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Postural stability associated with restricted ceiling height mining tasks

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Abstract. The manual material handling tasks in underground low seam mines present a myriad of ergonomic risk factors, which place inordinate demands on the miners' neuromuscular system. The mining industry requires work in restricted postures in mines with low-ceiling heights (low-seam mines). Material handling while in a restricted posture will cause an increase in the potential of loss of stability/balance to increase. Currently, such information does not exist for material handling while in a stooped/kneeling posture. The overall purpose of the study was to quantify postural instability of low seam miners while carrying out mine related tasks. For this study, a total of 25 miner subjects were tested. Each subjects' postural stability was quantified while performing simulated mining tasks under a low seam ceiling. The quantification of postural stability constituted exposure to individual and combined risk factors of 3 types of surfaces (firm-dry DCOF: 0.90, uneven-dry DCOF: 0.59 and firm slippery surfaces DCOF: 0.22); 2 types of environmental lighting (poor and glare); 2 types of postures (kneeling postures using one knee and two knees); and 4 types of mining tasks (stationary, lifting buckets of bits, lifting cables and scaling). Based on the results, the tasks of lifting of bits, cable lifting, scaling and stationary were ranked least to most stable as they relate to miners' postural balance, respectively. This finding is consistent with ranking of tasks producing the most to least number of observed slip events (during task performance) to be lifting of bits (19.4% slips observed), cable lifting (18.9% slips), scaling (16.3% slips) and stationary tasks (4% slips), respectively. Based on all the experimental conditions that were varied, the one knee posture was more unstable compared to the two-knee posture. A one-knee posture was rated higher in terms of both RPE and PSOS as compared to a two-knee posture, which is consistent with the objective measures of postural stability/balance. While consistency between subjective and objective measure supports the fact that miners were correctly judging the threat of instability associated with the one-knee posture, they were not successful in deploying appropriate and corrective postural responses to minimize slips during task performance with one-knee posture as this posture (as opposed to two-knee posture) produced the largest numbers of slips. This may suggest that a re-evaluation of the methods used to complete tasks be accomplished in order to develop changes in work methods that will minimize slips and/or falls during task performance.

Keywords: Low seam mining task, postural instability, miners, loss of balance, base of support, perceived sense of slip and fall

1. Introduction

The literature indicates that injuries associated with performing a manual task are a major part of all accidents in the mining industry both in the USA and other countries [7,11,25]. Based on MSHA data from 2001 to 2003 "handling materials and slips or fall" accounts for over half of the serious injuries (defined as those classified as permanently disabling and those which caused more than 20 days of lost

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work) reported [23,28,29]. Based on 2003 MSHA statistics, the underground injury rate was greater than the surface injury rate (6.3 vs. 2.6 per 100 FTE workers) [23,31]. The highest percentage of nonfatal lost-time injuries was 35% due to manual material handling followed by 24.9% for slips and falls [23]. The mining industry requires work in restricted postures in mines with low-ceiling heights such as low-seam mines [24]. These restricted postures require workers to exert higher muscle forces [15] and require higher energy consumption [12]. Additionally, restricted posture limits the weight that can be safely handled by workers [13]. Stooping or kneeling produces additional demand on visual, vestibular (due to tilted head, shoulder and abdomen), and proprioceptive (due to non-normal posture) systems and requires spatial adaptation for maintenance of balance while performing the task [10,33]. Under these circumstances, the worker's ability to maintain safe upright balance during task performance may be jeopardized, resulting in near fall and/or fall related incidents. Significant research work has been carried out in the area of work physiology and biomechanics of low back injury associated with mining tasks in restricted postures [14]. Gallagher et al.'s study of back injury in mines implied that kneeling postures may decrease stability and balance, however no quantitative data were given [13]. In summary, the literature is not comprehensive in the area of ergonomics of postural instability and potential loss of balance associated with mining tasks performed in restricted postures (kneeling and stooping) under individual and combined risk factors found in low seam mines. This is one of the major issues dealt with in this study.

Miners are exposed to a variety of risk factors, both individually and collectively, on a daily basis at their workplace. Some of these risk factors are: wet/muddy/slippery surface, uneven walking surfaces, restricted workspace, poor environmental lighting, limited ceiling height (in low seam mines), heavy lifting and high whole body vibration [11,25]. Manual handling of materials in a restricted workplace require miners to assume postures, that may pose dangers to his/her ability to maintain "safe" postural stability (i.e. without causing a fall or near fall incident to occur). The conditions which will allow "safe" postural stability during performance of manual material handling tasks (such as lifting) include: a firm foot placement and a big enough base of support (BOS) or stability boundary (BOS defined by the outer boundary of the feet during standing; during kneeling BOS is defined by the knee and toe placement) so that the body's center of gravity (CG) can stay inside the BOS and thereby minimize any potential loss of balance [1,2]. In a workplace with restricted ceiling heights, such as those found in the underground low seam mines, the miners may not have the luxury of taking an appropriate stepping action to increase their BOS during material handling task performance. Under these circumstances, miners are forced to perform their tasks while being at the outer edge of their stability boundary. When the body's CG is at or near its outer edge of stability boundary during task performance, a small perturbation in body motion (such as a sudden move or a shift of the load being handled) and/or reduction in the coefficient of friction (COF) of the standing/walking surface, could easily jeopardize a miner's ability to maintain upright balance. Therefore, manual tasks involving as lifting or thrusting action (which will increase the COF demand at the shoe/floor interface) such as performing a task with a Scaling Tool (Scaling Task) and/or walking in a stooped posture could place miners at a constant risk of loss of balance, which may result in a near fall and/or an actual fall event and possibly resulting in serious injuries. Manning et al. [21] reports risk of back injury during slips/falls. During unexpected events such as slips/falls or near falls may cause the trunk muscles to overcompensate thereby overload the spinal unit [22].

The manual material handling tasks in underground low seam mines present a myriad of ergonomic risk factors, which place inordinate demands on the miners' neuromuscular system. Generally, before a fall incident occurs, the worker first experiences postural instability or the propensity for postural instability, which in some cases may result in unrecoverable loss of balance. The ability to sustain upright balance requires continual input from several sensory systems. These include proprioceptors in the joints, pressure receptors in the soles of both feet, along with the visual and vestibular systems [33]. Continuous regulation of balance results through patterns of neuromuscular coordination along many afferent and efferent pathways. Workplace risk factors such as environmental lighting, glare, standing surface compliance and slipperiness, muscle fatigue, loss of peripheral vision and task type have been found to modify the effectiveness of the sensory system's functionality in the maintenance of postural stability of the worker in an unrestricted ceiling height [1,3,8,9,19]. However, currently such information does not exist for material handling in a stooped and kneeling posture with restricted ceiling height. This study provides this type of information.

The objectives of this study were: 1) to determine the postural imbalance of miners while performing simulated mining tasks in restricted and/or low-ceiling height spaces. 2) To determine the combined contributions of various risk factors on balance maintenance during task performance in a low-ceiling mine and/or in restricted height areas. These risk factors included environmental lighting, kneeling posture, and surface friction conditions.

2. Methods

2.1. Participants

Twenty five miners were recruited from the United Mine Workers of America, (UMWA) District 17, Local 2264, Pikeville, KY as well as mines in Middlesboro, KY. Subjects interested in participating were mailed a health survey questionnaire which obtained information about the subjects' current or past exposure to different chemicals/industries/hobbies that have the potential to affect their central nervous system, and hence, their postural balance. The following were the exclusion criteria based on the health survey questionnaire results: daily requirements of prescription medication which may act upon the central nervous system, significant history of dizziness and/or tremors, alcoholism, vestibular, neurological, or cardiopulmonary disorders, diabetic symptoms, and acute or chronic low-back or knee pain. Those who met the inclusion criteria were scheduled for a physical examination by a registered Nurse Practioner.

2.2. Risk factors/treatment conditions (*Independent Variables*)

2.2.1. Ceiling Restriction

The ceiling height under which miners had to perform the simulated mining tasks was 111.76 cm which was considered to be a medium ceiling height mine [28]. In low seam mines the ceiling heights could be as low as 91.44 cm.

2.2.2. Mining Surface/Contamination

Three surface conditions were used in this experiment: (1) dry firm surface which served as an ideal surface condition and as a baseline and was represented by a dynamic coefficient of friction (DCOF) of 0.90, (2) dry uneven surface which simulated the rocky surface of a mine and was represented by a DCOF of 0.59 and (3) firm-slippery surface which simulated slippery conditions from contaminants such as water/mud in the mines and was represented by a DCOF of 0.22. Mineral oil was selected as the medium for creating a slippery surface with desired COF between the shoe and the floor. Aluminum plates (#6061-T6, Brinell Hardness 85) were placed on top of the force platform, connected with a magnet, so that the contaminants were not placed directly on the force platform. 20 ml of mineral oil applied to the aluminum plate gave us the desired DCOF of 0.22 which will cause slipping but balance will be recoverable [16,27,30]. To determine the friction generated by the different shoe-lubricant and floor slipperiness combinations, a series of COF tests was conducted. Dynamic COF between a new shoe and testing surfaces (firm dry and firm slippery aluminum plates and irregular/uneven surface) were obtained using an existing computerized tribology set-up [9]. To create an artificial surface that mimicked a mine floor surface, but was durable and washable, coal was laid across a flat surface to create the positive form. A negative mold was then made from a synthetic cast (Synair Por A Mold S555) to be used as the mother mold. A prototype of 1' by 1' was poured using a polymer (Replicast 112, PTM&W Industries Inc., Santa Fe Springs, California). The prototype was inspected and approved by the President of the United Mine Workers Association (UMWA) Local 7093 in Pikeville, Kentucky. A total of 48 surfaces were poured to make 2 sets of surfaces, one for the dry condition and one for the slippery condition. These surfaces (firm and uneven) were placed on top of the force platforms and the surrounding area. A self-adhesive magnet (flexible magnetic sheet #8621, 0.06"x24", Magnet Sales and Manufacturing, Culver City, CA) was affixed to the top of the force platforms for attachment of the various surfaces.

2.2.3. Enviornmental Lighting

Two types of environmental lighting were used. The poor lighting condition represented the miners' working in light provided by their headlamps and equipment. Since in the underground mines, most of the lighting is limited to a miner's headlamp and equipment lighting, the workers are generally exposed to poor environmental lighting (0.96 fc) and glare type of lighting due to the equipment headlight directly shining into the eyes (5.8 fc). To create the glare lighting condition, a flashlight (Mag-Lite) was held by a staff member such that the light was pointed at the face of the subject. A light meter (Model 840021, Sper Scientific Ltd, Scottsdale, AZ) was used to measure the light level in foot-candles (fc).

2.2.4. Posture

All simulated mining tasks were carried out in two types of kneeling postures: One-knee or two-knee.

2.2.5. Simulated mining tasks

The following simulated mining tasks were completed for the postural balance testing: stationary, lifting a bucket of bits, lifting a cable, and scaling. All tasks were carried out on the large platform and lasted for 30 seconds. The subject kneeled on one knee or two knees for the balance testing. The one-knee posture was standardized with the left knee down. See Fig. 1(a) for the one-knee posture and Fig. 1(b) for the two-knee posture. The following describes the tasks in detail.

2.2.6. Stationary

For this task, the subject knelt below the restricted ceiling, relaxed with their wrists resting on each respective thigh for 30 seconds.

2.2.7. Lifting a bucket of bits

In the mine bits are attached to a ripper head on a continuous miner (a piece of equipment used to mine), which mines the coal. These bits become worn and are replaced on a regular basis. The bit replacements come in a bucket with approximately 25 bits in it. The bucket used in the experiment had a diameter of 18.4 cm, was 22.35 cm tall and weighed 7.4 kg. In the mines, the worker would asymmetrically lift the bucket from the ground up to the Continuous Miner (a machine which extracts coal from the mine wall). After the bits are replaced, the used bits are placed into the same bucket and

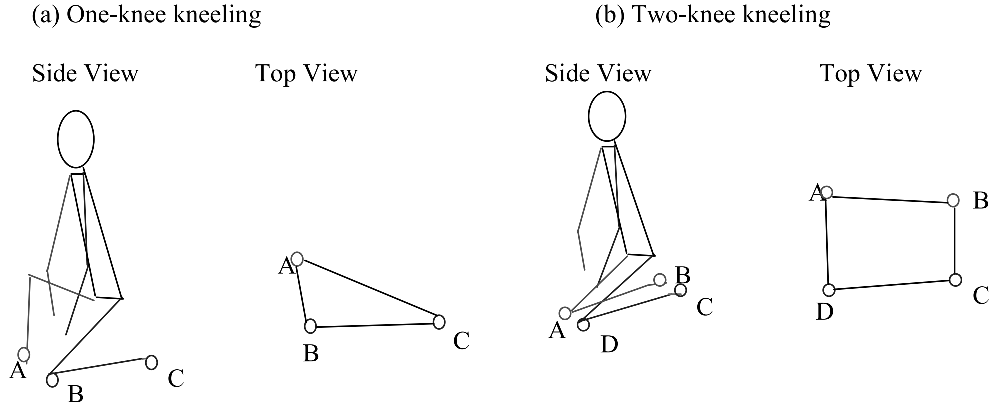


Fig. 1. (a) One-knee kneeling posture [Base of Support (BOS) markers at A = right ankle, B = left knee and C = left ankle] (b) Two knee kneeling posture [Base of Support (BOS) markers at A = right knee, B = right ankle, C = left ankle and D = left knee].

lifted down from the continuous miner. For our simulation, the bucket was lifted from the ground on the left side of the subject up to a 34” shelf on the right side of the subject and returned to the ground. A voice command to begin the lift was given 8 seconds into the 30 second trial. The subject began the trial kneeling in a relaxed position, as in a stationary trial. When given a voice command, the subject began the lift cycle.

2.2.8. Cable lifting

Electrical and water cabling is used throughout the mine. These cables are suspended from the ceiling using either clamps or hooks attached to roof bolts. As equipment and supplies move throughout the mine, these cables must be moved accordingly. To simulate the task of securing the cable, the subject lifted a section of “cable” from the floor level in front of the force platform, up to the false ceiling and then replaced the cable to the starting position. The cable was a rubber hose 115.57 cm long with a 6.35 cm diameter, weighing 7.4 kg. The subject began the lift on a voice command 8 s into the 30 s trials. The subject began the trial kneeling in a relaxed position, as in the stationary trial.

2.2.9. Scaling

Scaling is a task where the miner uses a slabber bar to pry coal from the ceiling surface manually. The subject began the trial kneeling with the slabber bar (weight = 4 kg) in their hands; on a voice command (8 s into the 30 s trial) raised the bar and inserted it into the first location on the scaling structure. The subject “pried” at the first location once and moved the bar to the second location (also on the scaling structure) and “pried” once. After the “pry” at the second location, the subject returned the bar to the starting position for the remainder of the 30-second trial.

2.2.10. Mining Equipment

It was important to simulate the amount of weight the miners wear on their tool belts and the type of equipment used in an ordinary workday. For that reason all miners wore Fab-plus Knee Pads (0.9 kg), Miners Cap MSA type I (0.5 kg). The miners also wore a nylon belt which was modified with weights to simulate the approximate weight of a self-contained rescuer (model # Sr-100) and Koehler Wheat Light (model # 5000 series with battery un2800). The belt with the self-rescue and lamp battery weighed 5.4 kg.

2.3. *Outcome measurements* (*dependent variables*)

The kinetic and kinematic data were collected using a real time video digitization Peak Motus system. Both kinetic and kinematic data were synchronized. This system consisted of (1) Peak Motus-configured computer with Peak Motus 2000 Trial Design and Display Core, Peak Motus 2000 3D Real Time Coordinate Acquisition system and the Peak Motus 2000 3D Calculations Module (version 6.1.11), (2) Nine 60 Hz Shuttered infrared sensitive Cameras. Each camera is linearized by Peak and has a fixed focal length and (3) infrared light sources. Both kinetic and kinematic data were collected at a sampling rate of 60 Hz.

2.3.1. *Kinetic outcomes*

These included the forces and moments in the three orthogonal directions collected using a piezoresistive force platforms (AMTI, Watertown, MA). The platform has a 2' by 4' surface (model LG6-4-1000, serial # 3891) that is large enough for a person to squat and/or kneel.

2.3.2. *Kinematic outcomes*

The spatial model consisted of 14 markers on the body, and several virtual points (4 on the force plate, 6 for the feet, 4 for the ceiling and 1 or 3 for the center of mass – this depended on whether the task required lifting/holding an object), and 2 markers on the object (if the task required lifting/holding an object). The markers on the body included right and left ankle, knee, hip, shoulder, temporal, elbow and wrist.

The virtual points for all trials were created using the Peak Motus system, not physical markers viewed by the cameras and included: Body center of mass, upper left of the large plate, lower left of the plate, lower right of the plate, upper right of the plate, upper right ceiling, upper left ceiling, lower right ceiling and lower left ceiling. The additional virtual points for the trials with an object were: center of mass of object (bucket of bits, cable or slabber bar) and the center of mass of the body and the object together. Due to difficulty digitizing the feet markers in Motus, the feet markers were eliminated. An estimation of their location was made by using measurements taken from the ankle marker on the shoe to the respective points (heel, 1^{st} MTP and 5^{th} MTP) on the shoe. These measurements were used in equations to create virtual points for these markers. Using standard anthropometric data, the additional load due to the miner's belt was added to the trunk segment of our model [34]. Since feet were not included in the spatial model, the trials added the feet mass to the shank. These adjustments were made to accommodate correct calculations of the position of CG for the body segments.

Two trials (lifting bucket of bits and lifting cable) required the subject to begin the trial in a relaxed position and then lift an object. Since lifting of these objects will modify the position of the CG of body segments during the lifting phase the Peak Motus system was programmed to calculate the CG with and without the object's weight. Custom software allowed using the appropriate value of the CG during the lifting phase. This type of analysis was necessary for the accurate calculation of postural instability variables described in the following paragraphs.

2.3.3. *Objective measures of postural sway*

Using the above mentioned kinetic and kinematic data, the following variables were calculated: Sway area (SA) is the area of the projection of the body's center of pressure (CP) on the horizontal xy plane due to postural sway, sway length (SL) is the distance traveled by the CP during the testing period, the medial lateral (ML or x-direction) excursion is the net deviation of the CP in the ML direction and the anterior posterior (AP or y-direction) excursion is quantitated by measuring the net deviation of the CP in the AP direction. These variables have been used in several research studies [1,3,17,18].

2.3.4. Required Coefficient of Friction

From the kinetic data, the horizontal force divided by the vertical force (H/V) is the required coefficient of friction ($\mathrm{COF}_{required}$). The minimum, maximum and average $\mathrm{COF}_{required}$ were calculated.

2.3.5. Objective measures of postural instability/imbalance

Three non-dimensional indices, which are based on those described by Bagchee et al. [1], were used to quantitatively determine the propensity of momentary loss of postural balance and/or instability associated with a sway pattern formed by the whole body CG with respect to the postural stability boundary (i.e. the BOS). These indices were calculated using the custom software (IPSB 2000, version. 1.1.10 Copyright All Rights Reserved, University of Cincinnati, 1998-2008). The three indices used to describe the propensity of postural instability/imbalance are briefly described as follows and details are given in our earlier publication [1].

2.3.6. Index of Proximity to Stability Boundary (*IPSB*)

IPSB measures how close the body's CG travels to a person's stability boundary. A lower value of IPSB implies that the subject has a greater propensity of postural instability/imbalance while performing a given task. A negative value of IPSB implies that subjects' CG is outside the stability boundary. The stability boundaries used for the one-knee and two-knee postures are shown in Fig. 1. Since the true stability boundary can extend beyond the marker placement (tip of toes rather than the ankle) in some trials the IPSB had a negative value, implying that the subject's CG was outside the stability boundary while in fact they were still inside but closer to the true stability boundary. During statistical analysis, those negative values were accounted for to indicate that the subject has a greater propensity of postural instability while performing a given task.

2.3.7. Weighted Residence Time Index (*WRTI*)

WRTI is the weighted measure of time that the subject's CG lies in various proximity zones to the stability boundary. The greater the residence time in the outer proximity zones, the greater is the propensity of postural instability/imbalance for a given task under specified intrinsic and extrinsic conditions. A higher WRTI implies poorer postural stability/balance.

2.3.8. Stability Area Ratio (*SAR*)

In addition to the proximity of the stabilogram (x-y plot of CG movement during the trial) to the stability boundary, i.e. BOS, it is also important to consider the spread of the stabilogram in comparison to the stability boundary. This comparison provides a composite estimation of the CG sway during the entire interval of the task. A ratio of the CG sway area to the stability boundary area is described as a non-dimensional SAR. A larger spread of the CG sway (i.e. stabilogram) will result in a higher value of SAR, which implies greater risk of the CG approaching the stability boundary (i.e. the BOS) and relatively higher postural instability/imbalance.

2.4. Subjective measurements

2.4.1. Rating of Perceived Sense of Slip/Fall (*PSOS*)

The PSOS scale included four questions regarding the subject's experience of postural instability/imbalance while performing the simulated mining tasks [8]. The subject answered these questions after each trial. Each question was scored between 0 to 2 by increments of 0.5. Zero meant that he/she perceived no postural instability/imbalance. The summation of the scores from the four questions defined the overall PSOS score. A score of eight meant that the subject perceived the greatest instability/imbalance. This summed score was used in the statistical analyses.

2.4.2. *Rating of Perceived exertion* (*RPE*)

Subjects were asked their perceived sense of exertion level after each trial using Borg's Self-Rating Scale which ranges from 6, which is "very, very light", to 20, which is "very, very hard" perceived exertion [5].

2.4.3. *Experimental procedures*

All subjects, upon completing the health screening, signed an informed consent form which was approved by the University of Cincinnati Institutional Review Board. All subjects wore laboratory supplied shorts which were designed to accept placement of reflective markers at the anatomical sites of interest described earlier and leather steel-toe boots, model #1778, Carolina Shoe Co. Each subject completed test sessions, which were randomized and blocked by surface type. Subjects completed all test sessions in one day. Each subject completed a total of 48 postural balance trials (3 surface conditions, 2 lighting conditions, 2 postures and 4 tasks) lasting 30 seconds each. The tester observed and recorded whether or not the subject slipped and/or fell during each trial. The tester also administered the PSOS and RPE questions following each trial. A safety harness was worn throughout the duration of testing and was attached to a safety lanyard to prevent fall/slip related injuries.

2.5. *Data analysis*

The data files were imported into the Statistical Analysis System (SAS) for data analysis. Continuous outcomes were analyzed in a mixed repeated measure analysis of covariance models by SAS Proc Mixed; discrete outcomes were analyzed by SAS Proc Genmod. SL, SA and the IPSB, SAR and WRTI outcomes were transformed to their natural logarithm to achieve approximate normality. In the models for the postural balance outcomes, the main effects of surface type (firm-dry, uneven-dry or firm-slippery), task (stationary, cable, bits and scaling), posture (one knee or two knees), and lighting condition (poor or glare) were included as classification variables. Two-factor interactions among each of these main effects were also included in the initial models, as were covariates. Backward elimination of insignificant interactions and covariates was performed until final models were determined that included only the main effects and significant two-factor interactions and covariates. Least square means are reported for continuous outcomes and odds ratios for discrete outcomes. An alpha-level of 0.05 was used to judge significance in all models.

3. Results

Twenty-five miners were recruited for this study. Demographic information is shown in Table 1.

3.1. *Effect of mining tasks and risk factors on objective measures of postural sway response using center of pressure* (*CP*) *data*

The objective measures of postural balance were based on postural sway outcomes, obtained from the force platform, such as SA, SL, ML and AP. In the following postural sway and required coefficient of friction (H/V) results are presented. Table 2 provides p-values from ANCOVA models for testing the effects of mining task, posture type, surface type, environmental lighting and significant two-factor interaction effects and co-factors. An increase in the postural sway variables implies potentially poorer postural balance and an increase in H/V implies that the task carried out required an increased level of shoe-floor friction.

Table 1
Miners' Demographics ($n = 25$)*

Variables		mean	s.d.
Age (year)		42.7	6.87
Weight (kg)		95.44	17.54
Height (cm)		177.78	7.66
Quadriceps (lbs)	Right	60.3	17.8
	Left	60.0	17.5
Hamstrings (lbs)	Right	48.0	13.3
	Left	48.9	12.9
Dorsiflexors (lbs)	Right	49.7	14.2
	Left	50.6	13.6
Plantarflexors (lbs)	Right	70.1	17.8
	Left	70.1	20.3
Foot Reaction Time (m. second)		35.7	4.5
Arm Reaction Time (m. second)		30.8	3.9

*Of the 25 miners, only 3 were females. On average, the miners had about 166 months of experience working in low and high seam mines and strip mines. Only nine miners reported to be involved in doing regular exercise, on the average six hours per week. On the day of the testing average blood pressure of all the miners was normal (129/83 mmHg).

Table 2
P values for testing the effects of task, posture, mining surface, lighting and co-factors on postural sway length, sway area, ML, AP and H/V. $n = 25$ for all variables except as noted otherwise

Effect	Sway Length	Area	ML ($n = 18$)	AP ($n = 18$)	H/V ($n = 18$)
Task	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Posture	0.25	**0.0143**	**0.0001**	**0.02**	**0.0034**
Mining Surface	0.58	0.48	0.11	**0.012**	**0.0135**
Lighting	**0.012**	0.058	0.16	0.67	0.83
Task*Posture	**0.0001**	**0.0001**	**0.0001**	**0.003**	**0.012**
Task*Surface	**0.0082**	**0.004**		**0.012**	**0.025**
Posture*Surface	**0.032**				
Regular Exercise*			**0.0023**		
Mine type*	**0.023**		**0.034**		
Avg Foot Reaction time*			**0.0097**		
Mean Blood Pressure*			**0.016**		

Statistically significant variables ($p < 0.05$) are shown in the bold.
*Only significant covariates are shown.

3.1.1. Effect of mining task

Type of task performed significantly affected all postural sway outcomes ($p < 0.0001$). The stationary task evoked less SA, SL, ML, AP and H/V. Figure 2 provides least square geometric mean responses of all the sway and H/V variables. For most of these outcomes, the bits task elicited the greatest postural sway response, 13907% greater than the stationary task in the case of SA, 351% greater for SL, 2301% greater for ML, 1514% for AP and 1066% for H/V. The mean sway responses for the cable and scaling tasks were typically between those of the stationary and bits tasks, with the exception of SL, AP and H/V. The cable task elicited greater AP sway than did the bits task. The differences in SL responses among bit, scaling and the cable tasks were not significant. The observed slips showed relatively higher slip incidence for bits (19.4%), cable (18.9%) and scaling (16.3%) tasks compared to the stationary tasks (4%).

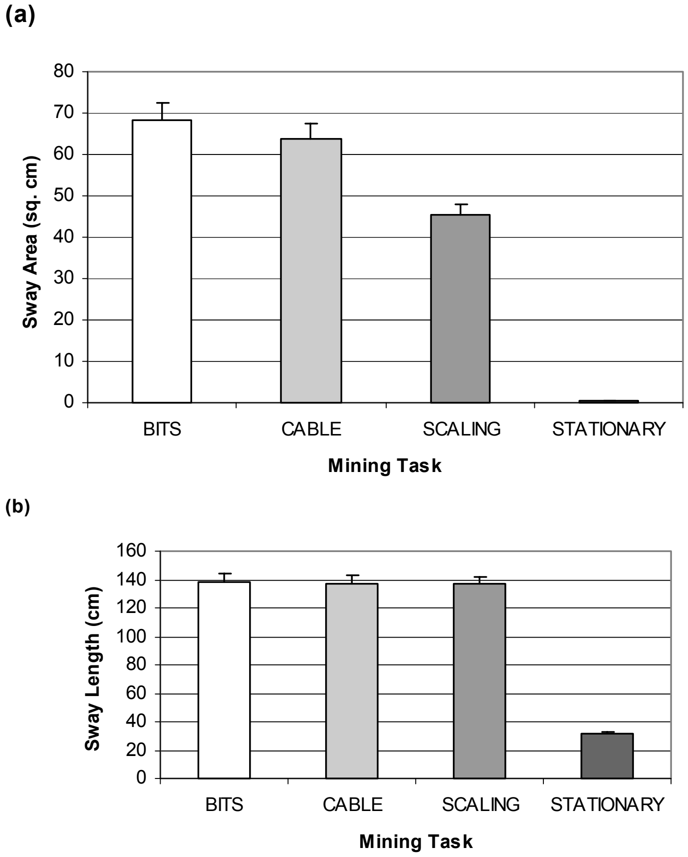


Fig. 2. Effect of mining task on (a) postural sway area (SA), (b) postural sway length (SL).

3.1.2. *Effect of kneeling posture*

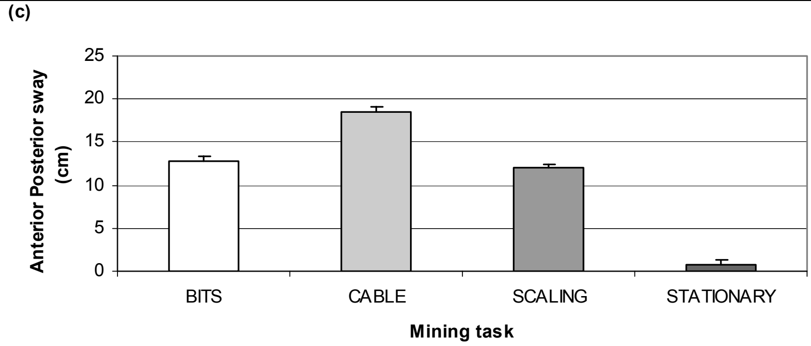
Type of kneeling posture used during task performance *significantly* affected three out of four of the postural sway outcomes (SA, ML and AP) and H/V. A one-knee posture was associated with somewhat greater SA (9.2%) but lessened excursion (13.4% and 6.2% for the ML and AP directions, respectively; figure not shown) and H/V (9.1%), as compared to a two-knee posture (Fig. 3).

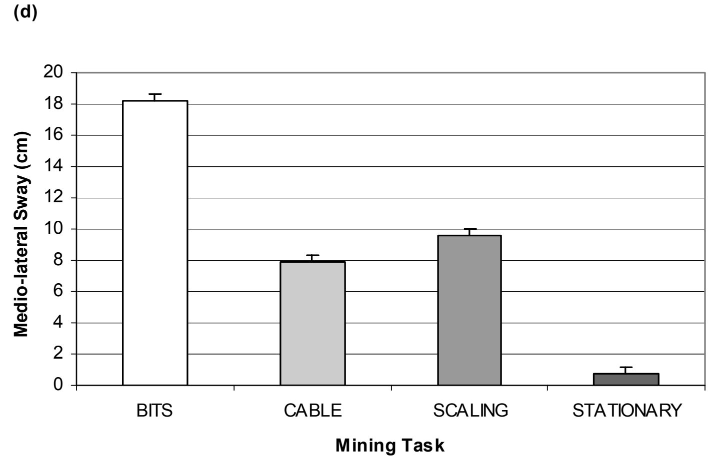
3.1.3. *Effect of mining surface*

The type of mining surface on which miners carried out their tasks significantly affected one of the postural sway outcomes (excursion in the AP direction, $p \leqslant 0.012$) and the H/V ($p \leqslant 0.04$) (Fig. 4). Excursion in the AP direction was found to be least for the firm-slippery surface (7.5% less than the firm-dry and 8.8% less than the uneven-dry surface) (Fig. 4). The uneven-dry surface had the greatest H/V (2.2% and 11.0% greater than the firm-dry and firm-slippery surfaces, respectively) (Fig. 4).

3.1.4. *Effect of environmental lighting*

Lighting significantly affected only SL ($p < 0.012$), with glare evoking slightly greater (3.7%) sway than did poor lighting.





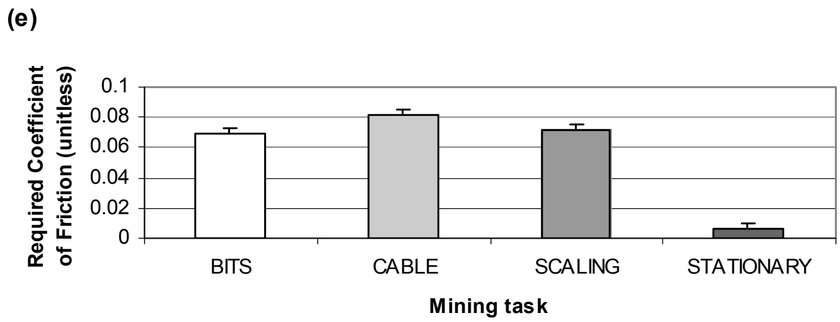


Fig. 2. (c) anterior-posterior sway (AP), (d) medio-lateral sway (ML) and (e) required coefficient of friction (H/V). SA and SL values shown are least square geometric means with the geometric standard errors of the mean and AP, ML and H/V are least square arithmetic means with the standard error of the mean.

3.1.5. Interaction Effects

Task was significantly interacted with posture for all of the sway outcomes and H/V. The greatest SA ($p < 0.0001$), SL ($p < 0.005$) and excursion in the ML direction ($p < 0.0001$) were found for the bits task when miners employed the two-knee posture (figures not shown). The largest excursion in the AP-direction ($p < 0.003$) and H/V ($p < 0.012$) were experienced by miners during the cable task while in the two-knee posture. Task was also significantly interacted with mining surface type for three of the postural sway outcomes (SA, SL and AP) and the H/V variable (Figures not shown). For the bits,

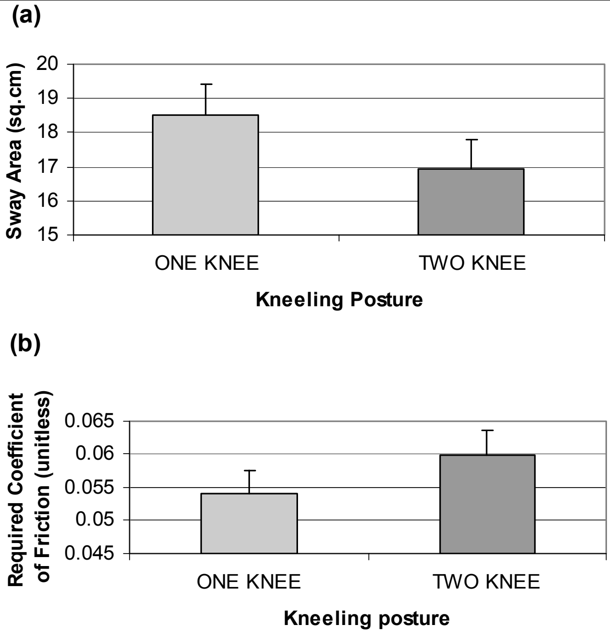


Fig. 3. Effect of kneeling posture on (a) postural sway area (SA), and (b) required coefficient of friction (H/V). SA values shown are least square geometric means with the geometric standard errors of the mean and H/V values are least square arithmetic means with the standard error of the mean.

cable and scaling tasks the SA and SL responses were the lowest for the firm-slippery surface compared to firm-dry and uneven-dry surfaces implying a cautionary body movement on slippery surface. The greatest SA ($p < 0.004$) was experienced for the bits task while the miners were on a firm-dry surface. On the average, in comparison to the stationary task the SL responses of all types of tasks performed on all surface types were relatively higher. The greatest SL ($p < 0.0082$) was found for the cable task while the miners were on an uneven-dry surface. The greatest excursion in the AP direction ($p < 0.012$) was found for the cable task executed on a firm-dry surface. The highest H/V ($p < 0.025$) was found for the cable task performed on an uneven-dry surface.

3.1.6. Cofactors effects

The excursion in the ML direction model included significant covariates. Average foot reaction time, mean blood pressure and the type of mine in which the subjects worked were found to affect this outcome. Regular exercise was found to be a significant predictor of SA and type of mine was found to be significantly associated with SL.

3.2. Effect of mining tasks and risk factors on objective measures of postural instability or imbalance using Center of Gravity (CG) data

While the above section described the effect of the mining task and other risk factors on the miners' postural sway, it did not provide a quantitative measure of postural instability, i.e., the actual risk of fall and/or loss of balance. Quantitative measures of postural instability/imbalance were derived by combining each subject's whole body CG movement data with each subject's base of support (BOS) area, which was calculated from the kinematic system. Three measures of postural instability/imbalance,

Table 3
P values for testing the effects of task, posture, mining surface, and lighting on CG based postural instability outcomes minimum IPSB, SAR and WRTI ($n = 18$)

Effect	IPSB	SAR	WRTI
Task	**0.0001**	**0.0001**	**0.0001**
Posture	**0.0001**	**0.0001**	**0.034**
Mining Surface	**0.047**	0.92	**0.0071**
Lighting	0.099	0.13	0.67
Task*Posture	**0.0001**	**0.0001**	**0.0001**
*Mean Blood Pressure	**0.018**		
Regular Exercise	**0.013**		
Avg Foot Reaction time		**0.0082**	
Physical Effort		**0.001**	
No.of hrs per wk. exercise		**0.0008**	
Avg Arm Reaction time			**0.042**

Statistically significant variables ($p < 0.05$) are shown in the bold.
*Only significant covariates are shown.

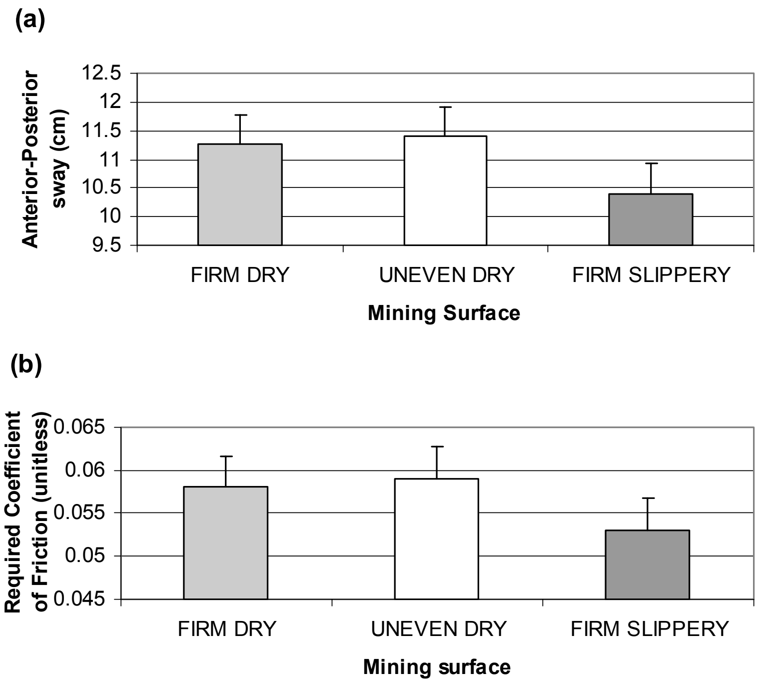


Fig. 4. Effect of mining surface condition on (a) anterior-posterior sway (AP), and (b) required coefficient of friction (H/V). AP and H/V values shown are least square arithmetic means with the standard errors of the mean.

minimum IPSB, SAR and WRTI, were calculated. The method of calculating the indices of postural instability/imbalance are described in the Methods section. The following results are based on data from a subset of subjects ($n = 18$) because a technical difficulty encountered with the kinematic data from the other seven subjects that resulted in these data not being collected. Table 3 provides p values based on ANCOVA models for testing the effects of mining task, posture, surface type, environmental lighting and significant two-factor interaction effects and co-factors. An increase in SAR and WRTI and a lower

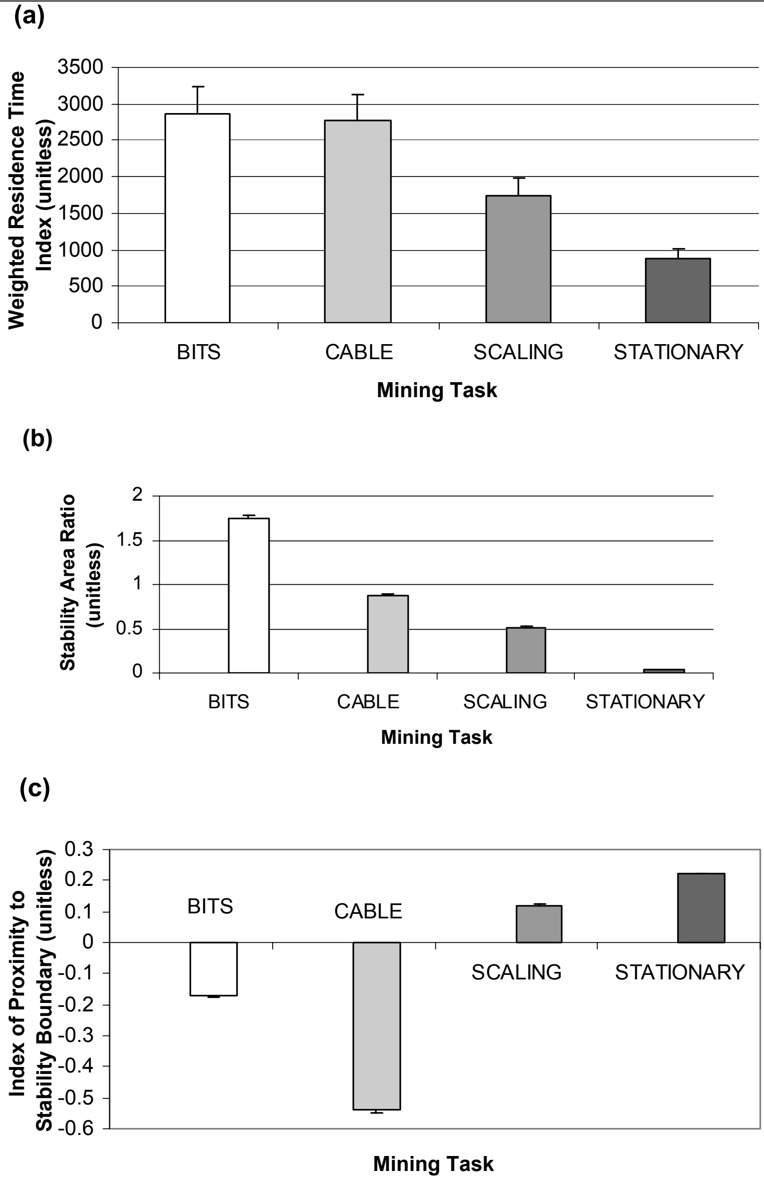


Fig. 5. Effect of mining task on (a) weighted residence time index (WRTI), (b) stability area ratio (SAR), and (c) index of proximity to stability boundary (IPSB) WRTI, SAR and IPSB values shown are least square geometric means with the geometric standard errors of the mean.

value of IPSB implies poorer postural stability and increased propensity for loss of balance.

3.2.1. Effect of mining task

Mining task was a significant predictor of all three postural instability/imbalance indices ($p < 0.0001$). The stationary task produced the greatest minimum IPSB (i.e. lowest), followed by the scaling and the bits task, while the cable task caused the least minimum IPSB. SAR and WRTI were greatest during the bits task, followed by the cable, scaling and stationary tasks (Fig. 5).

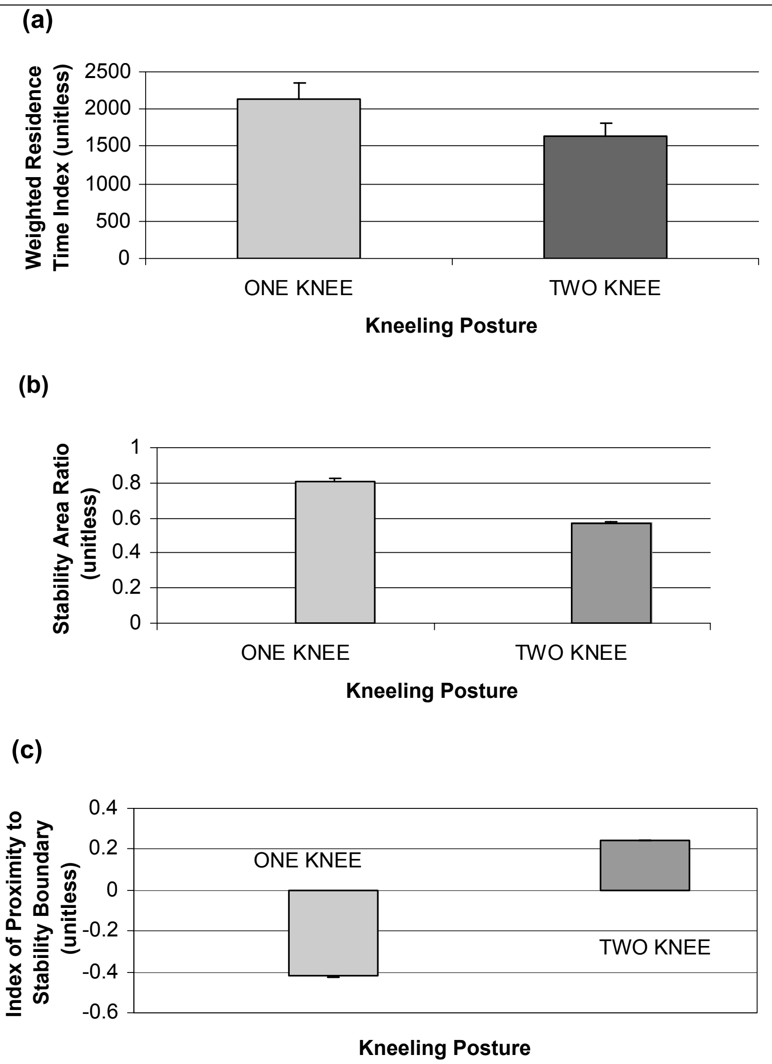


Fig. 6. Effect of kneeling posture on (a) weighted residence time index (WRTI), (b) stability area ratio (SAR), and (c) index of proximity to stability boundary (IPSB) WRTI, SAR and IPSB values shown are least square geometric means with the geometric standard errors of the mean.

3.2.2. Effect of kneeling posture

Type of kneeling posture used during the mining task performance was also significantly related to all three postural instability/balance outcomes (minimum IPSB and SAR, $p < 0.0001$; WRTI, $p < 0.034$). The one knee task elicited lesser minimum IPSB and greater SAR and WRTI than did the two-knee task (Fig. 6). The results provide further support that the one knee posture is more prone to producing postural imbalance than those with two knee posture.

3.2.3. Effect of mining surface

Mining surface type was found to be associated with minimum IPSB ($p < 0.047$) and WRTI ($p < 0.007$). The firm-dry and uneven-dry surfaces produced less minimum IPSB than did the firm-slippery surface. The firm-dry surface produced less WRTI than the uneven-dry and firm-slippery surfaces

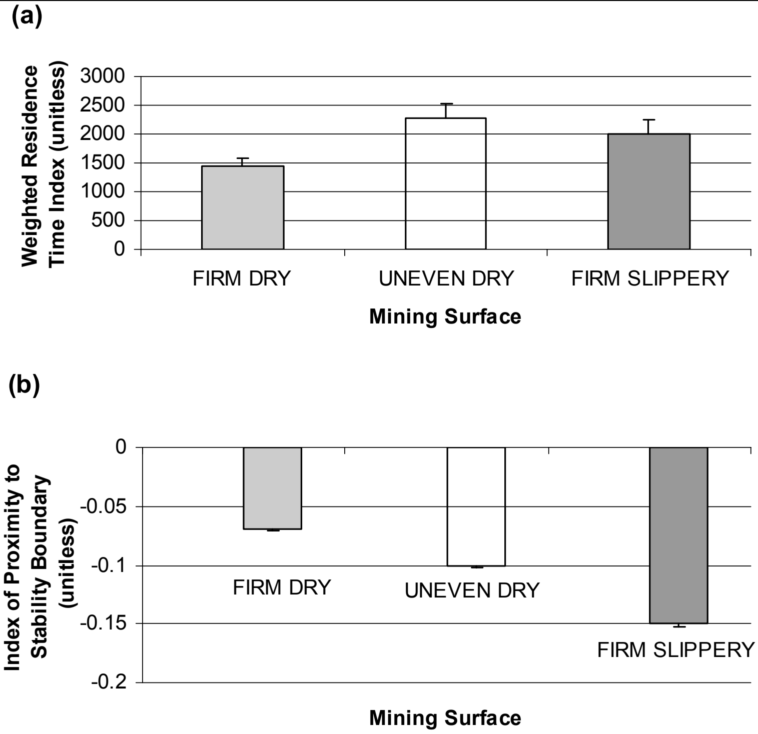


Fig. 7. Effect of mining surface on (a) weighted residence time index (WRTI) and (b) index of proximity to stability boundary (IPSB). WRTI and IPSB values shown are least square geometric means with the geometric standard errors of the mean.

(Fig. 7). Based on the above responses, the firm-slippery surface was more threatening to postural balance.

3.2.4. Interaction effects

The task by posture interaction was found to be significant for all three measures of postural instability/imbalance indices ($p < 0.0001$). Minimum IPSB was highest for the two knee posture while performing the scaling and stationary tasks and lowest for the one knee posture while performing the bits and cable tasks. SAR was greatest for the one knee posture during the bits task. WRTI was highest for the two knee posture during the cable task (Fig. 8). Lighting was not significant in any of the models for the CG-based postural instability/imbalance indices.

3.2.5. Cofactors effects

Significant covariates in these models included mean blood pressure, regular exercise, physical effort level, and number of hours participating in an exercise program and average arm and foot reaction time (Table 3).

3.3. Effect of mining tasks and risk factors on subjective measures of perceived postural balance and perceived exertion

Table 4 provides p values of the significant main effects, cofactors and two-factor interactions, based on ANCOVAs for the subjective measures of perceived sense of slip (PSOS) and rating of perceived exertion (RPE).

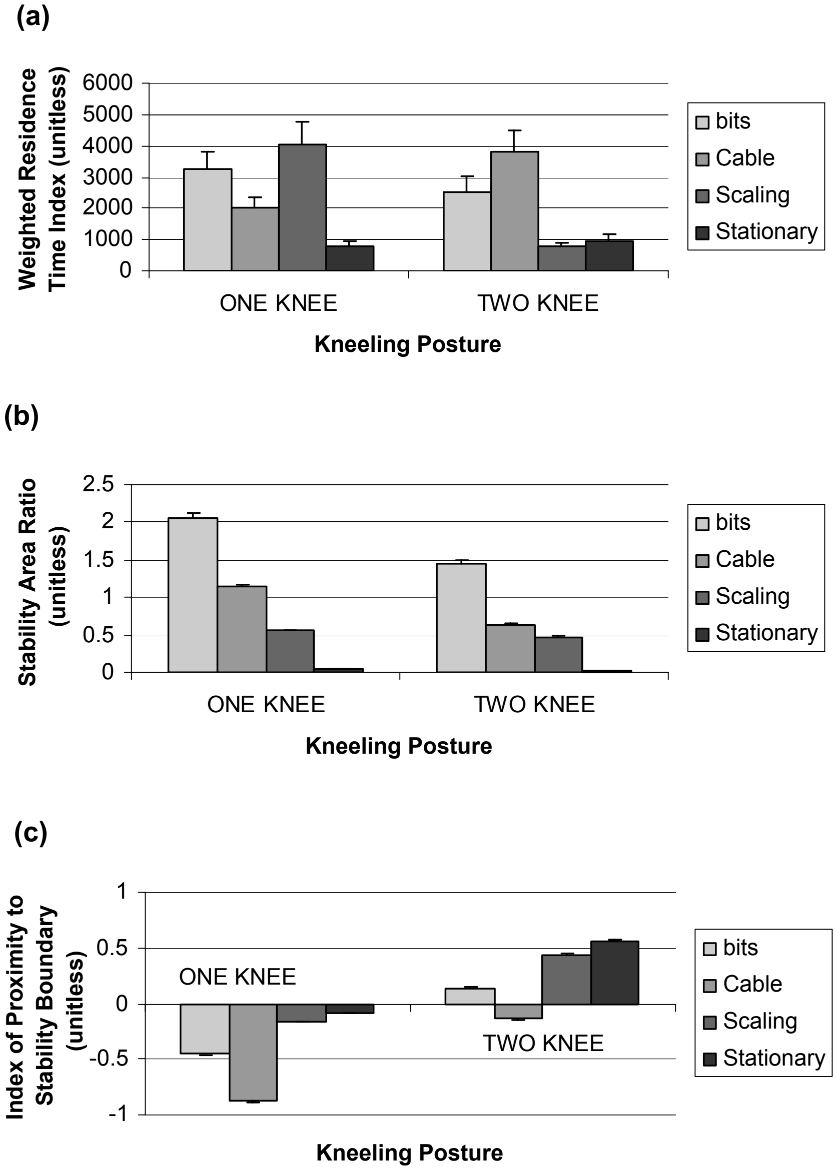


Fig. 8. Interaction of task and kneeling posture on (a) weighted residence time index (WRTI), (b) sway area ratio (SAR), and (c) index of proximity to stability boundary (IPSB). WRTI, SAR and IPSB values shown are least square geometric means with the geometric standard errors of the mean.

3.3.1. Effect of mining tasks

Mining task significantly affected both RPE and PSOS (Table 4). RPE and PSOS were both rated to be least during the stationary task (Fig. 9). This is consistent with the objective measure of postural sway and instability/imbalance responses reported in the above (Tables 2 and 3). RPE was rated to be the greatest during the scaling task (28.4% higher than the stationary task) and was rated only slightly less for the cable and bits task (22.1% and 21.5%, respectively, higher than the stationary task). PSOS was rated to be greatest during the scaling task (166% greater than the stationary task), followed by the

Table 4
P values for testing the effects of task, posture, mining surface, lighting and co-factors on perceived sense of slip/fall (PSOS) and rating of perceived exertion (RPE). Only statistically significant data are shown. $n = 25$

Effect	PSOS p-value	RPE p-value
Task	**0.0001**	**0.0001**
Posture	**0.0001**	**0.02**
Surface	**0.0001**	**0.0091**
Lighting	**0.046**	
Physical Effort Level	**0.0028**	**0.047**
Mean Blood Pressure	**0.026**	
Average Right Quadriceps	**0.0073**	**0.032**
No. of hours per week exercise	**0.013**	
Average Right Dorsiflexors		**0.047**
Task*Surface		**0.047**

bits (145% greater) and the cable (137% greater than the stationary task) tasks (Fig. 9).

3.3.2. Effect of kneeling posture

Type of kneeling posture used during mining task performance was found to be significantly related to both RPE ($p < 0.02$) and PSOS ($p < 0.0001$). A one-knee posture was rated higher in terms of both RPE (2.8%) and PSOS (33.5%) as compared to a two-knee posture (Fig. 9).

3.3.3. Effect of mining surface

The type of mining surface on which miners carried out their tasks was significantly associated with both RPE ($p < 0.009$) and PSOS ($p < 0.0001$). A firm-slippery surface was rated as eliciting the most exertion (5.0% greater than a firm-dry surface), followed by an uneven-dry surface (4.6% greater), with the least exertion perceived for the firm-dry surface (Fig. 9). PSOS was greatest for the firm-slippery surface, 59.6% greater than the uneven-dry surface and 53.3% greater than the firm-dry surface (Fig. 9).

3.3.4. Effect of environmental lighting

The miners found glare to significantly increase PSOS ($p < 0.046$); 11.9% greater PSOS was reported during the glare condition as compared to poor lighting (Fig not shown).

3.3.5. Interaction effect

A task by surface interaction suggested that the greatest RPE was experienced by the miners while performing the scaling task on an uneven-dry surface ($p < 0.047$) (Fig not shown).

3.3.6. Cofactor effects

A number of covariates influenced the miners' RPE, including physical effort level, and two muscle strength variables (right quadriceps and right dorsiflexors). Physical effort level, mean blood pressure, right quadriceps strength and the number of hours per week spent exercising were significant covariates of the PSOS outcome (Table 4).

3.4. Observed Slip events during performance of mining tasks

A repeated measure logistic regression analysis was performed using SAS PROC GENMOD to obtain the odds of slipping associated with mining tasks performed under various types of environmental lighting conditions, kneeling posture type and mining surfaces.

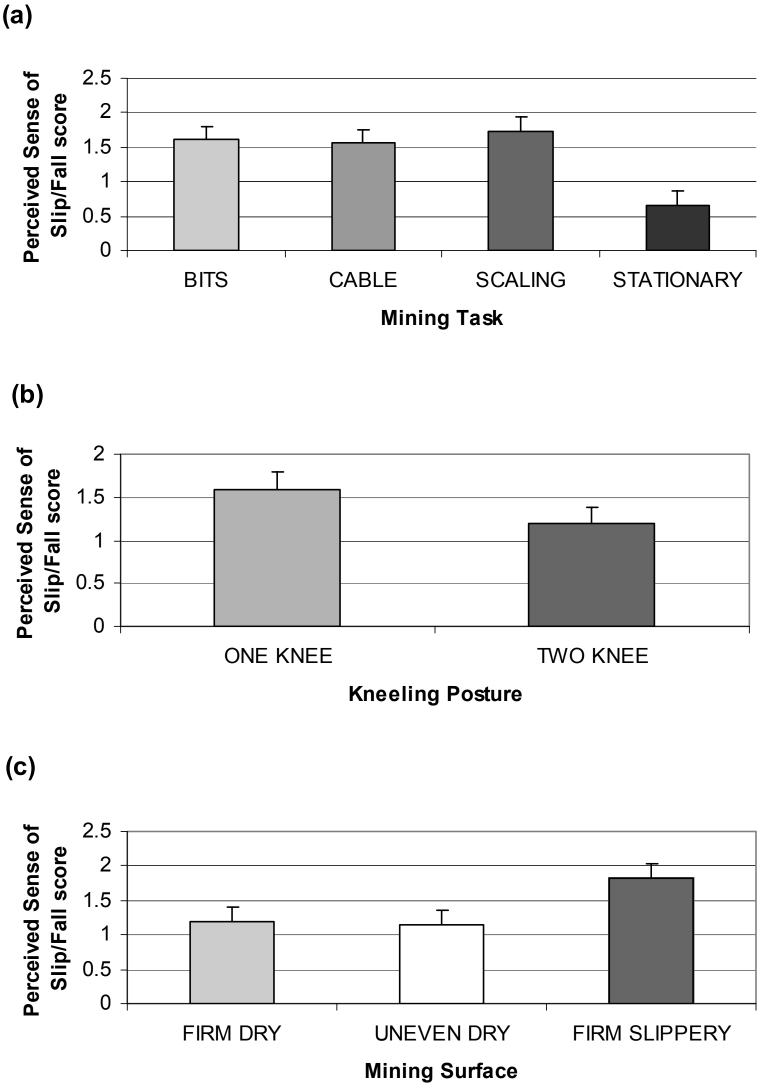


Fig. 9. Effect on perceived sense of slip/fall (PSOS) due to (a) mining task (b) kneeling posture and (c) mining surface and the effect on rating of perceived exertion (RPE) due to (d) mining task, (e) kneeling posture and (f) mining surface. PSOS and RPE values shown are the least square arithmetic means with the standard errors of the mean.

The type of mining surface was found to be significantly related to slips ($\chi 2$ (2) $= 14.95$, $p < 0.0006$). A slip was much more likely on the firm-slippery surface than on either the firm-dry surface (OR $=$ 16.7) or the uneven-dry surface (OR $= 16.7$). The percentage of trials producing slips ranked highest for firm-slippery surface (36.3%) and the firm-dry and uneven-dry surfaces came in second with 3.8% slips each. The type of task ($\chi 2$ (3) $= 13.32$, $p \leqslant 0.004$) performed and the environmental lighting ($\chi 2$ (1) $= 5.63$, $p \leqslant 0.02$) were significantly related to slips. A slip was 7.5 and 1.24 times more likely to occur when performing a bit task as compared to the stationary and the scaling tasks, respectively. The likelihood of slip occurrence during the cable and bit tasks was the same. In comparison to the stationary task, a slip was much more likely for either the cable (OR $= 7.5$) or the scaling tasks (OR $= 1.42$). The likelihood of slip occurrence during poor environmental lighting was 1.6 times higher than that for glare

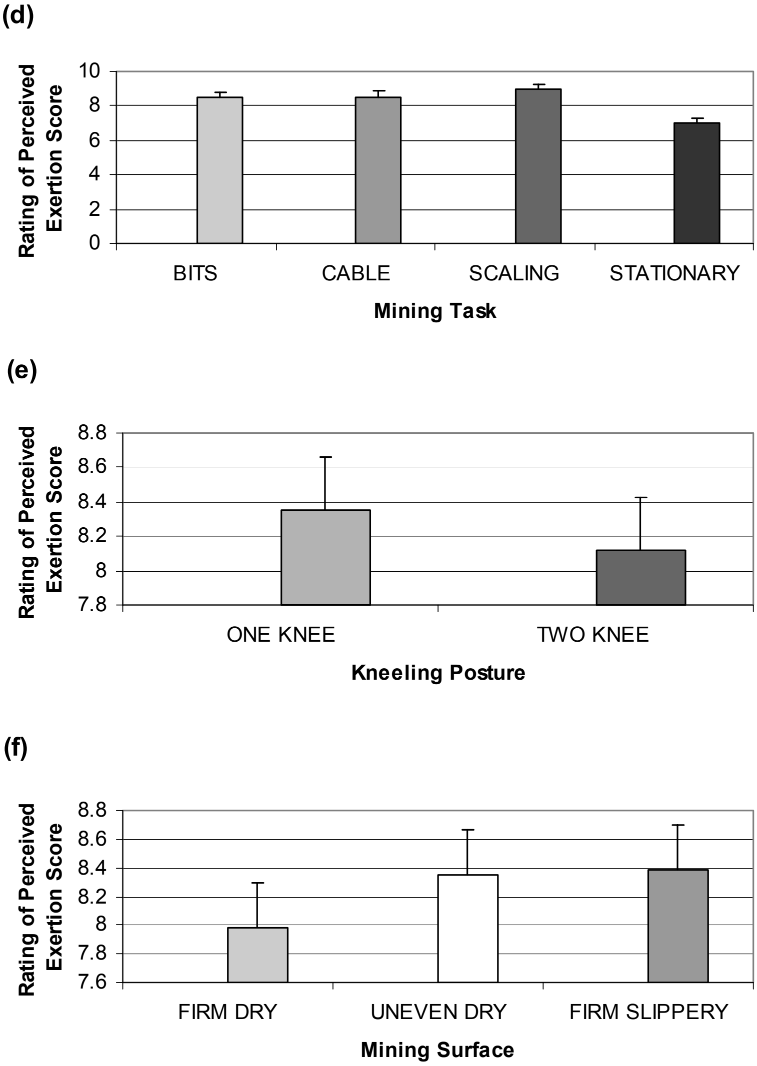


Fig. 9, continued.

lighting. The type of posture used during task performance was marginally ($p = 0.051$) significantly related to slips. The use of a one knee posture was 1.42 times more likely to cause a slip as compared to the two-knee posture.

4. Discussion

According to the results of CP and CG based outcomes the stationary task was generally found to produce significantly lesser postural sway as compared to all other tasks (bits, cable and scaling). These tasks also demonstrated increased postural instability, implying increased threat to the postural balance by the bits, cable and scaling tasks (Tables 2 and 3 and Figs 2 and 5). In comparison to the stationary task, all three other tasks which were dynamic in nature required increased shoe-floor friction to maintain safe postural balance (Fig. 2). During the bits task, which requires side-to-side motion the miners' postural stability should be at an increased risk and ought to require relatively increased shoe-floor friction levels, compared to the other three tasks that require no movement (stationary task) or movements primarily in the sagittal plane only (scaling task and cabling task). However, the H/V response (Fig. 2) indicated that all three tasks, as compared to the stationary task, required almost the same level of shoe-friction but slips were observed to be relatively higher for the bits (19.4%), cable (18.9%) and scaling (16.3%) tasks.

The H/V value observed for an uneven-dry surface was the highest compared to the firm dry and firm slippery surfaces, implying that the uneven dry surface has the highest shoe-floor COF requirement (Fig. 4). In this study, leather steel-toe shoes provided a COF of 0.59 for the uneven-dry surface, which appears to be sufficient to produce minimal observed slips (only 3.8% observed slips) compared to 36.3% of slips for the firm-slippery surface. It is interesting to note that while shoe-floor COF available under the slippery condition (0.22) was much higher than the required coefficient of friction for task performance on the firm slippery surface, over 36% of the reported slips events occurred on this surface (Fig. 4). This finding supports the results of previous investigators who reported that a shoe-floor COF of 0.22 will cause slipping without causing falls [16,30]. While in our study we did not observe any falls, two (IPSB and WRTI) out of three measures of postural instability did indicate significant postural instability during task performance on the firm slippery surface and the uneven dry surface (Table 3, Fig. 7). In spite of having sufficiently higher shoe floor COF (0.22) than the frictional demand (as measured by H/V) placed by the task performed, a high incidence of slip events provides evidence that shoe COF alone can not predict a slip incident, a finding that we had reported earlier for non-mining tasks also [8].

The results of all CG based postural instability outcomes (IPSB, WRTI and SAR) and one CP based postural sway outcomes (SA) suggest that the one knee posture is more unstable than the two knee posture (Tables 2 and 3 and Figs 3 and 6). While H/V demand is low in the one knee posture, the BOS for this posture is relatively smaller than for the two knee posture. This could be the reason that postural instability is much higher for the one knee posture (Fig. 6). Results also imply that use of the one knee posture may be prone to postural instability, requiring more postural muscle efforts as indicated by higher RPE score (Table 4 and Fig. 9). This is consistent with the finding of higher incidence of slipping with the one knee (16.2%) than with the two-knee (13.2%) posture during mining task performance. Based on the results from the repeated measure logistic regression model, the estimated odds of a slip incident are consistent with CG based postural instability response data, where the one knee posture produced the smallest IPSB, and largest SAR and WRTI compared to that for two-knee posture, implying that the one knee posture is more unstable (Fig. 6). Based on the postural instability indices, SAR and WRTI, the performance of the bits, cable and scaling tasks with one knee caused a relatively higher postural instability compared to the stationary task (Fig. 8). On the other hand, the IPSB index showed that performance of the bits and cable tasks with one knee caused a relatively higher postural instability compared to the scaling and stationary tasks (Fig. 8). This difference in responses could be due to the fact that while SAR and WRTI characterize overall postural instability, IPSB measures instability specific to a single instance when certain tasks cause the body's CG to push near the subjects' stability boundary. During performance of the bits and cable tasks, the upper torso and the arms are moving forward, upward and downward significantly more than that observed for the stationary and scaling tasks, thereby causing potential instances when the subjects' CG would approach or even cross the stability boundary.

An increase in the PSOS response implies that the body accurately perceived the threat to the postural balance due to various risk factors. Accurate perception of a postural threat should elicit, as a corrective postural muscle action, reduced postural sway responses in an effort to minimize postural instability. In the present study, glare lighting produced higher PSOS scores than the poor lighting condition, implying that the glare lighting may be more threatening to postural stability (figure not shown). Therefore, it appears that adequate compensatory mechanisms were in place to minimize postural instability, as all postural instability variables were not significantly associated with lighting (Table 3). In the present study, there were also some instances where correct perception of certain risk factors did not produce the expected compensatory response thereby causing increased postural instability. For example, while the PSOS score was the highest for the firm slippery surface implying accurate perception of the risk, only excursion in the AP direction was significantly reduced for the firm-slippery surface condition (Figs 4 and 9). However, the responses of IPSB and WRTI suggest poorer postural stability in spite of body's ability to correctly perceive the threat of the firm slippery surface associated postural imbalance. Probably this type of mismatch between inadequate compensatory response to overcome postural instability was one of the reasons for finding the highest level of slips (36.3%) for the task performed on a firm slippery surface. Similarly, while an increased PSOS score implies correct perception of a higher threat to the postural balance for the one knee posture (than the two knee posture, as shown in Fig. 9), the body was not able to elicit appropriate corrective postural muscle contractions to reduce postural instability for the one knee posture (based on WRTI and IPSB outcomes shown in Fig. 6). This mis-match between perception and the objective measure of postural instability provides evidence that under certain risk factors the human body is not capable of deploying the necessary postural corrective muscle actions. With aging workforce issues, a mismatch between perceived and actual risk becomes even more important as shown in an earlier study in which older workers walked on a slippery ramp surface [4]. In that study, these older workers significantly underestimated the slippery surface and as expected, the older workers' objective measure of postural balance was poorer than the younger group when they negotiated a slippery ramp surface. Therefore, future workplace and task designs should take into consideration risk factors that may cause a mismatch between perceived and actual risk that then leads to the diminished ability for the workers to maintain safe upright balance during task performance.

5. Conclusions

Based on the results, the lifting of bits, cable lifting, scaling and stationary tasks were ranked least to most stable, respectively in terms of the miners' postural balance. The miners reported increasing levels of perceived exertion as captured by the RPE scale, as the tasks performed ranged from stationary, lifting of bits, cable lifting and scaling. The type of knee posture used (one knee vs. two knee) during task performance also significantly influenced the miners' postural sway/stability as well as their subjective perception of exertion and their actual slips and/or falls. Based on the results, a one knee posture was more unstable, compared to the two-knee posture. A one-knee posture was rated higher in terms of both RPE and PSOS as compared to a two-knee posture, which is consistent with objective measures of postural sway and stability/balance.

The results from this study will help enhance an existing statistical model originally developed by us showing the relationship between postural instability and/or loss of balance and the independent variables characterizing the Environmental and JobTask factors for task performance in an environment simulating underground mines [2]. The enhancement of the model will add the effects of new risk factors (that are currently not available in the model), including restricted posture, glare, kneeling, new task types and different (uneven/slippery) surfaces which are typically found in low-seam underground mines. In future field studies, this statistical model can be used to help evaluate the propensity for postural instability and/or loss of balance by measuring, in a walk-through evaluation, existing risk factors at the mining worksite. A determination of which of the risk factors need to be corrected to reduce the propensity for postural instability and/or loss of balance will then be possible. Availability of such models will have significant impact in identifying risk factors during job and workplace analysis of mining sites.

Finally, based on results from this study, improved work practices/training can be developed to reduce the likelihood of workers' slips/falls while working in low seam mines. The results from this study will also provide guidelines for mining workplace redesign to allow appropriate sufficient floor spacing so that workers can increase their base of support, minimizing the potential of postural instability. Results from this study can also be used to provide scientific data about postural instability under various combinations of workplace risk factors as input into the MSHA's training programs where software is being developed to include the human factors issue and ergonomics training [7,26,31].

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