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Evaluation of knee joint forces during kneeling work with different kneepads

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A B S T R A C T

The main purpose of this study is to determine knee joint forces resulting from kneeling work with and without kneepads to quantify how different kneepads redistribute force. Eleven healthy males simulated a tile setting task to different locations during six kneepad states (five different kneepad types and without kneepad). Peak and average forces on the anatomical landmarks of both knees were obtained by custom force sensors. The results revealed that kneepad design can significantly modify the forces on the knee joint through redistribution. The Professional Gel design was preferred among the five tested kneepads which was confirmed with both force measurements and participants' responses. The extreme reaching locations induced significantly higher joint forces on left knee or right knee depending on task. The conclusion of this study is that a properly selected kneepad for specific tasks and a more neutral working posture can modify the force distribution on the knees and likely decrease the risk of knee disorders from kneeling work.

1. Introduction

Kneeling is a day-to-day activity for many different occupations including miners, electricians, plumbers, carpenters, carpet layers and floor layers (Gallagher et al., 2009; Jensen et al., 2010; Tennant et al., 2015). These workers often spend a large percentage of their daily working time kneeling. Previous research indicated that occupational kneeling postures are correlated with knee discomfort, symptom like tingling and numbness in the lower legs (Reid et al., 2010a; Chung et al., 2005). Kneeling with both knees in deep flexion was significantly more uncomfortable than the 90° flexed kneeling and kneeling in a crawling posture (Chung et al., 2003). Kneeling has also been considered as a primary risk factor in knee disorders, such as bursitis, osteoarthritis and meniscal lesions (Rytter et al., 2009a; Reid et al., 2010b; Jensen, 2008; McMillan and Nichols, 2005). Several studies about the carpet laying industry report that 8%–20% of this population was diagnosed with knee bursitis (Jensen et al., 2000a; Kivimäki et al., 1992) and a dose-response association between length of time on the job and tibiofemoral osteoarthritis exists among floor layers, who have a 3.6 times greater likelihood of osteoarthritis when compared with graphic designers of the same age (Rytter et al., 2009b; Jensen et al., 2000b).

The pathogenesis of knee disorders in relation to knee loading while performing kneeling work is still largely unknown. However, knee joint forces are shown to significantly increase during deep knee flexion (Nagura et al., 2002) and repetitive knee loading, especially in extreme postures, which may induce micro-injuries (Cooper et al., 1994). The static forces experienced on the knees were reported to vary between 22% and 68% of body weight (BW) when kneeling on one or both knees depending on the kneeling posture (Jensen et al., 2010). This high level of force on the knee combined with a substantial kneeling duration may accelerate the wear of cartilage and cause osteoarthritis and meniscal injuries (Jensen et al., 2010; Tennant et al., 2015; NRC, 2007). Jensen et al. (2010) investigated the knee joint loads by measuring the external knee forces in five different kneeling work positions in ten floor layers using computer dynography (Jensen et al., 2010). This study found that floor layers spent a high percentage of time in knee-straining work positions and high external forces were experienced in a crawling work position (3.5 BW) compared to leaning back on the heels while kneeling (0.3 BW). One study

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conducted by Porter et al. (2010) measured the pressure applied to the knee during five static postures used in low seam mining while not wearing kneepads and while wearing two different kneepads (articulated and nonarticulated) with ten subjects (Porter et al., 2010). The results obtained from a custom made capacitive pressure sensor indicated that the majority of the pressure (>60%) was on the combined patella tendon and tibial tubercle for kneeling postures.

Although kneepads are commonly used as personal protective equipment to protect against knee disorders during kneeling work in many industries, a high frequency of knee disorders suggests that kneepads alone may not be a sufficient means to control these disorders. More research is needed to understand the effect of different kneepads and the ability to redistribute forces during kneeling work. Hence a major goal of this study was to determine the change in knee joint forces with and without kneepads to quantify the effects of five different kneepads to provide guidance about how to modify exposure through kneepad design.

2. Methods

2.1. Subjects

Eleven students from the University of Utah (average age 30.5 ± 9.5 years; height 174 ± 5.9 cm; weight 154.6 ± 18.9 lbs) volunteered for this study and had at least some experience in work where kneeling was required. Participants were carefully selected who did not have any serious knee disorders in the past that may affect kneeling. All participants reviewed and signed an informed consent document approved by the University of Utah Institutional Review Board.

2.2. Measurement of knee joint forces

Two modes of knee force data were collected for this study. One is the ground reaction force data collected from force plates (OR-6, AMTI, Watertown, MA) at 1000 Hz; whereas the other is the contact force between the knee joint and the kneepad measured with a custom array of FlexiForce Sensors (FFS) model A201 (Tekscan, South Boston, MA). These sensors are resistive based technology and can measure a broad range of forces up to 1000 lbs. The FFS used in the present study is 7.5-inch long and 0.55-inch wide and 0.008-inch thick with an active sensing area of 0.375-inches in diameter. An A/D board, transfer box and cables were used to record the data from the FFS and synchronize it with video and force plates. Calibration equations were used in converting the voltage to force for each sensor using a 5th order polynomial equation. The calibration process was determined by placing the FFS on the force plate and using a force dynamometer to apply an increasing force from 0 to 100 lbs. Peak Motus software (Vicon Motion Systems, Oxford, UK) was used for syncing data from the force plate and the FFS during calibration.

Eight sensors were directly placed on the knee using two-way hypoallergenic adhesive tape. The configuration of sensor placement was designed based on previous research (Moore et al., 2009) and the average size of an adult male patella (Yoo et al., 2007). The positioning of the sensors was accomplished by initially marking a vertical line dividing the patella into two halves. Then, three sensors (sensor 1, 2, 3 in Fig. 1) were put along this line with a 15 mm increment and on the top, middle and bottom of the top periphery of the patella while the knee was flexed 90°. Two sensors (sensor 4 and 5) were placed at the same height as the bottom sensor on the patella 16 mm apart from the vertical line. The other two sensors (sensor 6 and 7) were placed horizontally 10 mm from the vertical line on each side and vertically 10 mm down from the bottom sensor on the patella. The last sensor (sensor 8) was placed on the tibial tubercle. Motion data were also collected using an 18-camera OptiTrack Motion system (ARENA by NaturalPoint, Corvalis, OR) with 36 markers on the participant to help verify positioning and mark events during each task.

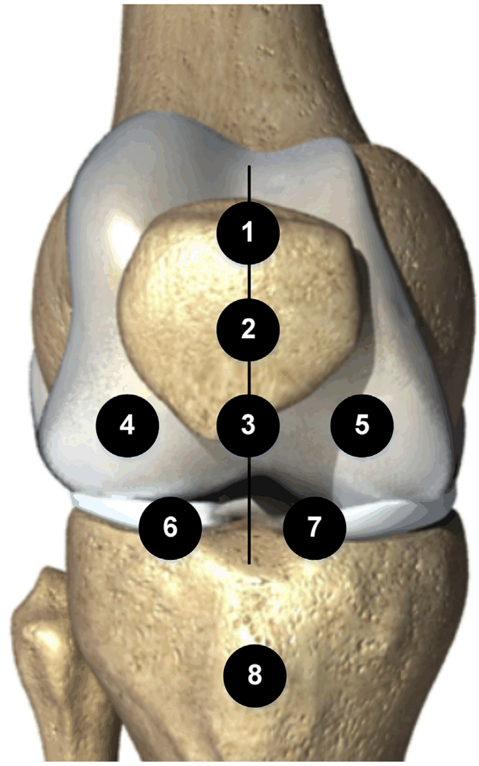

Fig. 1. Sensor placement on the knee. Sensors 1, 2, 3 were put along the middle vertical line with 15 mm increments between the top, middle and bottom of the patella, sensors 4 and 5 were placed at the same height as sensor 3 and 16 mm apart from the vertical line, sensor 6 and 7 were horizontally placed 10 mm from the vertical line and vertically 10 mm down from sensor 3, sensor 8 was placed over the tibial tubercle.

2.3. Experiment set-up and data collection

Five different types of kneepads (Fig. 2), which are commonly used by workers in various occupations and environments, were selected to represent difference in kneepad design, including, attachment, stiffness, cost and materials. They were Ultra Light, Rubber Nonskid, Hard Cap, Professional Gel and Armor Pant.

After a participant was fitted with the marker set and the sensors as explained earlier, the participant kneeled with each knee on a single force plate in an upright posture with the knees flexed 90° and the feet placed posterior in a comfortable posture (Fig. 3). A stack of five ceramic tiles (30 cm × 30 cm) labeled 'a' to 'e' was randomly placed in front of the participant. Five platforms with equal height as the force plates (10 cm) surrounding the workspace were labeled with 'a' to 'e' were from left to right. In every trial, the participant started in an upright and neutral position (knee flexion 90°, torso upright, arms to sides), then picked up one ceramic tile and put it in the designated position of the platform with the same label, after each trial the participant returned to the neutral position before picking and placing a subsequent tile. This sequence of movements represented a complete cycle. Each trial comprised completing the placement of five tiles in five complete cycles.

Participants were first asked to complete the kneeling task without any kneepads, which served as the control, and then with

Fig. 2. Different kneepads used in this study. (A) Ultra Light; (B) Rubber Nonskid; (C) Hard Cap; (D) Professional Gel; (E) Armor Pant.

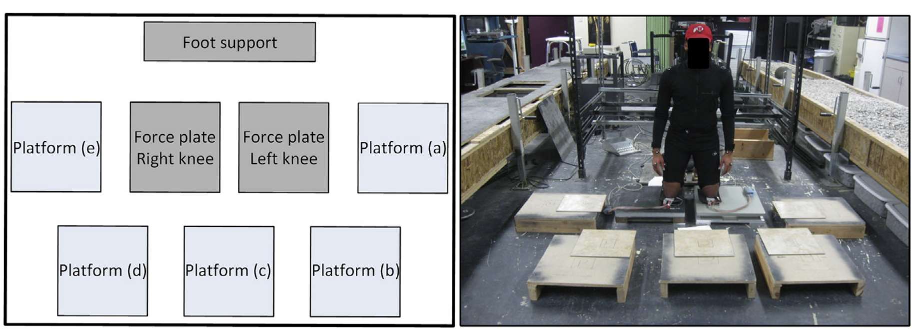

Fig. 3. Layout of the experimental arrangement with force plates at the center surrounded by wooden platforms and foot support.

different kneepads in a randomized order. Three trials were conducted for each of six conditions (five types of kneepads and without kneepad). After finishing each trial, the participant was asked to sit in a chair with 90° flexed knee to equalize the sensors and initialize readings. The sensors on the knee were also checked for possible movement away from the target regions and were adjusted as needed when changing the kneepads. Questionnaire data, which consisted of a series of questions related to comfort and pain were asked between each condition. These included asking the participant to identify the most uncomfortable location of kneeling, and provided a knee pain rating and kneepad comfort rating for each condition. The knee pain rating was divided into five levels, where 1 represented no pain at all and 5 represented unbearable painful. The kneepad comfort rating was on a scale of 1–10, with 1 being the least and 10 being the highest comfort while kneeling.

2.4. Data process and statistics analysis

The FFS data were converted from voltage to force using the calibration equations obtained previously. The knee contact forces were calculated by the summation of all the FFS. Each trial was divided into five cycles based on the locations of the wooden platform. The knee contact forces from each cycle were normalized to 101 points to represent 100% cycle, and divided by body weight for normalization using Matlab R2012b (The Mathworks, Inc., Natick, MA), and then averaged across three within-subject trials for the left and right knees separately.

The peak and average knee contact forces in a kneeling cycle were analyzed using SPSS 20 for Windows (IBM Corporation, Armonk, NY). A correlation analysis was used to determine the fit between the FFS values and force plate data. Descriptive statistics and one-way analysis of variance (ANOVA) were performed for the knee pain rating and kneepad comfort rating. Two-way repeated ANOVA were used to determine the effect of different kneepads and platform locations for left and right knees respectively. If the assumption of sphericity was violated, the Greenhouse-Geisser correction was used. Post-hoc tests were conducted using Tukey HSD test for pairwise comparison. The results were considered statistically significant when $p < 0.05$.

3. Results

3.1. Questionnaire results

Significant differences were found between each kneepad condition and without kneepad for both the knee pain ratings ($p = 0.001$) and kneepad comfort ratings ($p = 0.001$), but not between any kneepad conditions. The results in Table 1 indicate that kneeling without a kneepad was rated "4-very painful" which was never chosen when wearing any of the available kneepads. Between the kneepads, the Hard Cap was given a highest knee pain rating of 2.18. The Professional Gel had the lowest knee pain rating of 1.55 with 54.5% (six subjects) reporting no pain at all. This type of kneepad also had the highest kneepad comfort rating of 7.55 which was 1.8 higher than the lowest mean of 5.73 for the Ultra Light. When asked the question about which of the reaching locations was most uncomfortable, seven subjects reported discomfort at both location 'a' and 'e' (extreme left and right), three responded for location 'b' and 'd', and one responded only for location 'e'.

3.2. Effect of kneepads and locations

The knee contact forces obtained from the FFS accounted for only about 85% of the overall force magnitude collected from the force plate in the without kneepad condition. The FFS profile mimicked the profile of the force plate data well as determined with the correlation analysis ($R = 0.954$).

For the peak contact forces, the effect of the kneepad was statistically significant for left and right knees respectively ($p = 0.001$ and 0.004, Fig. 4a). Post-hoc tests indicated that peak contact forces without kneepad were significantly larger than the forces with kneepads for both knees ($p = 0.021$ and 0.016 for Ultra Light, $p = 0.008$ and 0.015 for Rubber Nonskid, $p = 0.010$ and 0.012 for Hard Cap, $p = 0.014$ and 0.025 for Armor Pant, and $p = 0.003$ and 0.005 for Professional Gel). The peak forces for the Armor Pant were found to be larger than the Professional Gel for both knees when comparing between different kneepads ($p = 0.022$ and 0.002).

For the average contact forces, the effect of kneepad was also statistically significant for left knee ($p = 0.001$) and right knee ($p = 0.001$, Fig. 4b). When comparing with the forces without kneepad, the average contact forces were significantly smaller for the Professional Gel for both knees ($p = 0.014$ and 0.020). A smaller average contact force was also found for the Rubber Nonskid, Hard Cap and Armor Pant in the right knee ($p = 0.027/0.025/0.038$). The average forces for the Armor Pant were significantly larger than the Professional Gel for both knees within different kneepads comparison ($p = 0.028$ and 0.022).

The effect of locations for peak and average contact forces were both statistically significant for left knee ($p = 0.001$ and 0.003) and right knee ($p = 0.008$ and 0.001, Fig. 4c, d). For the left knee, location 'a' and 'b' had higher peak and average values than location 'c' ($p = 0.014$ and 0.006 for peak, $p = 0.004$ and 0.002 for average), location 'd' ($p = 0.008$ and 0.010 for peak, $p = 0.003$ and 0.005 for average), and location 'e' ($p = 0.008$ and 0.015 for peak, $p = 0.002$ and 0.004 for average). For the right knee, location 'd' and 'e' had higher peak and average values than location 'a' ($p = 0.008$ and 0.012 for peak, $p = 0.025$ and 0.016 for average), location 'b' ($p = 0.017$ and 0.020 for peak, $p = 0.007$ and 0.003 for average), and location 'c' ($p = 0.024$ and 0.036 for peak, $p = 0.009$ and 0.005 for average).

4. Discussion

The purpose of this study was to determine the change in force distribution on the knees with and without kneepads to quantify the effects of different kneepad designs. The results from the objective force measurements, especially the peak forces, aligned well with subjective responses of pain and discomfort. The peak knee contact forces were found to significantly decrease when wearing kneepads during kneeling work (at least 40% compared to no kneepad, Fig. 4a). Previous research indicated that overly high knee forces was one of the main factors to increase the risk of joint injury and develop knee disorders (Tennant et al., 2015; Zhao et al., 2007). Our results also demonstrate that wearing kneepads during kneeling may be an effective way to protect the knee joint by dispersing the high point-loading over a larger area. Although the effect of the kneepad for average force was also significant, only the Professional Gel significantly reduced the magnitude of force for both knees compared to the no kneepad condition (Fig. 4b). These findings demonstrate that the kneepads evaluated in this study only have a limited ability to redistribute the cumulative load during prolonged kneeling, the practical significance of this modification and resulting knee disorder potential remain unknown.

The material used in the kneepad and the surface interface between the knee and the kneepad appear to play major roles in redistribution of the forces on the knee. The Ultra Light and Armor Pant were shown to have a relatively higher peak and average force than the other three kneepads (Fig. 4a, b). This result was confirmed with the participants' response of comfort which were expressed by a low kneepad comfort rating (Table 1). A possible explanation is that these two kneepads relied on foam padding alone, which only provide little in the way of added shock resistance once the foam is

Table 1
The knee pain rating and kneepad comfort rating.

	Ultra Light	Rubber Nonskid	Hard Cap	Armor Pant	Professional Gel	Without kneepad
Knee Pain Rating						
Mean (SD)	2.00 (0.63)	1.82 (0.75)	2.18 (0.60)	1.82 (0.75)	1.55 (0.69)	3.64 (0.67)[a]
Range	1–3	1–3	1–3	1–3	1–3	2–4
Kneepads Comfort Rating						
Mean (SD)	5.73 (2.15)	6.27 (1.49)	6.46 (1.57)	5.80 (2.35)	7.55 (1.44)	2.45 (1.51)[a]
Range	2–8	4–8	4–8	2–8	6–10	1–5

Note: For knee pain ratings, 1 - no pain at all, 2 – little painful, 3 – painful, 4 – very painful and 5 - unbearably painful. The kneepad comfort rating was on a scale of 1–10, with 1 being the least and 10 being the highest comfort while kneeling.
[a] represented a significant different with each kneepad condition.

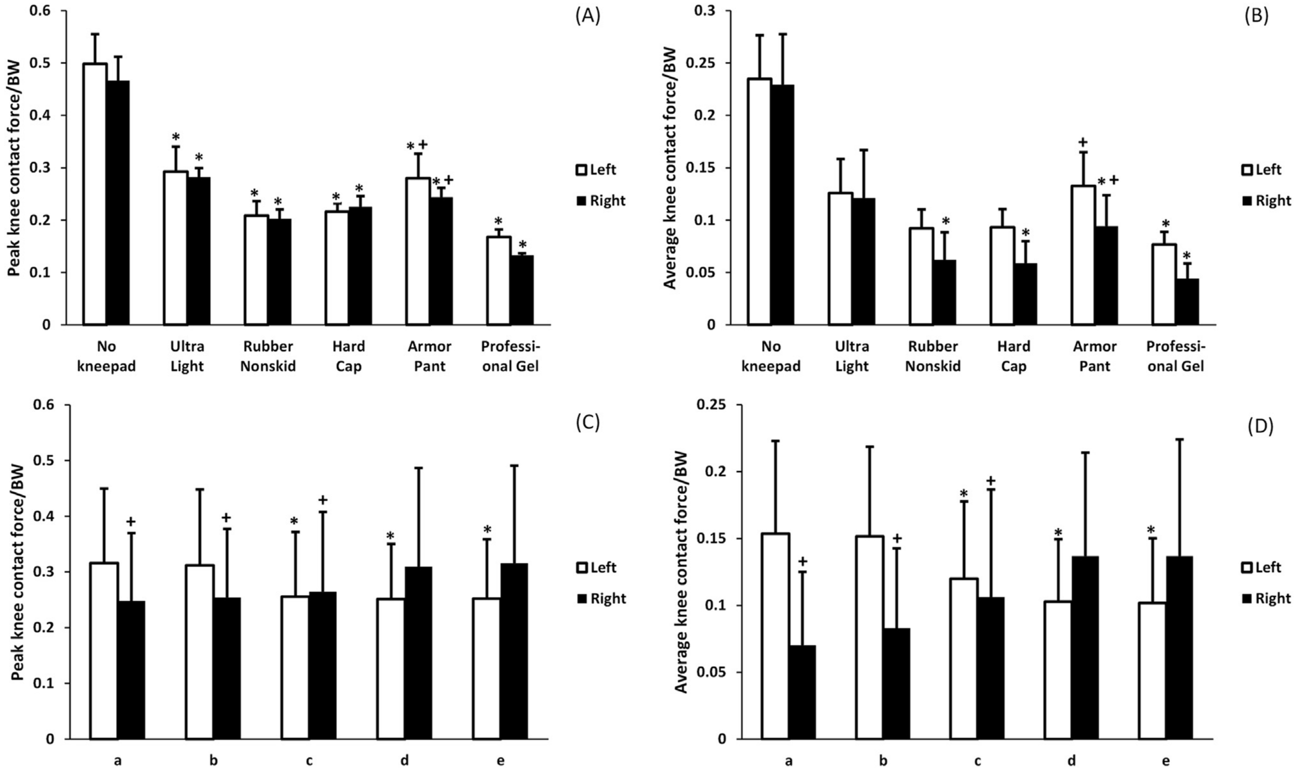

Fig. 4. Peak and average knee contact force by kneepads and locations. In (A) and (B), * indicates a significant difference from no kneepad condition. + indicates a significant difference with the professional Gel. In (C) and (D), * indicates a significant difference with location 'a' and 'b'. + indicates a significant difference with location 'd' and 'e'.

compressed as is often the case during prolonged kneeling postures. Their advantage is that of being very soft and light weight. While the Rubber Nonskid and Hard Cap use different outside materials (light weight fabric for Rubber Nonskid and hard plastic for Hard Cap), they both employ an outer shell and inner foam padding that rests directly against the region around the patella. The performance of the Rubber Nonskid and Hard Cap was better than the Ultra Light and Armor Pant (Table 1 and Fig. 4a, b) due to the additional protection from the hard outer surface which provided improved cushioning on the knee during longer duration kneeling. However, these kneepads did not provide a balanced position and tended to rotate the knee laterally, which increased the difficulty for the participants to balance while kneeling. The Professional Gel was rated as the least painful and most comfortable kneepad among the participants. This result was supported by more than a 70% reduction in the knee contact forces compared with the no kneepad (Fig. 4a, b), which mean the peak and average knee contact force significantly decreased to approximately 450 N and 200 N respectively when wearing the Professional Gel, from 1500 N to 700 N for the without kneepad condition. Two possible reasons for the Professional Gel as a priority selection were a larger cap on the outer side which appeared to redistribute the forces at the knee over a greater surface area, and the resilient gel offered better stability by improving contact with the knee when under load, even in the extreme postures (Pollard and Porter, 2011; Springer, 2006). Disadvantages of the Professional Gel design included, its greater weight, bulkier size and higher cost.

Locations 'a' and 'e' were reported as most uncomfortable by the participants, which agreed well with the knee contact forces measured with the sensors. The results revealed that the peak and average knee contact forces increased 24% and 28% at the corner (location 'a') than the center (location 'c') for the left knee, and corresponding values were 19% and 29% when comparing location 'e' to location 'c' for the right knee (Fig. 4c, d). No significant kneepad × location interaction effects were found in this study, but further analyses indicated the difference in performances of kneepads were greatest on the weight-bearing knee at the corners (location 'a' and 'e'). Work practices should instruct employees to reduce exposure to tasks requiring these extreme reaching positions when possible. However, when this is unreasonable, there are kneepads such as the Professional Gel that can help redistribute forces better than others. Additionally, repositioning to maintain a balanced distribution of body weight on both knees while wearing a suitable kneepad, such as the Professional Gel, can result in a greater reduction in knee joint loads.

The similar ratio between average and peak force (approximate one to two, Fig. 4a, b) without kneepad and with kneepad conditions in our study indicated that these kneepads tended to reduce the force for knee joint anatomical structures proportionally. A novel kneepad design could be centered on reducing the peak force through force redistribution on key structures such as the tibial tubercle to prevent excessive loads (Porter et al., 2010; Moore et al., 2009, 2012). However, some previous studies demonstrate that the kneepad alone may have limited ability on the overall application of stress to the knee during kneeling but for redistributing the loads to neighboring anatomical regions (Porter et al., 2010; Moore et al., 2009). Our literature review revealed no research documenting the effect of kneepads on the internal structures of the knee such as in the ligaments and meniscus. Future studies should focus on defining the change in internal forces and stresses while using kneepads to yield useful information for kneepad improvement and design.

The results of this study should be interpreted in consideration of some limitations. First, the sensors placed on the knee cannot cover the entirety of the knee in contact with the force plate surface. Therefore, the magnitude of peak and mean forces are likely underestimated which was observed by comparing the knee forces between the force plates and the knee sensors. However, the force percentage reductions from knee sensors detected represent valid differences between kneepad designs. Second, the contact force is dependent on the sensor placement on the knee and also the precision of the resistive based sensors. Although the same technique of placing the FFS on the knee was adopted for all the participants, the magnitude of force may change due to the individual difference of knee joint and 2.5% measurement difference of full scale based on the FFS repeatability. Third, the kneeling circumstance that the FFS measured with the kneepads included tissue deformation and was a little different than the calibration process made against the two hard flat surfaces (force plate and dynamometer) and may induce some potential error. Efforts were made to control this source of error by backing each sensor with a rigid disc to prevent deformation from bending. Finally, the simulated kneeling work envelope in the present study mostly represented common kneeling posture of floor layers which may limit the ability to extend the conclusion to other kneeling specific tasks.

5. Conclusion

In summary, knee joint forces were quantified for different kneepads in the present study to determine how kneepad design modifies forces on the knee joint. The results revealed that kneepads can redistribute forces on the knee joint during kneeling work. The Professional Gel was preferred among the five types of kneepads in this study. These results were confirmed with both objective force measurements and subjective responses by participants. The work location significantly affected the loading distribution on both knees. We determined that the location at the end of the reach profile induces higher forces on the knee closest to the reach location which was perceived as discomfort by participants. Working at a location in a more neutral posture, and with a suitable kneepad would efficiently reduce loading on individual knee joints. Future research will focus on evaluating the effect of postures on the internal structures of the knee joint to yield useful information for kneepad improvement with the goal to reduce knee disorder risk.

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