installation on a sloped roof surface, although it is generally accepted that most individuals kneel in some manner during the shingle installation process. In the current study the shingle installation process was segmented into four distinct task phases: (1) “placing” beginning from an upright deep flexion kneeling posture, (2) “preparing” the subjects pick up and position a pneumatic nail gun over the placed shingles, (3) “nailing” the subjects use the nail gun to mimic affixing the shingles to the simulated roof surface, and (4) “returning” subjects returned the nail gun to its original position and resumed to the starting upright kneeling posture (Fig. 2). The four phases of the shingling process were completed in numerical order (1–4) by all subjects during data recording. Subjects completed five separate trials (phases 1-4) of the simulated shingling process, and for each trial, the peak angle for each degree of freedom was found within each task phase. Each trial consisted of all four phases of the shingling process to be completed once. This required the subjects to place the shingles, grab the nail gun, affix the shingles then return the nail gun. After the subjects had returned to the upright kneeling position, data collection would stop, and a researcher would return the shingles to the starting location on the right side of the subject prior to the next trial (Fig. 2). There were not rigid locations for the placement of the shingles, or the nail gun given by the researchers to the subjects. The shingles were meant to be placed in front of the subject as so they could mimic comfortably affix the shingles to the roof surface. The gun was to be placed to the right of the subjects at a comfortable distance so it could be easily grabbed and replaced. The simulated shingling method conducted on a roofer simulator (Figs. 3 and 4), which can be positioned at three different slopes (0°, 15°, and 30°). The simulated shingling procedure was repeated at each of these slopes.

Outcome measures for the current study were the three-dimensional (sagittal, frontal, and transverse) L5/S1 trunk angles, during each of the four phases and for each of the three combinations of roof angle. Data analysis was completed using SPSS v25 (IBM Corp. Armonk, NY) and *p*-values were set to 0.05. The kinematics were analyzed using three (one for each cardinal body plane) two-way—4 (shingling phase) X 3 (slope)—repeated measure analysis of variance (ANOVA). Mauchly's Test of Sphericity was used to determine the sphericity of the data. If Mauchly's Test showed the data were spherical, then no correction was needed. Fisher's least significant difference (LSD) post-hoc pairwise comparisons were used to determine specific differences between conditions. If Mauchly's Test indicated sphericity was violated, the Greenhouse-Geisser correction was used if epsilon was less than 0.75, and if epsilon was greater than 0.75 the Huyhn-Feldt correction was used to determine significance.

3. Results

As hypothesized, shingling on a sloped surface compared to a level surface extensively altered 3D trunk kinematics. The results comparing shingling on a level surface compared to a sloped surface are summarized in Fig. 5.

3.1. Sagittal plane

Peak trunk flexion angles did have a significant interaction between task phase and roof slope ($p \le 0.001$). Significant main effects for task phase ($p \le 0.001$) and roof slope ($p \le 0.001$) were also present. Task phase post-hoc pairwise comparisons revealed that phase 1 trunk flexion (75.10°±14.29°) was significantly larger than phase 3 (62.6°±11.02°) and phase 4 (69.99°±13.35°) peak trunk flexion. Phase 2 peak trunk flexion (72.61°±13.66°) was significantly larger than phase 3 peak trunk flexion. Phase 3 peak trunk flexion was significantly smaller than phase 4 peak trunk flexion. Slope post-hoc pairwise comparisons revealed that peak trunk flexion was significantly larger on a slope of 0° (81.07°±11.39°) than on a slope of 15° (68.05°±12.07°) and a slope of 30° (61.10°±15.78°). Peak trunk flexion on a slope of 15° was significantly larger than a slope of 30°.

3.2. Frontal plane

3.2.1. Right lateral bending—Peak trunk right lateral bending angles did have a significant interaction between task phase and roof slope ($p \leq 0.001$). Significant main effects for task phase ($p \leq 0.001$) and roof slope (p=0.003) were also present. Task phase post-hoc pairwise comparisons revealed that phase 1 trunk right lateral bending (20.41° ± 13.27°) was significantly larger than phase 2 (16.53° ± 6.25°) and phase 3 (13.87° ± 11.91°) peak right lateral bending. Phase 2 peak right lateral bending was significantly smaller than phase 4 (23.12° ± 9.90°) peak right lateral bending. Phase 3 peak right lateral bending was significantly smaller than phase 4 peak right lateral bending. Slope post-hoc pairwise comparisons revealed that peak right lateral bending was significantly larger on a slope of 0° (20.72° ± 8.68°) than on a slope of 15° (16.33° ± 10.66°). Peak right lateral bending on a slope of 15° was significantly smaller than a slope of 30° (18.40° ± 11.65°).

3.2.2. Left lateral bending—Peak trunk left lateral bending angles did not have a significant interaction between task phase and roof slope (p=0.164). Significant main effects for phase ($p \leq 0.001$) were present; however main effects for slope were non-significant (p=0.245). Task phase post-hoc pairwise comparisons revealed that phase 1 trunk left lateral bending (11.14° ± 10.97°) was significantly smaller than phase 2 (20.43° ± 12.82°) and phase 3 (20.00° ± 13.32°) but significantly larger than phase 4 (2.10° ± 5.89°) peak left lateral bending. Phase 2 peak left lateral bending was significantly larger than phase 4 peak left lateral bending. Phase 3 peak left lateral bending was significantly larger than phase 4 peak left lateral bending.

3.3. Transverse plane

3.3.1. Right axial rotation—Peak trunk right axial rotation angles did have a significant interaction between task phase and roof slope (p=0.001). Significant main effects for task phase (p=0.011) were present; however main effects for roof slope were non-significant (p=0.086). Task phase post-hoc pairwise comparisons revealed that phase 1 trunk right axial rotation (13.42° ± 11.22°) was significantly larger than phase 3 (10.01° ± 11.57°) and phase 4 (9.71° ± 8.01°) peak right axial rotation.

3.3.2. Left axial rotation—Peak trunk left axial rotation angles did have a significant interaction between task phase and roof slope ($p \leq 0.001$). Significant main effects for phase ($p \leq 0.001$) were present; however main effects for slope were non-significant (p=0.076). Task phase post-hoc pairwise comparisons revealed that phase 1 trunk left axial rotation (16.56° ± 10.88°) was significantly larger than phase 2 (11.55° ± 8.81°), phase 3 (13.81° ± 11.87°) and phase 4 (13.12° ± 12.02°) peak left axial rotation.

4. Discussion

Before this study, it was epidemiologically understood that roofing work leads to low back MSD injuries (Holmstrom and Engholm, 2003; CPWR, 2018). In addition to quantifying the trunk kinematics during a shingling process, the current study also defined different phases within the shingle installation task and found that the different task phases will present different kinematics. Roof slope and task phase had statistically significant influence on the trunk kinematics. The new developments presented in this study enhance the understanding of the trunk kinematics during different phases of the shingling process while kneeling at various slopes. This further understanding may be useful for developing training materials or interventions which may help reduce MSD risk in this working population.

4.1. Slope's specific effect on trunk kinematics

As hypothesized, roof slope did influence the kneeling trunk kinematics. While no other kneeling data existed for direct comparison, it is well established that slope can influence gait kinematics (Sun et al., 1996; Lay et al., 2006; Han et al., 2009; Dixon and Pearsall, 2010; Tulchin et al., 2010; Dixon et al., 2011; Wade et al., 2014; Breloff et al., 2019). In the sagittal plane, as the slope increased, the trunk flexion decreased. This observed change makes sense as the increasing slope will position the work surface closer to the body, and thus an individual will have to flex the trunk less to reach that work surface. One insight from this result is that the decrease in flexion resulting from an increase in slope could reduce MSD risk in the trunk of roofing workers as extreme posture is considered a factor for MSD risk. However, other factors are present such as the reduced normal force and increased shear forces must be considered. In the frontal plane, slope had an effect on right lateral bending. Right lateral bending on the level surface was larger than on the 15° slope; conversely right lateral bending at 30° was larger than at 15°. These results give no clear insight on how slope influences right lateral bending while kneeling and affixing shingles to a roof surface. It can be speculated that the extreme slopes (0° and 30°) incite changes in other kinematics (possibly the lower extremity) that require compensatory changes in the right lateral bending. Slope did not alter the rotational trunk kinematics. This suggests that regardless of the steepness of the sloped roof, the amount of rotation needed to complete the task did not change.

4.2. Phase effect on trunk kinematics

In practice, there are no well-defined and standardized phases for the shingling process. In our study, we selected logically sensible task demarcations for performing statistical comparisons. In the current study the task phase had a significant influence on kneeling trunk kinematics. This is not all that surprising as each phase represents very different body segment movements which need to be completed in order fix a shingle to a roof surface. Interestingly, trunk flexion during phase 3 "nailing"—the subjects would use the nail gun to mimic affixing the shingles to the simulated roof surface—was the smallest compared to the other four phases. This observation suggests the "nailing" of affixing the shingles could present the least risk of developing a MSD in the trunk due to extreme posture. However, the metrics used for analyses were the peak joint angles; thus, the amount of time in an awkward posture was not considered. When considering MSD risk of phases of a work task, this should be considered in future studies. That said, it was an interesting finding that the trunk flexion angle was smallest during the 'work phase' of the shingling process. The smaller trunk angle could imply that the lumbar muscle activation is smaller during this phase (Hu et al., 2016). Right lateral bending during phases 1 and 4 was larger than phases 2 and 3. This might be because the nail gun and the shingles were always placed on the right side of the subjects in this simulated work task. Therefore, the subjects were required to lean to the right in order to first grasp the nail gun and then replace the nail gun at the end of each shingling trial. Although the subjects were right handed, in practice there is no standardized positioning of the nail gun or shingles; nail gun and shingle placement at actual worksites will vary. While the use of a prescribed protocol allowed for the determination that increased bending will occur when grabbing the nail gun or the shingles, the relation to common practice might be limited. Similar conclusions can be drawn from the left lateral bending as well as the axial rotations. Statistically significant differences were observed between the different task phases. These differences may indicate that different phases of the shingling process require different movements, however it has been reported in automobile workers that trunk/back musculoskeletal disorders increase with mild and severe trunk flexion as well as increased lateral bending and axial rotation (Punnett et al., 1991). Thereby solidifying that residential roofers will always have an increased trunk MSD risk due to the nature of their job, but due to the lack of a standardized shingling procedure in the workplace, it may be difficult to directly make recommendations to improve MSD risk during this task that requires kneeling on a sloped surface.

4.3. Interaction of slope and phase

Interaction effects were observed in all but one (left lateral bending) of the measured kinematics which implies that to know how the trunk kinematics are influenced by a sloped roof surface, the pitch (steepness) of the roof must be considered. The three slopes used in this study (0°, 15°, and 30°) represented large changes in the working surface and would likely incite different movements to complete the task. Our results (Fig. 5) show that there is not necessarily a systematic change in trunk kinematics with the changing slope. For example, the left axial rotation increased from 0° to 30° for the first three task phases, but in phase 4, there was a decrease in left axial rotation from 0° to 30°. However, the trunk flexion does follow a very systematic pattern in that as the slope increases from 0° to 30° the amount of trunk flexion decreases among all four phases. Though the authors made choices in the protocol that may have incited phase kinematic changes, the observed interactions between slope and task phase suggest that the pitch of the roof will have a major influence on how the trunk kinematics within each phase will respond during a kneeling shingling process.

4.4. Limitations

One possible limitation in this study is the use of non-roofers as test subjects. The use of novice individuals is acceptable because it allowed for the observation of how extreme postures influence individuals when they first encounter a sloped working environment. Furthermore, this study only used young adult subjects, though working roofers have a larger age range. This is justifiable, as the majority of injuries suffered by roofers are in the age range of 18–24 years (BLS, 2017). Additionally, the task phase definitions were created by the authors, as no standard exists for delineating phases of roof shingling. If the task phases were defined differently, this could have altered the results. Furthermore, this study focused on trunk MSD risk, as the subjects ‘worked’ in three-point postures, MSD risk at the shoulder and arm need to be considered in the future. Finally, the rigidity of the scientific procedure (i.e. the authors choice on where to place the shingles and nail gun) make explicit recommendations difficult at this point. Future research in this area should allow subjects (professional and novice) to go about the shingle installation procedure in their own manner, thus providing a more realistic observation of the shingling process. Some of the study results suggest that certain roof pitches and work phases might increase MSD risk due to extreme trunk postures, however these conclusions can only be drawn during a kneeling posture. A further study will need to determine how trunk kinematics change when shingling installation is completed using a bending posture, rather than a kneeling posture.

5. Conclusion

The purpose of this study was to determine how trunk kinematics were influenced by the steepness of the sloped roof and the phases of the shingle installation process. It was determined that trunk kinematics are indeed influenced by the steepness of the sloped working surface, and that to truly understand influence of the trunk kinematics during kneeling, the roof slope must be known. While the results indicate that roof slope and task phase do change trunk kinematics, and this has been shown to be associated with musculoskeletal disorders, the extension of the results must be carefully considered due to numerous variations in workplace shingling processes. The authors made procedural decisions that elicited some observed changes in kinematics that might not represent what happens in the work place. Thus, future research may benefit from allowing both novice and professional roofer subjects to use a more extensive assortment of shingling procedures to affix the shingles to the roof surface.

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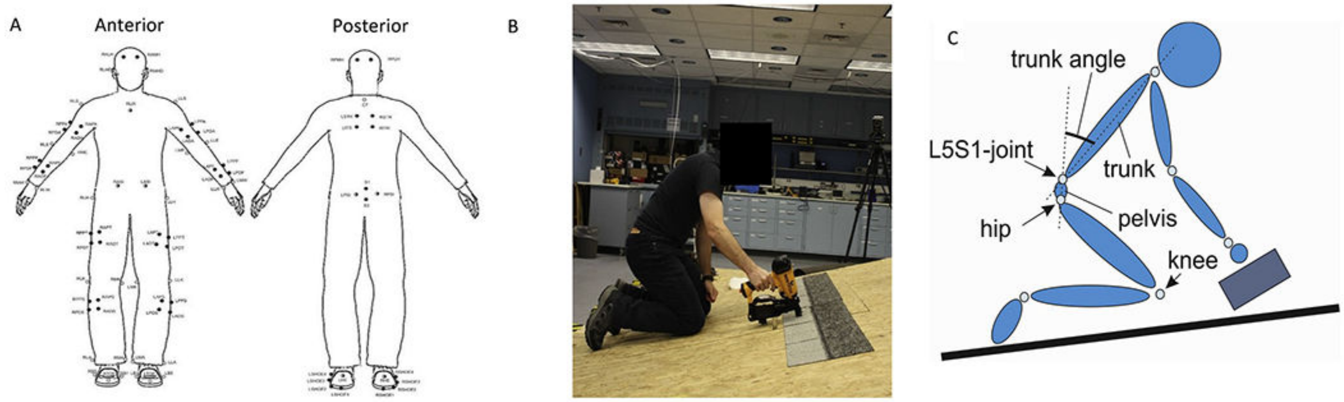

Fig. 1.

A) Retro-reflective marker set utilized for recording human motion. B) Subject affixing shingles to a roofing surface. C) Rigid body model which allowed for the calculation of the trunk angle.

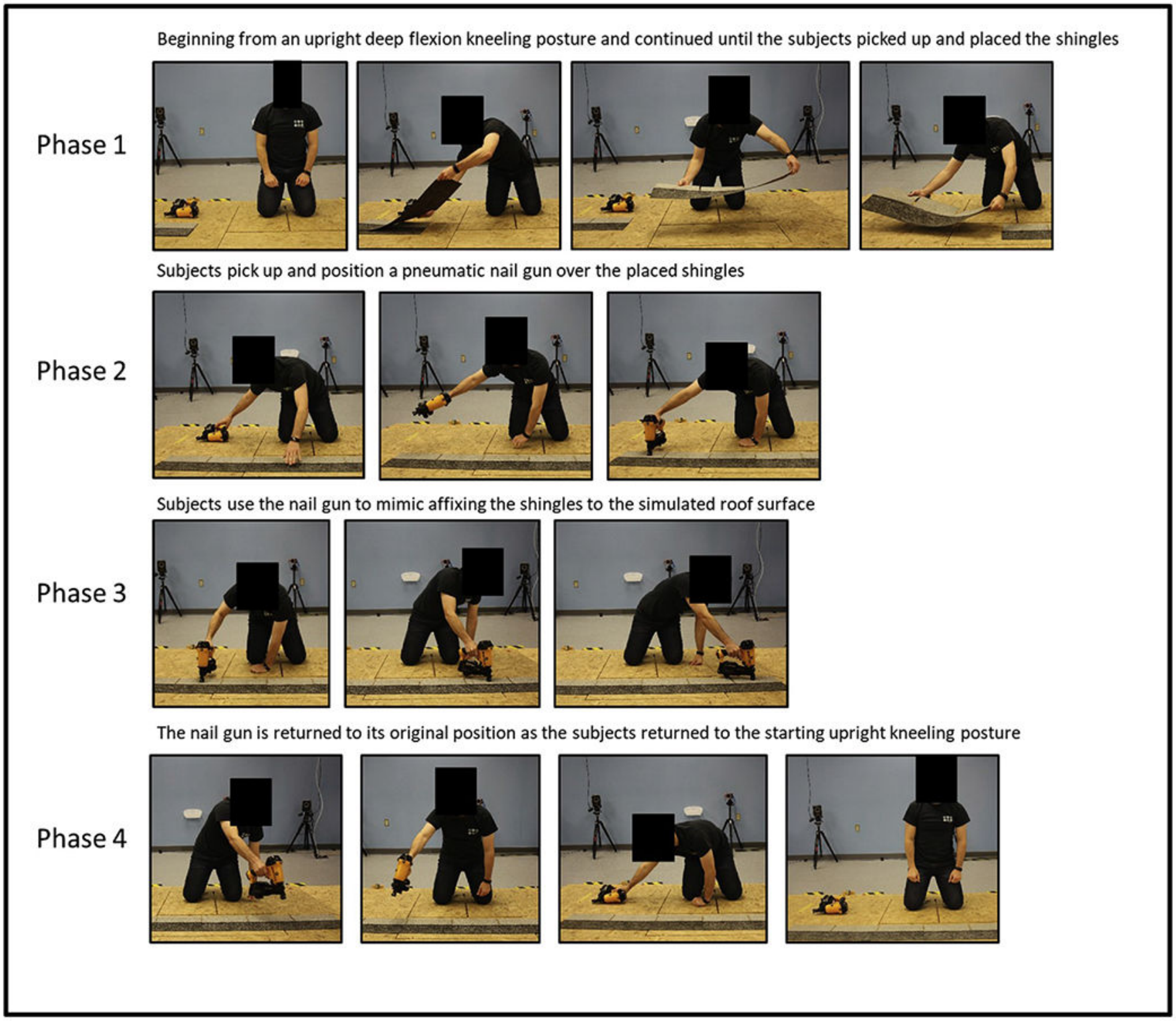

Fig. 2.

Shows subject using a nail gun to affix shingles to the simulated roof with four phases. Phase 1: “placing” beginning from an upright deep flexion kneeling posture. Phase 2: “preparing” the subjects pick up and position a pneumatic nail gun over the placed shingles. Phase 3: “nailing” the subjects use the nail gun to mimic affixing the shingles to the simulated roof surface. Phase 4: “returning” subjects returned the nail gun to its original position and resumed to the starting upright kneeling posture.

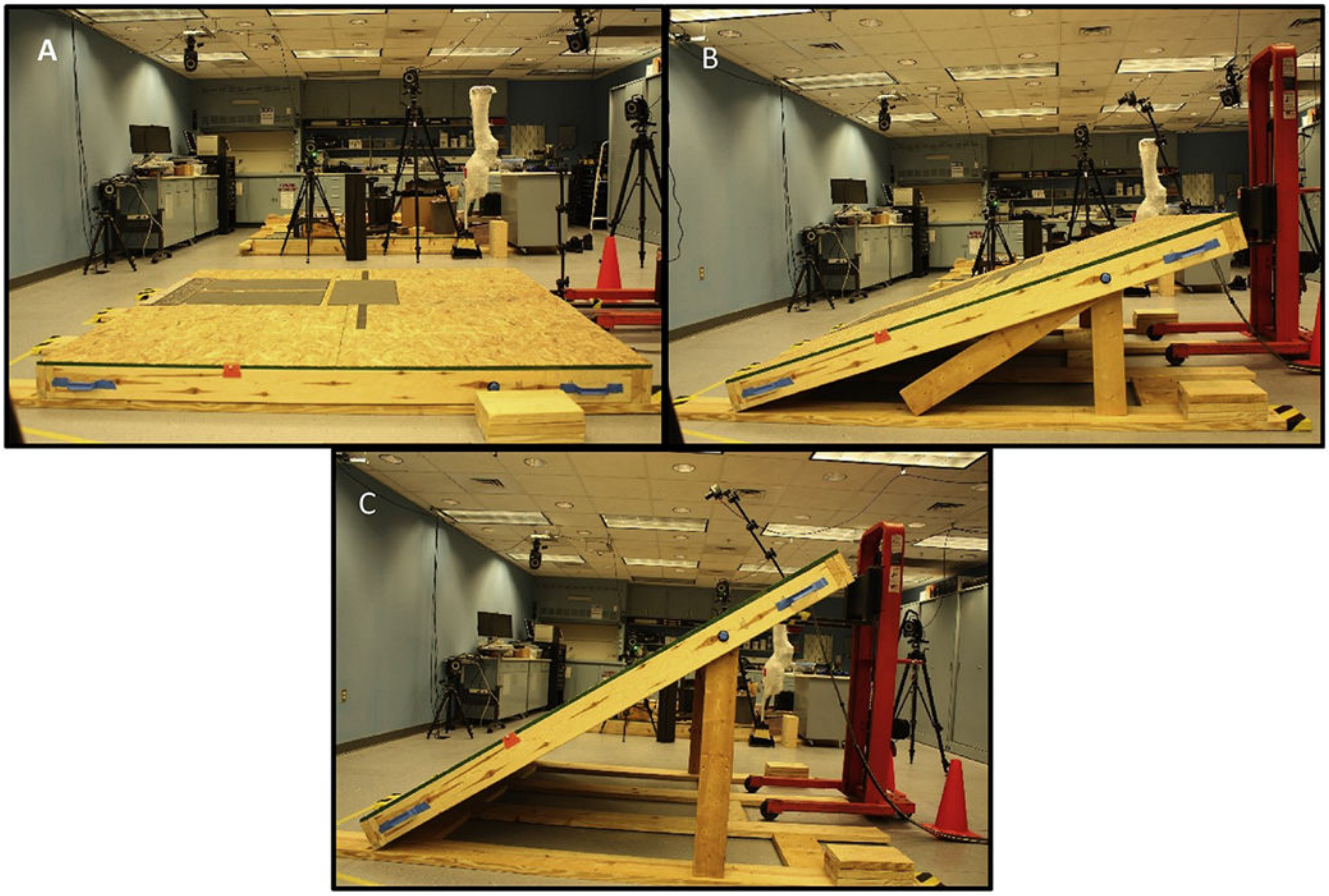

Fig. 3.

Instrumented roofing simulator segment used for the study. The roofing surface can be adjusted from flat O-degrees (A) to 15-degrees (B) and 30-degrees (C) using custom fabricated retractable legs.

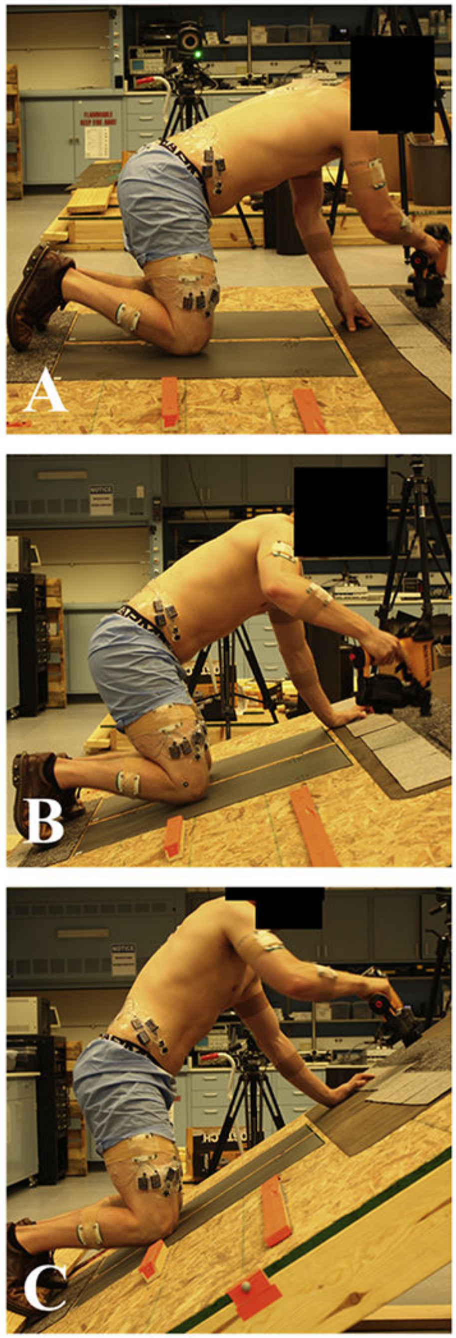

Fig. 4.

Demonstrates a subject during the shingle affixing phase on each of the three slopes angles tested: A) 0°, B) 15°, and C) 30°.

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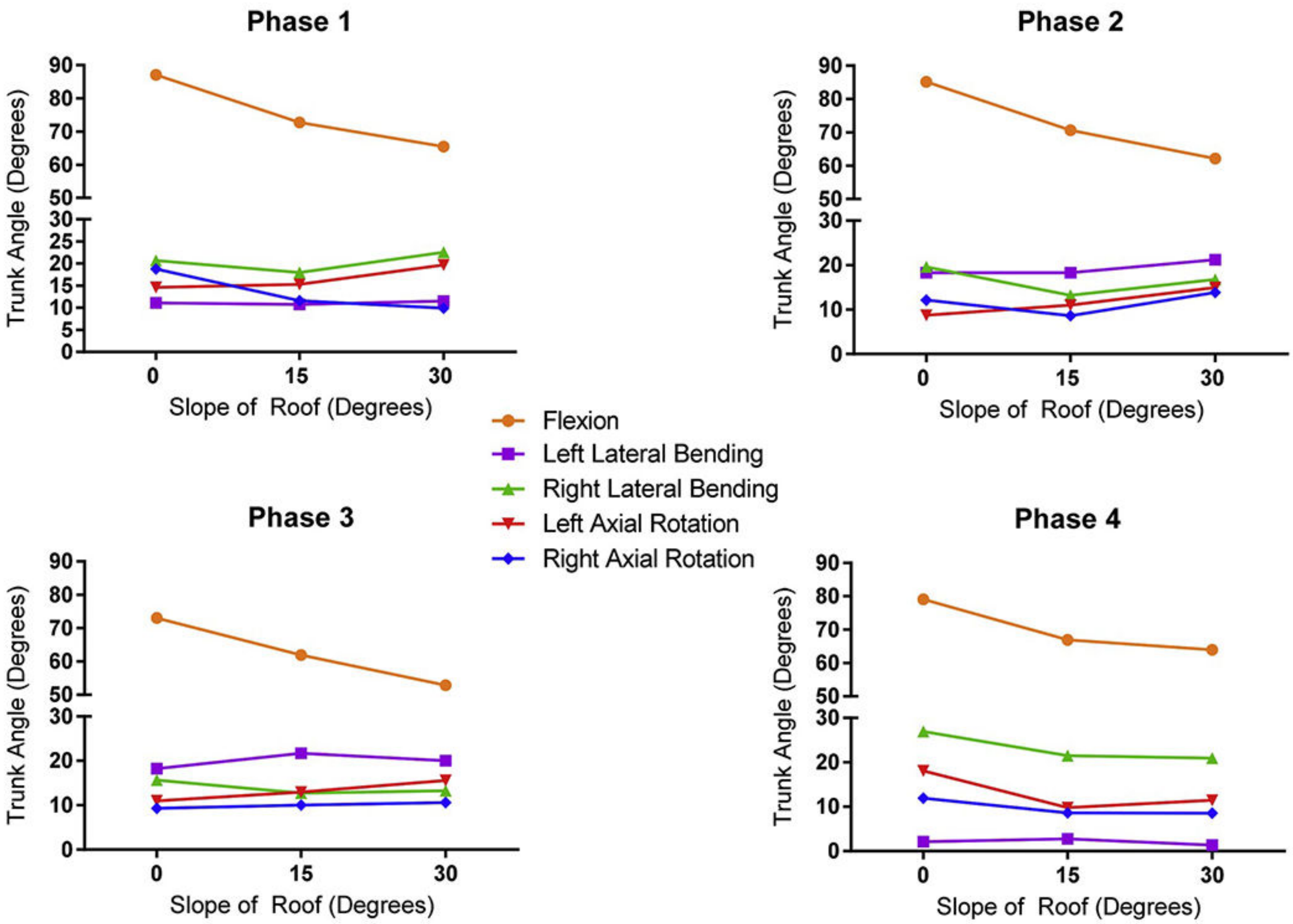

Fig. 5.

Calculated trunk kinematics during a simulated shingling procedure summarized by task phases. Phase **1:** “placing” beginning from an upright deep flexion kneeling posture. Phase 2: “preparing” the subjects pick up and position a pneumatic nail gun over the placed shingles. Phase 3: “nailing” the subjects use the nail gun to mimic affixing the shingles to the simulated roof surface. Phase 4: “returning” subjects returned the nail gun to its original position and resumed to the starting upright kneeling posture.