

Walking Speed and Head Pitch With Health Monitoring by Wearable Helmet System in Coal Mines

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Abstract— A relative human performance evaluation of a miner's walking speed and head pitch with health was managed on miners wearing two types of LED cap lamps with wearable sensors. To get the better lighting, walking speed and head pitch are indirect indicators. The better that miners can see the floor, the faster they can walk and the less they pitch their heads downward to illuminate the floor with their cap lamps. NIOSH researchers developed a non-contact way by using two small wireless, wearable inertial measurement units (IMU) to quantify human performance. Data were observed in an underground coal mine in the field from nine coal miners. The field results showed no statistical difference between the two cap lamps for walking speed. However, there was a trend of 2-degree lower head pitch for one of the cap lamps. The field testing procedures were then replicated in a controlled laboratory environment and the results indicated a 5-degree lower head tilt when using the same cap lamp and a corresponding difference in walking speed. Monitoring sensors will capture the miner's health and gas levels in the coal mine.

Keywords—Head orientation, inertial measurement unit (IMU), illumination, mine safety, wearable sensors.

I. INTRODUCTION

AN underground mine presents many unique work challenges given that it is a dynamic environment that includes dust, low reflective surfaces, low visual contrasts, and moving machinery. One important challenge is producing competent lighting for miners to work safely. Lighting is critical to miners; they depend heavily on visual cues to detect mine hazards [1]. Mine illumination typically consists of a low background light level with a relatively high-intensity light spot from a miner's cap lamp, which is often a miner's most important light source [2].

Mine hazards of primary concern, given the risk they pose to miners, are slip, trip, and fall (STF) hazards and struck by or pinning hazards from moving mining machinery.

To improve the safety at underground coal mines, NIOSH (National Institute for Occupational Safety and Health) researchers have focused on developing a new LED cap lamp to improve the ability of miners to detect hazards, including those which result in a STF accident. NIOSH has developed an LED cap lamp that provides more illumination of these hazards by using multiple LEDs and secondary optics. When compared to other commercially-available LED cap lamps, the NIOSH LED cap lamp improved floor hazard detection up to 82%, and improved peripheral motion detection crucial for detecting moving machinery hazards up to 79% [4]. These visual performance improvements were accomplished without increasing discomfort glare [5]. These results were obtained from testing subjects in the NIOSH Mine Illumination Laboratory (MIL) at Bruceton, PA. The MIL is a simulated underground coal mine environment. The interior is 488 cm (192 in) wide by 213 cm (84 in) high and is coated with a rough-textured material that has a dark color and a uniform spectral reflectivity of about 5% for the visible spectrum, which is typical for coal. The MIL contains instrumentation, networked computers, and electromechanical apparatuses, developed by NIOSH researchers for testing trip hazard detection, peripheral motion detection, and glare.

We inferred that as floor illumination increased, walking speed would increase and head pitch would decrease-i.e., the better that miners can see the floor, the faster they can walk and the less they need to pitch their heads down to illuminate the floor with their cap lamps. Thus, walking speed and head pitch serve as indirect indicators of improved human performance due to an increase in floor illumination.

The primary objective of this study was to decide if the light beam distribution from the NIOSH LED cap lamp affected how miners walk. Specifically, we were to determine if there are statistically significant differences in average walking speed and head pitch when using the conventional LED cap lamp and the NIOSH LED cap lamp. A pilot experiment was conducted in the field and was followed by a more in-depth testing in a laboratory environment.

II. METHODS

A. Subjects

Two categories of subjects were recruited for the study. The first group consisted of miners who took part in the field evaluations, and the second group consisted of personnel at the Bruceton, PA, location of NIOSH who took part in the laboratory evaluations. The protocol for all subjects was approved by the NIOSH Human Subjects Review Board.

1) *Miner Subjects:* These subjects were recruited by first meeting with mine management to discuss the NIOSH LED cap lamp and the field testing that we intended to perform. From this, the mining company suggested employees that would be appropriate candidates to participate in the study. Researchers then met with these miners. The miners gave a verbal consent and were instructed about their right to withdraw freely from the research at any time without penalty. The miners took a brief survey which documented their years as a coal miner, their present job, years on that job, and age. All of the miners had used an LED cap lamp for at least the past 3 years.

2) *Laboratory Subjects:* These subjects were Federal employees and they were not specifically involved with this cap lamp research. Most of the subjects were not familiar with miner cap lamps or they had used them infrequently. A total of 23 subjects participated: 20 male and 3 female. While gender was not a variable in this study, the percentage distribution for gender was representative of the U.S. miner population. The subjects signed an informed consent form and were instructed about their right to withdraw freely from the research at any time without penalty.

B. Experimental Design

The design for the field test is a 2 (Cap Lamp: Standard versus Development) × 2 (Walking Day: Initial Day versus Final Day) mixed design. Cap Lamp type and Walking Day are both within-subject variables. The design for the laboratory test is a one-independent variable, within-subjects design. Only the cap lamp (Stand versus development) was manipulated during the test.

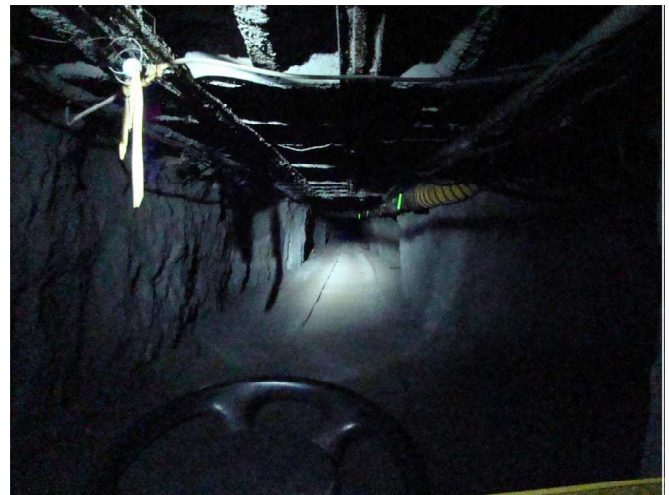


Fig. 1. Circular beam spot of the Standard cap lamp used at the field test site.

The photograph was taken at the NIOSH Safety Research Coal Mine.

C. Cap Lamps

Two types of LED cap lamps were used: a standard cap lamp (Standard) and a NIOSH LED cap lamp (Development). The Standard cap lamp was the one commonly used at the mine. Both cap lamps were “corded” models, meaning that the Headpiece was connected via an electrical cable to a belt-worn battery pack. The Standard cap lamp used a single phosphor white LED as the primary light source, along with an optical reflector to direct the light as a spot of about 6° as depicted by Fig. 1. The Development cap lamp uses multiple, phosphor white LEDs as the primary light source along with secondary optics to direct the light to specific hazardous areas in the mine as depicted by Fig. 2. The intent is to provide more illumination in order for miners to better detect STF hazards located on the mine floor and to better detect moving machinery associated with struck-by or pinning accidents. For each cap lamp, the electrical and photometric data are listed in Table I. Each cap lamp was energized from fully charged cap lamp batteries. Both cap lamps were MSHA-approved. Illuminance data (Table II) were collected at 0.61 m (2.0 ft.) intervals along the mine walls and floor at a distance of 3.05 m (10 ft.) from the beginning of the walking path. More detailed illuminance data for each cap lamp is provided (Figs. 3 and 4).

TABLE I
CAP LAMP ELECTRICAL AND PHOTOMETRIC DATA

Cap lamp	Supply Voltage (Vdc)	Supply current (amp)	Supply Power (Watt)	Peak wavelength (Nm)	Correlated Color tem (K)
Std	3.95	0.53	2.09	456	6603
Dev	4.10	0.35	1.44	448	6356



Fig. 2. Light distribution of the NIOSH LED cap lamp. The photograph was taken at the NIOSH Safety Research Coal Mine.

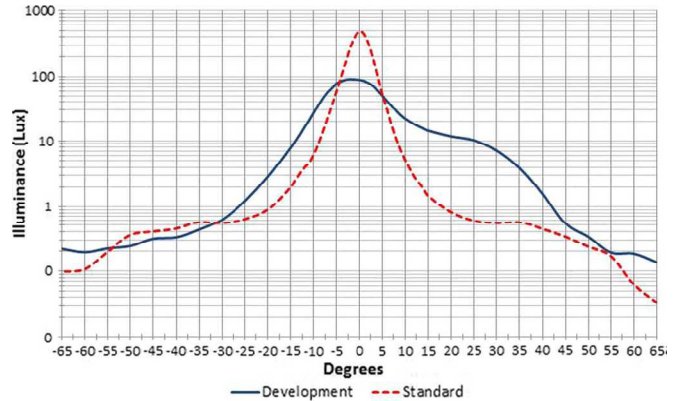


Fig. 4. Cap lamp illuminance distributions in the vertical plane.

TABLE II

MINE WALL AND FLOOR ILLUMINANCE DATA MEASURED 3.05 m (10 ft.) FROM THE BEGINNING OF THE WALKING PATH

Cap lamp	Left wall illuminance(lux)		Right wall illuminance(lux)		Floor illuminance(lux)	
	Min, max	avg	Min, max	avg	Min, max	Av g
Stan d	0.16,0.35	0.24	0.15,0.32	0.26	0.17,3.62	0.96
Dev	0.14,1.19	0.59	0.13,1.25	0.56	0.11.16.26	0.49

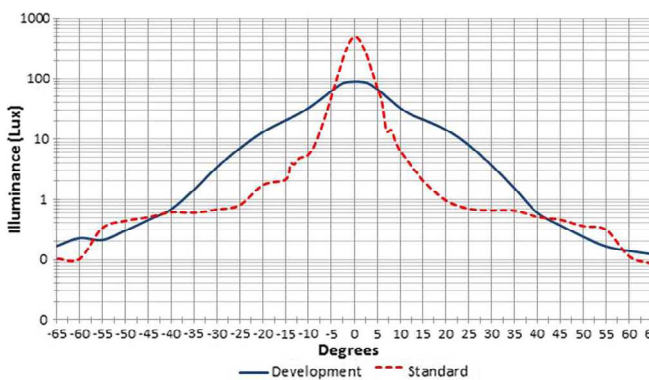


Fig. 3. Cap lamp illuminance distributions in the horizontal plane.

III. EXPERIMENTAL LAYOUT AND APPARATUS

A. Hardhat Instrumentation

Each subject was fitted with two major components of instrumentation which were used to collect walking speed and head pitch (rotation about the Y axis) data. The hardhat (Fig.5)

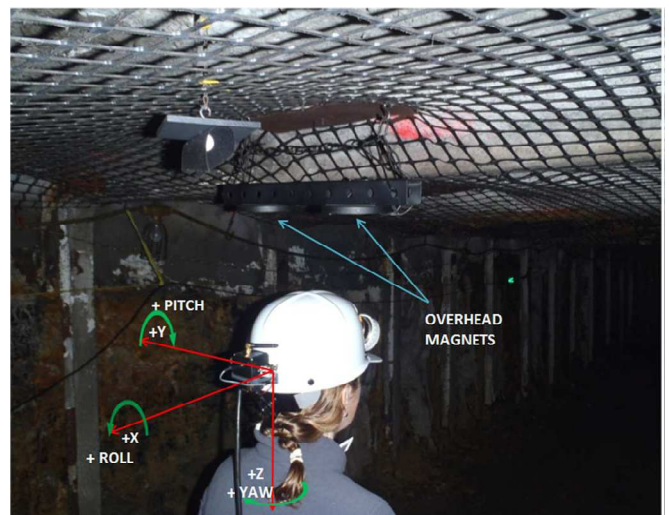


Fig.5. Tracking hardhat worn by a researcher.

was fitted with a 6-axis, wireless inertial measurement unit (IMU; Micro strain 3DM-GX2). In addition to the 3-axis accelerometer and 3-axis gyro, the IMU also contains a 3-axis magnetometer. The magnetometer was used to identify the start/stop locations on the walking path; it did so by examining the signal for spikes observed as the subject would pass under ceiling-mounted magnets (Fig. 5). Additionally each subject wore a similar IMU (minus the magnetometer) which was used to detect footfall. While the IMU sensed accelerations and rotations of the hardhat, only the pitch angle was used for the purposes of this study.

B. Test Layout and Procedures

1) *Miner Test Layout and Procedures:* Researchers laid out a walking path on the mine floor as illustrated by Fig. 6. The route was designed with the following criteria: it must present the subject with the challenge of both following an unfamiliar path (near-field vision) and identifying targets on the wall (mid to long-range vision). In this way the path would be non obvious and present a scenario where it would be possible to test the effects of the different lighting distributions. The path was indicated with approximately 50 high-visibility markers. The markers were 75 × 75 mm (3 × 3 in) with a 25 × 25 mm (1 × 1 in) green reflective sticker on an orange background (Fig. 6, lower right). The markers were placed approximately half a meter apart over the total distance. While the subjects were told to follow the path on the floor, they were also responsible for locating seven wall-mounted targets distributed along the path. The wall targets were large, black alpha-numeric characters printed on 216 × 279 mm (8.5 × 11 in) white paper with two 25-mm (1-in) square reflective stickers on them to aid in localization (Fig. 6, upper right). The wall targets were hung at consistent heights, suspended from the roof of the mine via cable ties. During the first walk of the path, the alpha-numeric targets were placed in a pre-determined location; the targets were moved to a second pre-determined location and changed to a second set of alpha-numeric characters during the second walk of the path.

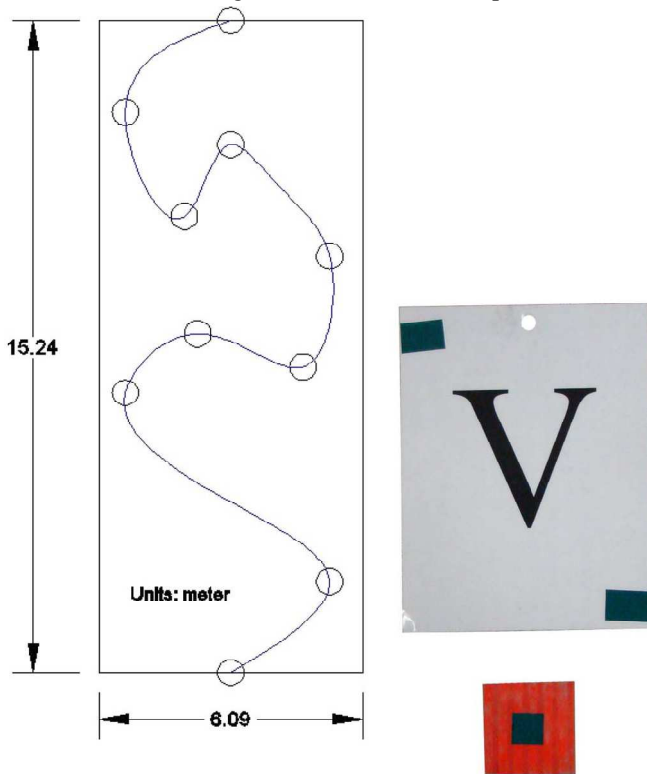


Fig.6. Plan view layout (left) of the walking path, 15 m (50 ft.) long, traversing approximately 26 m (85 ft.) as one passes through all the points that connect it.

Subjects were also told to begin behind the overhead magnets (Fig. 5) used to indicate the start point and walk past the overhead magnets located at the stop point so that their elapsed time could be recorded. Once the subjects reached the end of the path, they were instructed to proceed back. While the cap lamp was being switched between the Standard and the NIOSH LED lamp, one researcher replaced and rearranged the visual targets. In this way, we recognized that the visual targets remained novel between lamps; however, we wanted to account for the fact that some learned behavior of the path may be present in the data. Once testing was completed, the instrumented hardhat and leg band IMU were removed. The miners were then asked to keep and use the NIOSH LED cap lamp for approximately four weeks. After this trial period, NIOSH returned to the mine and repeated the objective walking experiment a more time.

2) *Laboratory Test Layout and Procedures:* Inside the Mine Illumination Lab, each subject sat in a darkened environment for 15 minutes to enable retinal dark adaptation. Prior to the start of the evaluation, researchers explained the test procedures. Next, subjects wore the same NIOSH-supplied hardhat and legband as used by the miners in the field test. Note that top periphery vision is limited by the brim of the hardhat in all cases, reducing the field of view relative to

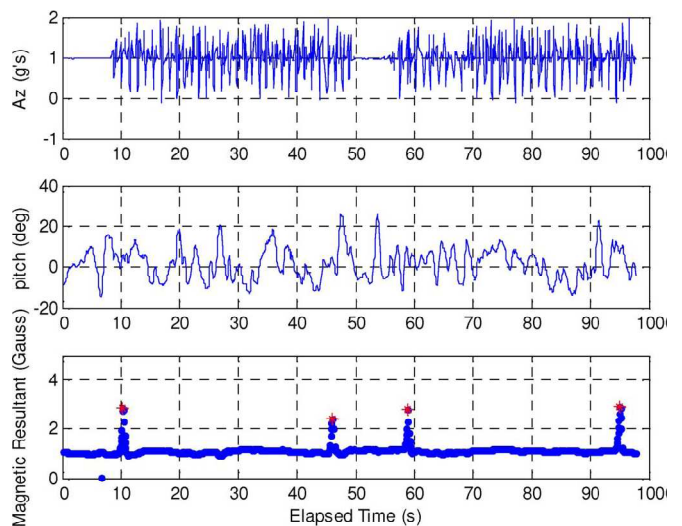


Fig. 7. Typical data from both legband (top graph) and hardhat IMU (middle graph). Note the spikes in the magnetic field (bottom graph) which enables the distance flagging of the start/stop points.

normal (no hardhat) vision. The subjects followed the same procedures as the miners while they walked the path (Fig. 6) inside of the MIL, which simulates an underground coal mine environment.

C. Signal Capture and Analysis

Data from both the hardhat and legband IMU were wirelessly transmitted to an RF receiver located approximately 5.49 m (18 ft.) from the start of the walking path. This RF receiver was connected to a laptop running LabView which served as the data acquisition system, enabling the researcher to view the data in real time. The LabView program displayed the head pitch angle (deg.), the leg acceleration in the Z direction (g's), and the resultant magnetic field strength vector (Gauss) as measured by the magnetometer located on the hardhat. LabView was used to sample the acquired data at 100 Hz, which was then post-processed in Matlab with a custom, semi-automated script (typical results in Fig. 7, below). Spikes in sensor behavior were also smoothed by using an average of the fore and aft neighboring points. In order to consistently and automatically find the start/stop points of the walking path, the script looked for localized peaks in the magnetometer data and identified the start/stop of the outgoing and return trip.

For each segment, the elapsed time, average speed, average head pitch, and standard deviation of head pitch were calculated and reported. The leg band IMU data were largely not used but are planned to be part of a more detailed gait analysis in future studies.

TABLE III
FIELD TEST AND LABORATORY TEST RESULTS
MEANSPRESENTED—STANDARD DEVIATIONS IN
PARENTHESES

Test	Standard cap		Development cap	
	Pitch (deg)	Time (Sec)	Pitch (deg)	Time (Sec)
Field 1	23.19(7.16)	28.25(1.8)	21.31(5.34)	28.54(3.13)
Field 2	22.38(9.92)	29.72(4.11)	20.20(6.26)	30.98(4.09)
Laboratory	7.26(12.87)	34.52(6.80)	1.89(10.21)	33.47(6.11)

IV. RESULTS

A. Field Results

The design for the walking study was a 2 (Cap Lamp: Standard versus Development) × 2 (Walking Day: Initial Day versus Final Day) mixed design. Cap Lamp type and Walking Day are both within-subject variables. Head pitch (measured in degrees) and walking time (measured in seconds) are both

reported. A repeated-measures Analysis of Variance (ANOVA) was used to analyze the data. Specifically, there was a 2-degree difference in head pitch (Table III) when miners wore the Development cap lamp relative to the Standard cap lamp, $F(1, 6) = 28.77, p = .17$. While this result is not statistically significant, the trend is meaningful and warrants further investigation in a controlled environment. The effect of Walking Day, the interaction between Walking Day and Cap Lamp, and all effects for walking time were negligible, both $p > .25$.

B. Laboratory Results

All walkers wore both cap lamps (Standard versus Development cap lamps). The cap lamp presentation order was counterbalanced so that half of the participants wore the Standard cap lamp during the first walking trial and half wore the Development cap lamp during the first walking trial. In order to ensure that battery life was preserved, two Development cap lamps were used during the experiment. The difference in head pitch for the two Development cap lamps was not statistically significant, $p > .1$. We therefore included both Development cap lamps in one analysis. A repeated measures t-test was applied to the head pitch and walking time data. The results for the laboratory test show about 5° lower downward head pitch (Table II) while participants wore the Development cap lamp compared to the Standard cap lamp thus participants looked up more than while wearing the Standard cap lamp. This difference was statistically significant, $t(22) = -4.21, p < .01$. Moreover, walking time was faster while participants wore the Development cap lamp ($M = 33.47$ sec, $SD = 6.11$ sec) compared to the Standard cap lamp ($M = 34.5$ sec, $SD = 6.8$ sec), $t(22) = -2.54, p < .05$.

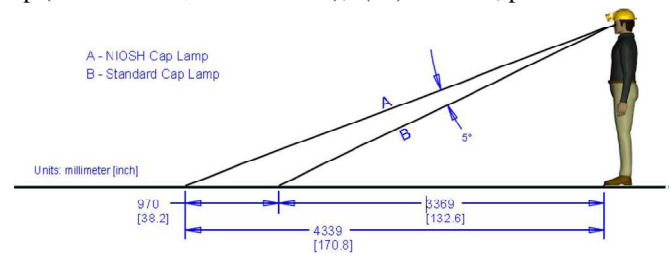


Fig. 8. Laboratory data line of sight comparison between the Development cap lamp (sight line A) and the Standard cap lamp (sight line B) for a 50th percentile male. The horizontal visual range increases 970 mm (38.2 in) when using the NIOSH LED cap lamp.

V. MONITORING

Miners health will be monitored with the help of heart beat sensor, it works based on the principle of light modulation by blood flow through finger at each pulse in the rate of beats per minute (BPM). The another one is gas sensor, it is used to

detect the presence of various gases within the area, those sensors are used for safety system. A gas detector can also sound an alarm to operators in the area where the leak is occurring, giving them the opportunity to leave the area. This type of device is important because there are many gases that can be harmful to organic life, such as humans or animals.

This type of device is used widely in industry and can be found in a variety of locations such as on oil rigs, to monitor manufacture processes and emerging technologies such as photovoltaic. They may also be used in firefighting.

VI. DISCUSSION

A. Overview

Field data indicated that the mean head pitch angle was -22.79° for the Standard cap lamp versus -20.76° for the Development cap lamp. This change in angle shows that the miners' head pitch was directed higher (away from ground) while wearing the Development lamp. While this result is similar in magnitude to the expected installation error, the trend was consistent across separate test sessions. A 2-degree change is relatively small; however, it translates to a significant extension of 0.46 m (18.1 in) for the line of sight intersection with the floor when using the Development cap lamp. Laboratory data indicated that the mean head pitch angle was -7.25° for the Standard cap lamp versus -1.89° for the Development cap lamp. This resulted in an approximate 5-degree difference that translated to a line of sight intersection with the floor of about 0.97 m (38.2 in) when using the Development cap lamp (Fig. 8). Thus, the miners would have an improved field of view that could enable them to better detect other hazards (e.g., moving machinery) in front of them. Overall, the field and laboratory head tilt data both indicate less head tilt with the Development cap lamp. Also, the laboratory data indicate a small but statistically significant increase in walking speed when using the Development cap lamp. The increased field of view gained by the development cap lamp coupled with the increased illumination of the floor provided by the cap lamp's light distribution enables one to collect more information about the visual environment. The increase in peripheral vision improves the miner's ability to detect and mitigate hazards, since vision is the primary system used to identify and avoid obstacles [7] and in particular peripheral vision is of key importance in obstacle avoidance [8]. The reduction in head tilt may also be beneficial, as downward head positions have been linked to reduced postural stability in standing through changes body position and vestibular function [9]. Determining the contribution of the visual environment, afforded by the cap lamp lighting distribution, to postural walking stability is beyond the scope of this paper but is currently being addressed by a separate

NIOSH study. In another instance, mean head pitch angles for the Standard cap lamp were -22.79° in the field and -7.25° in the laboratory. This 15.54-degree difference could be indicative of a learned behavior for the miners to tilt the head downward to better illuminate the floor.

B. Limitations

Because the field environment was an actual production coal mine, the conditions were less than ideal and difficult to control (e.g., variable roof height, excessive water, and dust on the floor). Roof height was a major issue given that the roof undulated significantly, causing some of the taller miners to occasionally stoop or bend their head to the side in order to avoid hitting their head. Thus the head pitch data were affected by this; however, we tested in the same environment between the independent tests. Secondly, statistically significant differences in walking speed in the field were not evident and we reason that the roof undulation could be an extraneous factor as well as the poor floor conditions of dust and water. Combined, these factors would limit how fast the miners could safely walk. Obviously, these extraneous factors were not present for the laboratory tests that resulted in a statistically significant increase in walking speed when using the Development cap lamp. This small sample size of miners increases the probability that the results could have occurred by random chance.

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