The effect of kneepads on balance while kneeling or squatting

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In all industries, maintaining balance is essential to ensure that workers can safely perform their job duties. In low-seam underground coal mines, workers perform their duties while kneeling, squatting, and crawling with kneepads. In this study, researchers examined the effects of kneeling and squatting on balance measures under the right knee (for kneeling) and right foot (for squatting) with and without kneepads. Results showed that kneepads did not significantly affect balance. Posture had a significant effect on balance measures, with squatting postures showing reduced balance compared to the kneeling postures. For the kneeling postures, ground force measurements were also correlated to balance measures. Posterior tibial forces were shown to have the greatest correlation to mediolateral and anteroposterior average velocities. Force and balance measures highlight a compromise between loading and balance, where improved balance is achieved with increased knee loading.

INTRODUCTION

Many occupations require workers to assume kneeling or squatting postures to perform their job. Restricted workspaces can force workers to stoop, kneel, or squat sporadically or for their entire shift. In underground low-seam coal mines, workers are forced to kneel or squat in high knee flexion throughout their shift. Many low-seam coal miners choose to wear kneepads to protect their knees from the mine floor, which may contain sharp rocks. While kneeling or squatting and wearing these kneepads, they must also perform work activities such as shoveling, operating mining equipment, using powered tools, and handling materials.

In any occupation, the ability to safely perform routine activities while unsupported (i.e., without leaning or sitting on an object) requires that workers maintain their balance. This is true during ingress/egress from equipment, squatting and using powered tools, or kneeling upright and performing a manual materials handling task. Mezzarane and Kohn (2008) noted a decrease in sagittal plane postural sway when bilaterally kneeling upright. They proposed that this improved stability was the result of the decreased instability associated with kneeling, with the center of mass being closer to the ground. Materials handling while in restricted postures can increase the potential for loss of stability or balance. Bhattacharya et al. (2008) measured postural stability of 25 underground coal miners while performing differing mining tasks in kneeling and stooping postures in varying surface conditions. Measures of interest included the sway area, sway length, and mediolateral and anteroposterior excursion. Results showed kneeling on one knee to be more unstable than kneeling on both knees, with miners reporting that they felt more unstable when kneeling on one knee.

Maintaining balance is a dynamic task characterized by the acquisition of and coordinated response to sensory information from multiple body systems. Kneeling or squatting places additional demands on the visual and proprioceptive systems and requires spatial adaptation for maintenance of balance while performing work tasks (Diener et al., 1986; Vander et al., 1978). In these conditions, the workers' ability to maintain their balance while working may be diminished, resulting in loss of balance. This loss of balance may be catastrophic in an underground mine where mining equipment is often remotely operated and attributed to multiple pinning and striking accidents each year. (Colley et al., 2006)

Little research exists on balance while in kneeling or squatting postures. Further, research on kneeling balance has neglected to include kneepads, which are likely to affect kneeling stability. Previous research has examined the effects of kneepads on long-term gait patterns, finding no significant effect (Castagno, 2004). However, due to the variability in kneepad design (material, size, and fixation methods), there still exists a possibility that some kneepads may affect gait dynamics or balance when kneeling or squatting. Specifically when kneeling on one's knees, the kneepads rather than the knees make contact with the ground. The surface of the kneepad may introduce more propensity for the user to slide (as when there is little surface friction) or rotate (as when there is little ground contact area).

The goal of this research was to determine the effect of kneepad usage on kneeling and squatting balance. Typically, standing balance is quantified by the motion of the center of pressure as a subject stands with both feet on one force plate. However, due to the complexities of the kneeling postures and the asymmetry of kneeling on one knee, the authors chose to quantify the balance at the knee by measuring the motion of the center of pressure under the subject's right knee (for kneeling postures) or right foot (for squatting).

METHODS

Ten subjects (7 male, 3 female) recruited from the National Institute for Occupational Safety and Health (NIOSH) in Pittsburgh, PA, participated in this study. The average ± standard deviation (SD) of age, weight, and height were 34 ± 17 years, 683 ± 98 N, and 169 ± 8 cm, respectively. Subjects were healthy, with no history of knee surgery. Prior to participating, each subject read and signed an informed consent form approved by the NIOSH Human Subjects Review Board.

To ensure kneeling, work area height was restricted to 1.2 m (48 in). Four postures were selected based upon those observed to be commonly adopted in low-seam mining: Squat, Near 90, Near Full, and One Knee (Figure 1). Subjects performed each posture for three kneepad conditions: no kneepads, articulated kneepads, and non-articulated kneepads (Figure 2). 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 firm inner padding. The non-articulated kneepads consisted of a soft outer rubber shell and soft inner foam padding. Testing was blocked by kneepad condition, which was randomized, and, within these blocks, the testing order of postures was also randomized. One trial per kneepad condition was collected for each posture.

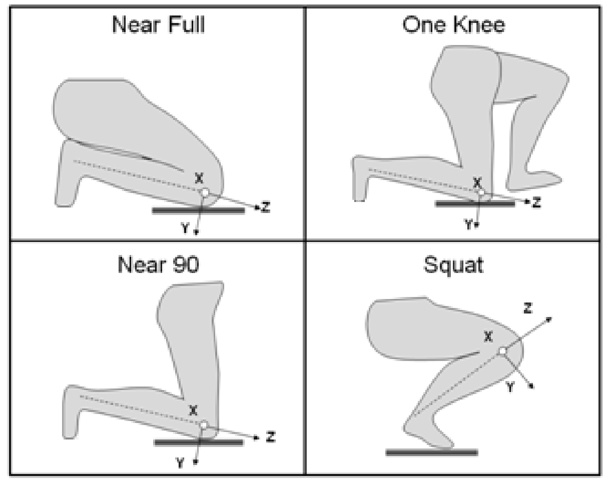

Figure 1: Postures studied with orientation of the anatomical tibial coordinate system. The x-axis was in the lateral direction of the right knee, the y-axis was in the anterior direction of the right knee, and the z axis was in the superior direction of the right knee. The black bar indicates the placement of the force plate.

A motion capture system (Eagle; Motion Analysis Corporation, Santa Rosa, CA) was utilized to determine the orientation of the knee as the subject assumed the four postures at a sampling rate of 60 Hz. With the use of kneepads, it was not possible to place markers on the medial and lateral epicondyles of the knee. Instead the locations of these markers were determined from a calibration trial per the methods in Pollard (2008). Two different marker sets were used: (1) anatomical marker set and (2) measured marker set. These were modified versions of the Cleveland Clinic marker set (Kirtley, 2006). The anatomical marker set was composed of the measured marker set with 8 additional anatomical markers. Calibration data of the combined marker sets were collected to acquire the anatomical marker locations relative to the measured markers. During actual testing, the anatomical markers were removed. The estimated locations of the anatomic landmarks were accurate to within an average of 9% for all postures. Euler angle decomposition was used to determine the knee angles relative to the anatomical coordinate system of the knee (shown in Figure 1).

A force plate (0R6-5-2000; Advanced Mechanical Technology, Inc., Watertown, MA) was used to capture the center of pressure (COP) location and ground reaction forces on the right knee for Near Full, One Knee, and Near 90 and the right foot for Squat (see force plate placement in Figure 1). Force plate data were collected at 1020 Hz using the software provided by the Motion Analysis Corporation (EvaRT 5.0; Motion Analysis Corporation, Santa Rosa, CA) through an analog-to-digital board (PCI-6071E; National Instruments, Austin, TX). Posterior ground reaction forces were calculated by transforming the force data in reference to the force plate coordinate system to the anatomical tibial coordinate system, as shown in Figure 1. Transformation matrices were created allowing the relative orientation of the tibia to be determined from the position of cluster markers located on the thigh and shank during testing (Pollard, 2008). COP data were analyzed using a custom MATLAB script. Average and RMS velocity of the COP data were calculated for both the mediolateral and anteroposterior directions. Total sway area of the COP was also calculated. Balance measures with higher values were indicative of increased postural sway and decreased stability.

Figure 2: Kneepads used in this study. Outer shell, inner padding, and side views of the articulated kneepad (A) and the non-articulated kneepad (B). Both kneepads used straps that attached a little above and below the crease of the knee.

Prior to each trial, the subject was shown a diagram (similar to Figure 1) and asked to assume each posture. Minimal verbal feedback was given unless the subject was assuming a posture with knee angles grossly different than what was expected. Force data were collected for 10 seconds. Each trial was performed once and the subject was provided seated rests between trials.

A split-plot analysis of variance (ANOVA) was performed to determine if significant differences existed in the balance measures between postures and kneepad conditions. A regression analysis was performed on each balance measure as a function of ground reaction forces. Polynomial regression was performed for several measures where the data indicated a non-linear relationship. Alpha values were set at 0.05 for all analyses. All statistical analyses were performed using Statistix 8.0.

RESULTS

Mean included, varus/valgus, and internal/external rotation angles at the right knee were determined for kneeling, squatting, and standing, as shown in Table 1. Near Full and Squat had similar included knee angles and resulted in end-range knee flexion. Near 90 and One Knee had decreased knee flexion.

Table 1. Mean (standard deviation) of the knee angles for all postures and kneepad conditions.

		Included	V/V	I/E
Non-articulated	Near 90	66.9 (14.0)	2.1 (4.7)	6.0 (6.9)
	Near Full	24.4 (14.9)	0.8 (4.4)	10.7 (8.5)
	One Knee	51.1 (29)	2.7 (3)	7.0 (13.2)
	Squat	20.9 (13.2)	-1.1 (1.8)	19.0 (13)
Articulated	Near 90	67.9 (11.1)	0.6 (5)	7.1 (6)
	Near Full	19.1 (9.0)	1.6 (3.5)	15.7 (8.7)
	One Knee	53.5 (20.7)	0.1 (2.1)	5.2 (8.2)
	Squat	18.8 (12)	0.5 (1.2)	20.8 (11.6)
No Kneepad	Near 90	61.2 (14.5)	-0.6 (5.7)	5.8 (7.4)
	Near Full	17.5 (9.3)	0.6 (3.3)	13.5 (10.2)
	One Knee	43.2 (25)	0.4 (4.3)	8.3 (10.6)
	Squat	19.7 (11.7)	1.4 (1.4)	19.5 (13.2)
	Standing	173.8 (3.2)	-0.9 (3)	-0.8 (0.6)

No significant differences were identified for the balance measures with respect to kneepad conditions. Consequently, data were collapsed across all kneepad conditions (no kneepad, articulated, and non-articulated). Significant differences in all balance measures were found between postures ($p<.001$) with Squat having the highest level when compared to the kneeling postures (Figure 3). Since the Squat posture was significantly greater in the majority of balance measures and different in physical form from the three kneeling postures (i.e., the knee does not make contact with the ground when squatting) it was excluded from the subsequent analysis.

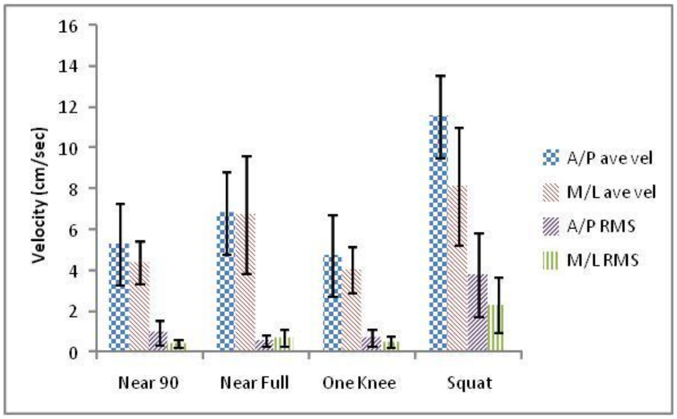

Figure 3: Balance Measures (Mean ± SD) of the average velocity (ave vel) and root mean square (RMS) of the COP in the anteroposterior (A/P) and mediolaterial (M/L) directions by posture.

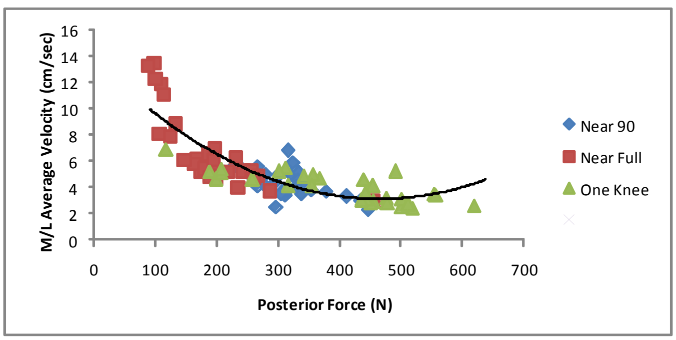

Figure 4: Average velocity of the COP at the right knee in the M/L direction as a function of posterior tibial force.

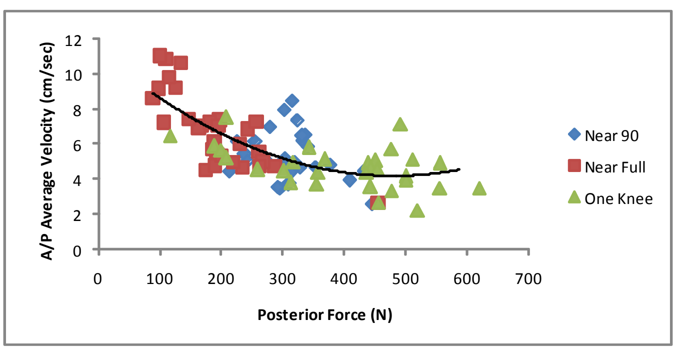

Figure 5: Average velocity of the COP of the right knee in the A/P direction as a function of posterior tibial force.

To further examine the posture effect on the balance measures, a regression analysis was performed. A significant correlation was found for most balance measures, showing a decreasing balance measure (improved balance) with an increasing posterior force on the knee. Posterior tibial forces were shown to have the greatest correlation to mediolateral (Figure 4) and anteroposterior (Figure 5) average velocities, with polynomial fits having r-squared values of 0.6972 and 0.5090, respectively, when combining data across kneeling postures.

DISCUSSION

In this study, the motions of the centers of pressure of the right knee (for kneeling postures) and right foot (for squatting) were measured while subjects performed a static kneeling or squatting trial with and without kneepads. Kneepads had no significant effect on the balance parameters of interest. However, the authors believe that the inherent instability present when kneeling or squatting masked the degree of instability attributed to the kneepads resulting in no significant effects.

Of the regressions studied, the posterior force applied to the tibia when kneeling was shown to have the greatest correlation to the balance parameters, with higher posterior forces resulting in decreased sway parameters. This result was somewhat unexpected, as previous research found that kneeling on one knee (which had the highest posterior forces) to result in decreased balance (Bhattacharya et al., 2008). The stability attained while in kneeling or squatting postures is highly dependent on the tasks being performed, and future research will be necessary to determine the most and least stable restricted postures (kneeling on one knee, upright kneeling on both knees, kneeling near full flexion, deep squatting) for differing tasks.

Kneeling near full flexion had the highest average velocities in the mediolateral and anteroposterior directions of all the kneeling postures. This posture was also associated with the smallest posterior forces. In this posture, many subjects chose to sit on their heels, thereby distributing their body weight through their feet (via heel-gluteus contact) and calves (via thigh-calf contact). This position reduces the amount of body weight placed on the knees, resulting in decreased posterior ground reaction forces on the knee.

In most balance research, balance measurements are obtained for trials over 60 seconds in length. In this study, subjects performed these postures for 10-second trials, which is a limitation of this study. The researchers expected that any longer trials would only exacerbate those differences in balance measures as subjects would be required to maintain their balance for a longer period. The small sample size (10 subjects) used in this study was also a limitation. However, with more subjects the authors expect the trends shown in Figure 3 to remain unchanged. Additionally, the differences in kneepad conditions were not statistically significant and increasing subjects or trial length is not expected to make these differences statistically significant.

The use of one force plate for COP measurements was also a limitation in this study. The postures of interest created two (Squat), three (One Knee), and four (Near 90 and Near Full) points of ground contact. However, in all the kneeling postures, most of the bodyweight was supported by the knee(s). In squatting, this bodyweight is supported almost equally by the feet. The authors feel that given this distribution of support, any loss of balance or instability at the right knee (Near 90, One Knee, and Near Full) or right foot (Squat) would contribute to a loss of balance. Therefore, the balance measurements obtained under the right knee is representative of a subject's overall balance.

Kneeling and squatting are complex postures which result in increased loading on the internal knee structures along with increased postural sway when compared to standing. Squatting increases postural sway but also affords great mobility and allows for rapid changes in postures. Kneeling postures are more sedentary and provide increased stability when more body weight is supported by the knees. Kneeling near 90° or even kneeling on one knee allows a worker to very easily change their posture, by leaning or beginning to crawl providing some mobility. Kneeling near full flexion requires that a worker raise their pelvis before they can crawl, thus affording limited mobility. This study identified a trade-off between balance and knee loading. When working in restricted workspaces, workers are forced to compromise—knee loading for kneeling stability and increased mobility for decreased stability. This is a necessary consideration when examining postures in restricted workspaces.

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DISCLAIMER

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

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