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Pressure distribution on the anatomic landmarks of the knee and the effect of kneepads

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ABSTRACT

This study examines stress transmitted to anatomic landmarks of the knee (patella, combined patella tendon and tibial tubercle) while in static kneeling postures without kneepads and while wearing two kneepads commonly worn in the mining industry. Ten subjects (7 male, 3 female) simulated postures utilized in low-seam mines: kneeling in full flexion; kneeling at 90° of knee flexion; and kneeling on one knee while in one of three kneepad states (no kneepads, non-articulated kneepads, and articulated kneepads). For each posture, peak and mean pressure on the anatomic landmarks of the knee were obtained. The majority of the pressure was found to be transmitted to the knee via the combined patellar tendon and tibial tubercle rather than through the patella. While the kneepads tested decreased the maximum pressure experienced at the combined patellar tendon and tibial tubercle, peak pressures of greater than 25 psi were still experienced over structures commonly injured in mining (e.g. bursa sac – bursitis/Miner's Knee). The major conclusion of this study is that novel kneepad designs that redistribute the stresses at the knee across a greater surface area and to other regions of the leg away from key structures of the knee are needed.

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1. Introduction

According to the 2007 Mine Safety and Health Administration (MSHA) database of reported cases of accident/injury/illness, 227 knee injuries occurred in underground coal. Furthermore, the associated total number of days lost in 2007 was 13,681 and the incidence rate was 0.5 per 100 full-time equivalents. In 2007, the median days lost due to a knee injury in coal operations was 41 days. This was nearly twice that which was observed for the back (22 days).

In underground coal mining, the working height of the mine typically coincides with the height of the coal seam. Low-seam mines are those mines with a seam height of no more than 42″. At the National Institute for Occupational Safety and Health (NIOSH), an analysis of musculoskeletal injury data from eight low-seam coal mines was conducted (Gallagher et al., 2009). These data indicated that the highest frequency of injury was to the knee. In fact, when compared to the low back, the frequency of knee injury was 1.7 times greater. Additionally, the average cost was $13,121 per knee injury which was quite similar to that for the low back ($14,378). Using this average cost per knee injury and the 227 knee injuries reported to MSHA in 2007 for all underground coal mining, it can be estimated that, in 2007, the financial burden of knee injuries in underground mining was nearly three million dollars.

Many other studies have demonstrated that low-seam mine workers suffer multiple forms of injury to the knee such as meniscal tears, osteoarthritis, ligament tears, and bursitis, or 'Beat Knee' (McMillan and Nichols, 2005; Roantree, 1957; Sharrard and Liddell, 1962; Sharrard, 1963, 1965; Watkins et al., 1958). These injuries are likely attributed to the low working heights, confining workers to kneeling and squatting postures, which have both been associated with knee injuries (Baker et al., 2002, 2003; Coggon et al., 2000; Cooper et al., 1994; Felson et al., 1991; Sharrard and Liddell, 1962; Tanaka et al., 1985).

Sharrard (1963, 1965) recorded the stresses at the knee when a mine worker was shoveling coal while starting from a kneeling at full-flexion posture. When compared to the mine worker's initial full-flexion posture, the stresses at the knee varied a large amount during the activity. Furthermore, Sharrard (1963) reported that the greatest proportion of miners suffering from 'Beat Knee' were those that knelt in one place for extended periods of time (i.e. static postures).

Mine workers use kneepads of varying types to help redistribute and diminish the effects of the stresses applied to the knee while kneeling. However, the effectiveness of the kneepads is unknown. Despite the fact that nearly all low-seam coal mine workers wear

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kneepads, knee injuries continue to occur and are relatively severe as was discussed earlier. Thus, a detailed understanding of the stresses at the knee while in postures associated with low-seam mining both with and without kneepads may provide insight into the injury mechanism. Pilot data indicated that nearly all the stress at the knee is transmitted from the ground via the patella, patellar tendon, and tibial tubercle while kneeling. Therefore, the objective of this study was to determine stress transmitted to the knee through these landmarks while in static postures associated with low-seam mining without kneepads and while wearing two commonly used kneepads (one articulated and one non-articulated).

2. Methods

2.1. Subjects

Ten subjects (7 male, 3 female) participated in this study. The average age was 34 years (SD = 17) with an age range of 19–60 years. The average weight and height were 683 N (SD = 98) and 169 cm (SD = 8) (154 pounds (SD = 22) and 66 in (SD = 3)), respectively. Prior to participation in the study, each subject was asked a series of questions to determine if they had ever had any serious injury to the knee; none of the subjects had ever had surgery on their knees. One subject was diagnosed with bursitis which did not require any intervention and a second subject had slight nerve damage due to a motorcycle accident. Additionally, some subjects reported that their knee would "click." However, when asked if they ever experienced a "catching" or "locking" feeling (a possible indicator of a meniscal injury), they responded that they had not. Prior to participating in the study, each subject read and signed an informed consent form approved by the NIOSH Human Subjects Review Board.

2.2. Experimental design

NIOSH researchers interviewed over 60 low-seam mine workers whereby the mine workers identified the posture they utilized to perform various mine tasks (e.g. building stoppings, hanging curtain). As a result of these data, the postures utilized in this study were selected (Fig. 1). Two working heights were investigated 97 cm (38″) and 122 cm (48″). Since low-seam mines are generally those of working heights of 42″ or less, these heights represented a typical working height classified as a low-seam and a working height that was higher than a low-seam but still required the mine worker to adopt kneeling and crawling postures to perform their tasks. The 10″ total difference in the two working heights selected allowed researchers to determine if differences in seam heights in and around the low-seam level would significantly affect pressure at the knee. It should be noted that all postures were not performed at both seam heights, only those postures that were reasonable for a seam height were investigated. For example, a mine worker would not kneel at 90° of knee flexion in a 38″ mine as this would be extremely difficult at such a low working height.

Subjects performed each of the above postures for three kneepad conditions: no kneepads, articulated kneepads, and non-articulated kneepads. The articulated and non-articulated kneepads were selected based on their widespread use in the mining industry. Several distributors of kneepads to the mining industry were contacted in 2007 and asked to provide the most frequently ordered kneepads for the previous year. From these data, the most commonly requested articulated and non-articulated kneepads were selected. The articulated kneepads consisted of a hard outer shell with hard rubber padding on the inside. The straps were also rubber and crossed a few inches above and a few inches below the crease of the knee. The non-articulated kneepads consisted of a soft outer rubber shell and soft inner foam padding. Again, the straps crossed a few inches above and below the crease of the knee.

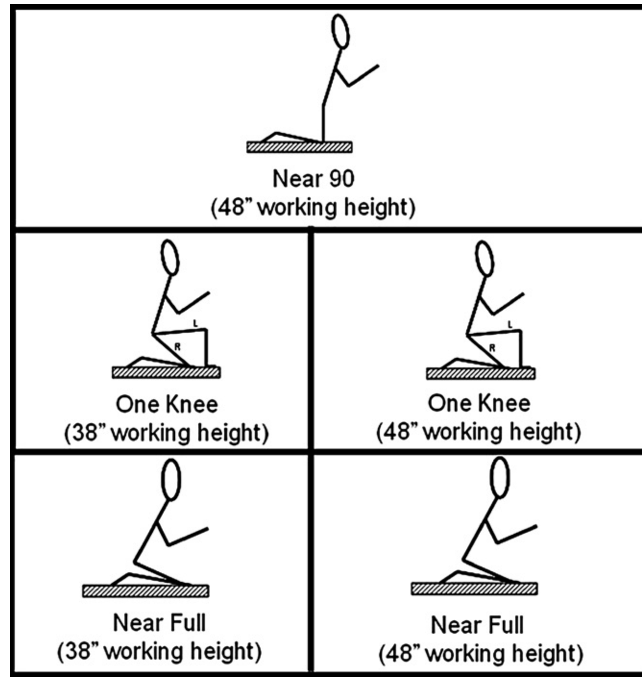

Fig. 1. Schematic showing each posture tested during the experiment. Kneeling at 90° knee flexion (Near 90), Kneeling on right knee (One Knee), Kneeling at full flexion (Near Full).

2.3. Subject preparation

A custom-built pressure sensor was used to measure pressures (TactArray T2000; Pressure Profile Systems; Los Angeles, CA). The sensor used capacitive sensor technology and was pre-shaped to conform to the knee when flexed at 90°. The sensor consisted of 196 individual pressure sensing units that varied in sizes ranging from 1.101 cm^2 to 1.464 cm^2 (0.1707 in^2 to 0.227 in^2) and was 3.2 mm (0.13 in) thick. Due to the pre-shaped nature of the sensor, the distance (dead space) between the sensing units was not constant across the sensor. With the sensor affixed to the knee, the distance between sensing units in the medial-to-lateral direction was constant at 1.7 mm (0.065 in). However, in the superior-to-inferior direction, the distance between sensing units varied from 3.1 to 4.7 mm (0.121–0.187 in) in the region where the patellar tendon and tibial tubercle rested and from 3.1 to 8.2 mm (0.121–0.322 in) in the region where the Patella rested (Fig. 2). Additionally, there was extra fabric on either end of the sensor so that a piece of Velcro could be sewn on to this fabric. To affix the sensor to the leg when the knee was at 90° of flexion, an Ace® bandage was first wrapped around the thigh so that half of the bandage was unwrapped and the bottom edge of the bandage was two inches from the crease of the knee. A rectangular piece of Velcro was then adhered such that half attached to the skin and the other half to the bandage. Eight pieces of hypoallergenic athletic tape were then applied in an asterisk pattern such that half of the tape was adhered to the Velcro on the thigh and the other half was adhered to the skin of the thigh. The corresponding piece of Velcro on the sensor was then adhered. The remainder of the Ace® bandage was then wrapped around the thigh, and metal fasteners were used to attach it to itself. In a similar manner, the inferior end of the sensor was adhered to the

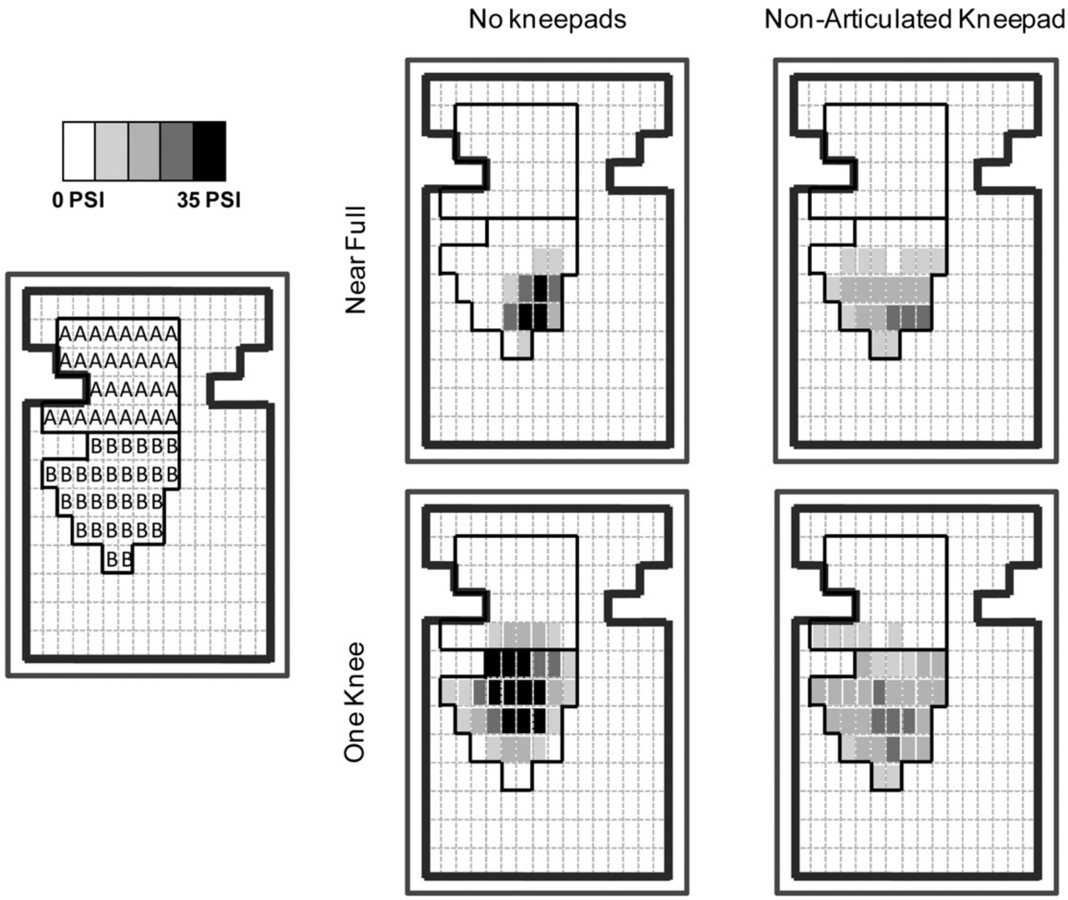

Fig. 2. Sensor pad layout with sensing units identified during palpation as the Patella (A) and the PTT (B) for a representative subject with the shaded cells identifying the pressure distribution during kneeling in full flexion (Near Full) and kneeling on one knee (One Knee) for the same subject.

lower leg. This method of fixation demonstrated that the sensor did not move while the subject performed the postures described above.

It was next necessary to determine which sensing units corresponded to various anatomic landmarks (patella, patellar tendon, and tibial tubercle). Using a wooden dowel, a researcher palpated the perimeter of these landmarks and the sensing units corresponding to each landmark were identified (Fig. 2). The same researcher palpated the anatomic landmarks for all subjects. Preliminary tests were conducted to determine the researcher's repeatability for palpating the landmarks. Based on this information, it was decided that the patellar tendon and tibial tubercle (PTT) would be grouped together since their small size resulted in unacceptable intra-observer repeatability. Palpating the patella and the combined PTT were both repeatable to within 6.7% of the total area. These anatomic landmarks were also palpated at the conclusion of testing to ensure that the sensor had not moved. Palpations indicated that the pressure sensor did not significantly shift during testing.

2.4. *Testing procedure*

The order in which the three kneepad states were tested (no kneepad, articulated kneepad, non-articulated kneepad) was randomized. Within each kneepad state, the order in which postures were tested was then randomized as well.

The subject first donned the required kneepad, if necessary, according to the randomized order. Subjects were then instructed to place their knee in a reference position in order to zero the pressure sensor. This position was 90° of knee flexion for postures that were initiated with the knee in this posture. The reference position was a squat for postures that were initiated with the knee in a fully flexed position (e.g. full flexion). A researcher directed subjects to view a stick-figure chart of test postures as the principal way to inform them of the posture they were to assume. The subjects were also instructed to keep their hands central to their body. Some subjects chose to hold their hands in the air around their chest while others let their hands rest on their thighs or at their sides. In some instances, subjects inquired as to whether or not they were in the correct posture. In these cases, a general verbal response was given to the subject. Subjects were given leeway to assume the posture in a way that maximized their comfort unless the subject assumed a posture that was considerably different from that which was requested. For example, a subject was instructed to enter a posture of 90° of knee flexion, but actually positioned themselves in a posture near full flexion. In such cases, the researchers instructed the subjects to adjust their posture.

Once the subject was in the posture of interest, the data collection system was initiated and a researcher instructed the subject that data collection had begun. Data were collected for a 10-s interval and the subject was told to stop. Immediately afterward, the data were saved and reviewed for acceptability by viewing a color map display of the pressure distribution. Between tests, the subjects were instructed to sit in a chair and place their knee near 90° of flexion making sure not to apply a load to the sensor. The sensor was then allowed to recover until the maximum and average pressures across the sensor were one pound per square inch or less. If an error occurred during data collection, the sensor was allowed to recover and then the trial was repeated.

2.5. Data processing/analysis

Pressure data were obtained for every sensing unit at each time point for the 10 s of data collected at a variable sampling rate of approximately 5 Hz. The equipment used was unable to provide a consistent sampling rate, variations of up to 0.5 Hz were observed. The ratio of pressure between the patella and the combined PTT was determined first. The patella and combined PTT both consisted of several sensing units. In order to arrive at a pressure ratio calculation, the pressure across these sensing units was first summed for both the patella and the combined PTT. This was done for all time points. At each time point, the sum of the patellar pressure was then divided by the sum of the combined PTT pressure and the sum of the patellar pressure, creating a ratio for each point in time. These ratios were then summed together across all time points and then divided by the total number of time points. This yielded the mean pressure ratio between the patella and the combined PTT (see Appendix for detailed equations).

Next, it was necessary to characterize the magnitude of pressures across the patella and combined PTT. The mean pressure for both structures was determined for every time point. This value was then summed and divided by the total number of data points. This yielded the mean of the mean pressures on the patella and combined PTT across all time points.

The mean maximum pressure was determined by summing the maximum pressure at each time point and dividing by the total number of time points. Finally, some measurement of the distribution of stress across the structures was necessary. To do this, a measure of variance was calculated. The variances were calculated for the patella and combined PTT at each time point. These variances were then summed and divided by the total number of time points yielding the mean variance across each structure.

Statistical analyses were performed using Statistix 8.0 for Windows. Analyses performed included a split-plot analysis of variance (ANOVA) and a priori orthogonal contrasts. Contrasts for kneepad states included: 1) comparisons of the no-kneepad state versus wearing kneepads, and 2) comparing the non-articulated versus articulated kneepads. Contrasts for posture states included: 1) comparison of kneeling with both knees in full flexion to kneeling on the right knee only (across both heights), and 2) comparing the 38″ work height to the 48″ work height. All contrasts were tested using a T statistic with an alpha = 0.05. As an exploratory analysis, multiplicity corrections were not applied in the data analyses (Bender and Lange, 2001). Specifically, a comparison-wise Type I error rate alpha level of 0.05 was employed.

3. Results

For all postures tested, the majority (>60%) of the pressure was placed on the combined PTT region (Fig. 3). A significant difference ($p < .05$) was observed for kneepad conditions, posture, and subject for the mean pressure ratio. On further analysis it was found that no significant difference existed between the no-kneepad state and the two kneepad states, while a significant difference existed within the two kneepad states with the articulated kneepad exhibiting a greater mean pressure ratio for the PTT region ($p < .0001$). On further examination of the posture significance, the kneeling at full-flexion (near full) condition showed a significantly greater mean pressure ratio for the PTT region ($p < .0001$) when compared to the kneeling on right knee (one knee) conditions. No significant difference between the 38″ and 48″ working heights was observed for any dependent measures.

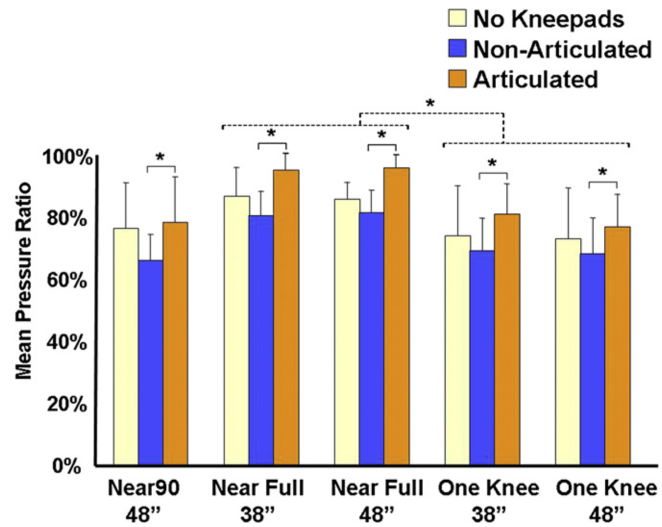

Fig. 3. Mean pressure ratio at the PTT region across postures (*$p < 0.05$).

The mean of the mean pressure at the patella region showed that only modest amounts of pressure (<10 psi) were applied to the patella for all postures (Fig. 4). A significant difference ($p < .05$) was observed for kneepad conditions, posture, and subject. As with the pressure ratio, it was found that no significant difference existed between the no-kneepad state and the two kneepads states, but a significant difference existed between the two kneepad states with the non-articulated kneepad exhibiting a greater mean of the mean pressure for the patella region ($p < .0001$). On further examination into the significance of the posture condition, it was determined that the one knee condition showed significantly greater mean of the mean pressure for the patella region ($p < .0001$) when compared to the near full conditions.

The mean of the mean pressure at the combined PTT region showed a considerably higher level of applied pressure (>15 psi) than that which was observed for the patella region (Fig. 5). As with the mean of the mean pressure for the patella region, a significant difference ($p < .05$) was observed for posture and subject. In contrast to the patella region, the PTT region did not show

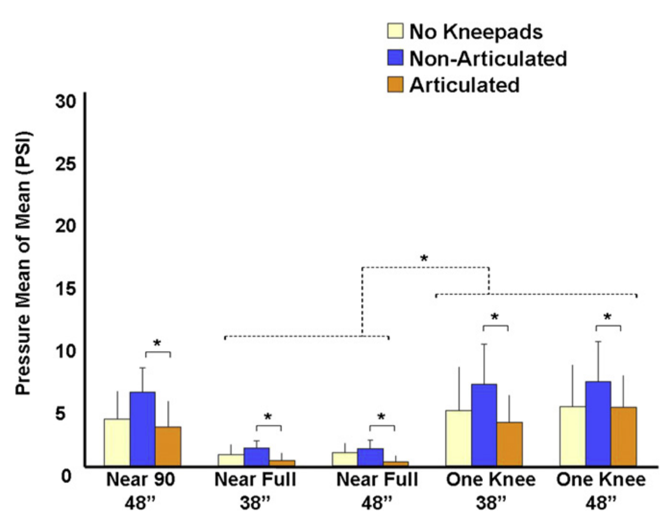

Fig. 4. Mean of the mean pressure at the patella region for the various postures (*$p < 0.05$).

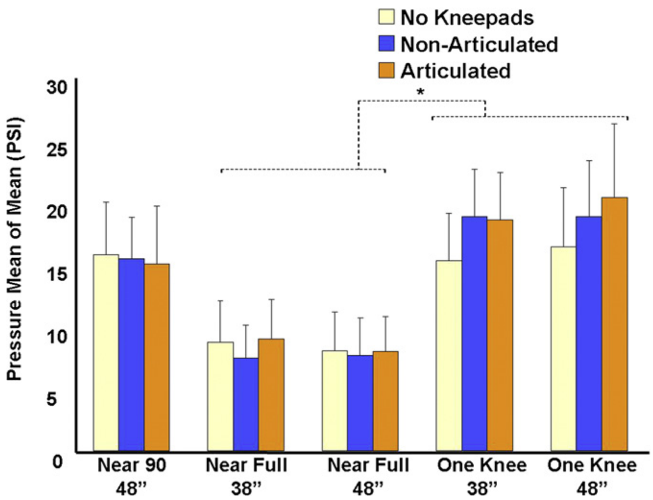

Fig. 5. Mean of the mean pressure at the PTT region for the various postures (*$p < 0.05$).

significant difference due to kneepads. As compared with the patella region, the reverse trend was found for the PTT region when looking at the one knee versus near full condition with the one knee showing significantly greater mean of the mean pressure ($p < .0001$) when compared to the near full conditions.

The mean of the maximum pressure at the patella region showed that highly variable (1.3 ± 1.1 to 27.1 ± 17.2 psi) maximum pressure was applied to the patella for the different postures (Fig. 6). As with the mean of the mean pressure, significant differences ($p < .05$) were observed for kneepad conditions, posture, and subject for the mean of the max pressure. Again, it was found that no significant difference existed between the no-kneepad state and the two kneepad states, but that a significant difference did exist between the two kneepad states with the non-articulated kneepad exhibiting a greater mean of the maximum pressure for the patella region ($p = .0006$). Additionally, the one knee condition showed significantly greater mean of the maximum pressure for the patella region ($p < .0001$) when compared to the near full conditions.

The mean of the maximum pressure at the PTT region showed a considerably higher level of pressure (>25 psi) than that which was observed for the patella region for all postures regardless of the kneepad condition (Fig. 7). A significant difference ($p < .05$) was observed for kneepad conditions and posture, but not between subjects for the PTT region. No significant difference existed between the two kneepad states, but a significant difference existed between the no kneepad and the two kneepad states with the no-kneepad state exhibiting a greater mean of the maximum pressure for the PTT region ($p < .0001$). Looking at significant differences within posture, the only significant difference was found between the near full compared to the one knee conditions, with the one knee postures exhibiting a greater mean of the maximum pressure ($p < .0001$).

The mean of the variance at the patella region showed considerably different magnitudes of variance across postures (~ 0 psi^2 for near full postures to ~ 60 psi^2 for all other postures). Similarly, significant differences ($p < .05$) were observed for posture and subject, but not for the different kneepad conditions. The one knee condition showed a significantly greater mean of the pressure variance for the patella region ($p < .0001$) when compared to the near full conditions.

The mean of the variance at the PTT region showed relatively consistent levels of variance across postures (~ 175 psi^2 for no-kneepad conditions and ~ 75 psi^2 for both kneepad conditions). Significant differences ($p < .05$) were observed for posture and kneepad condition but not for subject. The no-kneepad condition was found to have a significantly greater mean of the variance for the PTT region when compared to the two kneepad states ($p < .0001$). No significant difference was found between the two kneepad states. The one knee condition showed significantly greater mean of the variance for the PTT region ($p < .0001$) when compared to the near full conditions.

4. Discussion

In this study, the stress transmitted to the knee through the patella, patellar tendon, and tibial tubercle were determined while in static postures associated with low-seam mining without kneepads and while wearing two kneepads commonly used in the industry (one articulated and one non-articulated). The results yielded several important pieces of information. The majority of the pressure was found to be transmitted to the knee via the combined patellar tendon and tibial tubercle. The kneepads better distributed the stresses at the combined patellar tendon and tibial tubercle

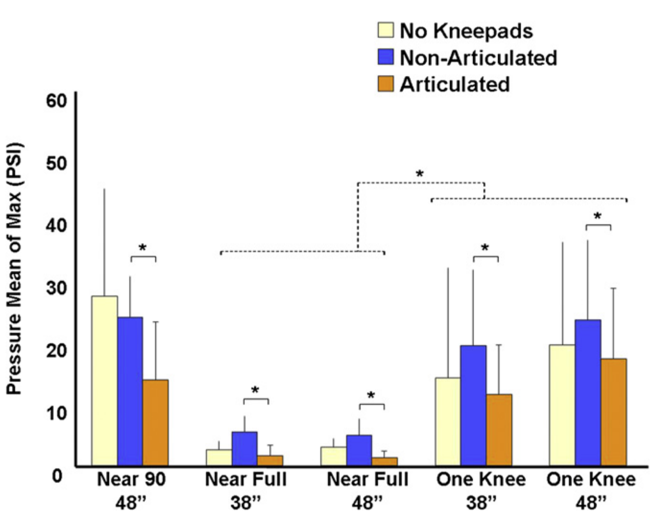

Fig. 6. Mean of the maximum pressure at the patella region for the various postures (*$p < 0.05$).

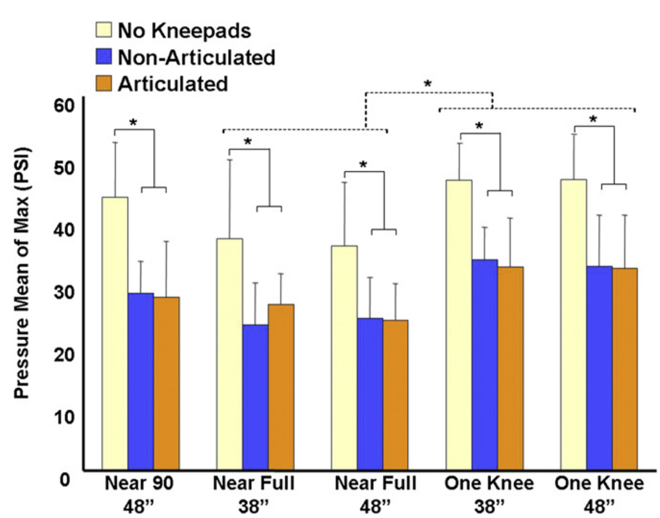

Fig. 7. Mean of the maximum pressure at the PTT region for the various postures (*$p < 0.05$).

region across a larger surface area decreasing the maximum stresses experienced by these structures. However, peak pressures of greater than 25 psi were still experienced.

The mean pressure ratio calculation was designed to identify if the kneepad design, in regards to both construction and padding, affected how the pressure was applied to the knee during kneeling postures. The mean pressure ratio showed that the majority (over 60%) of the pressure applied to the knee during kneeling is applied to the PTT region. While the kneepads tested did not drastically affect how this pressure was distributed, the two kneepads did show limited ability (~10%) to transfer loading to/away from the PTT region. The non-articulated kneepad transferred slightly more pressure from the PTT to the patella as compared to the no-kneepad condition, while the articulated kneepad exhibited the opposite trend. The overall impact on the stress distribution amongst knee structures was minimal. While the articulated and non-articulated kneepads use different materials, they both employ an outer shell and an inner padding that rested directly against the knee region. These data suggest that alternative design ideas be investigated so that the stresses applied to the key anatomic structures of the knee may be distributed to other, perhaps less harmful, regions. For example, a novel kneepad design that redistributes the forces at the knee across the larger surface area of the shin could drastically reduce the magnitude of stress on the knee.

To understand how the loading of the stress across the patella and the combined PTT regions reacted to the postures and kneepads tested, the mean of the mean pressure and the mean of maximum pressure was calculated. The difference observed in the average pressure applied to the patella region, while significant, had little effect on the total pressure levels. Additionally, while the expected drop in the mean maximum pressure from no kneepad to kneepad conditions was observed, no significant difference was observed between the kneepads.

These findings demonstrate that the kneepads tested had little affect on the overall application of stress to the knee. Without the use of kneepads, high variation was observed due to "hot spots" developing over small areas while nearby areas were nearly unloaded. As expected, both kneepads drastically reduced the variation (60% reduction) for the PTT region, indicating that kneepads are effective for distributing pressure across the knee. Unexpectedly, the two kneepads tested did not respond differently with respect to variation of pressure application for both regions, indicating that the differences in the material of the kneepads had little effect at distributing the stress over the patella and the PTT.

The reduction in point-loading and decreased variation can help explain the necessary comfort factor for working in kneeling postures and why some form of kneepad is preferred to none at all. The results show that although kneepads have a slight effect on the peak pressure levels and the variance observed during kneeling postures, the current design/materials used have a relatively negligible change on mean pressure. In other words, although the overall pressure was not reduced significantly, the kneepads tested redistributed the pressure more evenly across the knee structures. Thus, same or similar materials may be useful for future novel kneepad designs that attempt to redistribute the forces at the knee over larger surface areas.

The pressure measurements indicate what happens while kneeling in full flexion. During full-flexion postures, low pressure (<3 psi mean, <10 psi peak) is applied to the patella; this is a third or less of what was seen in other postures. Additionally, it was found that kneeling in a full-flexion posture exhibited almost 50% less pressure applied to the patella and the PTT when looked at as a whole. Although far from the ideal, working in a full-flexion posture appears to provide the most direct and immediate stress relief to the surface of the knee and therefore comfort to the knee for mine workers that must work frequently in a kneeling posture. Prolonged use of the posture, however, may lead to less obvious deterioration and weakening of other important knee components of the knee joint, e.g., tissue damage to the meniscus, stretching of ligaments and tendons.

One hypothesis of this study was that seam height would have a significant effect on the pressure measured at the knee. The analysis showed that the two seam heights tested (38″ and 48″) had no significant effect on any of the dependent measures. One explanation is, that while the postural difference on a whole body scale would be different between the two heights, the knee posture/included angle did not drastically change and therefore did not affect the pressures observed.

An early qualitative clinical investigation of bursitis (Watkins et al., 1958) suggested that the majority of force found during kneeling postures is transferred through the tibial tubercle. Similar to the results of the current study, Watkins et al. also found that kneepads might redistribute this load to neighboring anatomical features of the knee altering the types of injuries experienced by the worker. As with the current study, these results also suggest that simply changing the type of material used in the kneepad may not be sufficient. Rather, a novel design of kneepads may be required that deliberately alters the loading of the knee such that key anatomic structures are not vulnerable to excessive loads. Other published findings that evaluated the external pressure applied to the structures of the knee were sought to compare with the results of this study, but none were found. Nevertheless, some studies have evaluated the pressure on the cartilage of the knee while in various postures such as deep knee flexion (Li et al., 2005; Hefzy et al., 1998). Future studies should consider evaluating the effect that postures associated with low-seam mining have on the internal structures of the knee. Specifically, the forces in the primary ligaments and meniscus as well as the pressure on the cartilage will yield important information for kneepad designs aimed at reducing injury risk.

For example, the forces in the knee structures have been extensively studied using robotic technology (Rudy et al., 1996; Song et al., 2004). In some of these studies, an anterior or posterior load was applied to simulate a clinical exam. During this safe application of load (134 N), the measured forces found in posterior cruciate ligament, the primary ligamentous stabilizer to posterior loads at the knee, have been shown to be as high as 129 N (Harner et al., 2000). Additionally, load-to-failure studies have been performed to determine the point of failure of the posterior cruciate ligament (Kennedy et al., 1976). Determining the forces in the posterior cruciate ligament during postures associated with low-seam mining would provide insight into the relative risk to that structure during these postures. Other factors such as the internal and external rotation of the tibia during these postures may pose additional risk to other structures of the knee and have also been investigated previously (Sharrard and Liddell, 1962; Pollard, 2008).

4.1. Limitations

The results of this study should be interpreted in consideration of the limitations. The pressure sensor design and construction needed to accommodate the shape of the knee in flexed positions and was of a cupped design. The largest gap areas were in the central portion of the curved section of the sensor pad, or where the superior region of the patella resided. Since the inferior border of the patella was the only portion experiencing loading, the impact of these larger gaps is likely minimal. However, "hot spots" may have been missed in the PTT region. Therefore, the results of this study likely underestimated the peak and mean stresses in this region.

Only two seam heights and three kneepad conditions were tested in a limited number of postures for this study. While these conditions are not representative of all situations for underground low-coal mining, it was decided to limit the study to these conditions due to concerns about the length of subject testing. Information received through in-mine observations and feedback from miners indicated that the conditions tested would represent the majority of circumstances a low-coal miner would find themselves using. For example, the two kneepads used in the study were found to be the most widely used in the mining industry. Moreover, while only static postures were evaluated, dynamic postures will be addressed in future efforts to determine if such postures and motions are different from the findings of this study. During the no-kneepad condition, subjects did experience minimal discomfort at the knee while simulating the various postures. However, subjects indicated that the presence of the pressure sensor (3.2 mm thick) provided sufficient cushioning. Thus, it is unlikely that this discomfort greatly altered their posture.

5. Conclusion

The goal of this study was to investigate the impact of posture and kneepads on the application and distribution of pressure across the bony structures of the knee. In particular, this study sought to determine if the designs of the current kneepads used in the low-seam mining industry responded differently to the tests performed, and if different postures resulted in different levels of stress to the knee. From the results of this study, it can be concluded that kneepads currently used in low-seam mining are an effective tool for decreasing the peak pressure on the bony structures of the knee by distributing the forces across more surface area of the superior portion of the tibia. However, a substantial magnitude of stress still exists and is located near key anatomical landmarks of the knee (e.g. bursa sac). Therefore, novel kneepad designs are needed to significantly reduce the magnitude of pressure applied to the structures of the knee. The new design should focus on redistributing the pressure away from the PTT region of the knee to other parts of the lower leg such as the shin.

Future work will focus on the design and fabrication of a kneepad that demonstrates durability for use in the harsh mining environment and a reduction in the stresses at the knee for postures associated with low-coal mining. The advantages and increased effectiveness of the new kneepad design compared to traditional kneepads will be evaluated and validated with laboratory and field testing.

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Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

Appendix

A_{ij} represents a matrix of the cells that make up the Patella (P) region (see Fig. 2) with $i =$ sample number and $j =$ cell number.

B_{ij} represents a matrix of the cells that make up the Patellar Tendon & Tibial Tubercle (PTT) region (see Fig. 2) with $i =$ sample number and $j =$ cell number (Equations for the patellar tendon & tibial tubercle region are shown, patella equations are similar).

Mean pressure ratio: the average over time of the ratio of the sum of a region over the sum over both regions

$$\frac{\sum_{i=1}^{n} \frac{\sum_{j=1}^{m} B_{ij}}{\sum_{j=1}^{q} A_{ij} + \sum_{j=1}^{m} B_{ij}}}{n}$$

$n =$ total number of samples, $m =$ total number of cells in B, $q =$ total number of cells in A.

Pressure mean of mean: the average of a region averaged over time

$$\frac{\sum_{i=1}^{n} \frac{\sum_{j=1}^{m} B_{ij}}{m}}{n}$$

$n =$ total number of samples, $m =$ total number of cells in B.

Pressure mean of max: the maximum of a region averaged over time

$$\frac{\sum_{i=1}^{n} \max(B_i)}{n}$$

$n =$ total number of samples.

Pressure mean of variance: the variance of a region averaged over time

$$\frac{\sum_{i=1}^{n} (\mathrm{stdev}(B_i))^2}{n}$$

$n =$ total number of samples.

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