International Journal of Industrial Ergonomics 64 (2018) 23–30

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

# Measuring the mass and center of gravity of helmet systems for underground workers

Blake LeClair [a], Philip J. O'Connor [a], Stephen Podrucky [b], W. Brent Lievers [a, c, *]

[a] Bharti School of Engineering, Laurentian University, Sudbury, Ontario, Canada
[b] Jannatec Technologies Inc., Sudbury, Ontario, Canada
[c] Centre for Occupational Safety and Health (CROSH), Laurentian University, Sudbury, Ontario, Canada

ARTICLE INFO

*Article history:*
Received 27 June 2016
Received in revised form
10 August 2017
Accepted 12 October 2017

*Keywords:*
Helmet
Cap lamp
Mass
Center of gravity
Underground worker

ABSTRACT

Advances in communication and monitoring technology are expected to increase the numbers of accessories that will be added to the helmets of industrial workers. Unfortunately, no guidelines currently exist for the maximum weight, or weight distribution, that can be safely supported by the head and neck in these contexts. The goal of the current work is to quantify the mass and center of gravity (CG) of helmet systems (i.e., helmet plus accessories) currently worn by underground workers. To this end, a custom measurement device was created using a headform representative of a 50th percentile male. Two different helmets and six cap lamps were investigated. Each helmet had ear protection that was considered in each of four extreme positions. The maximum helmet system mass was approximately 1 kg and the CGs ranged from 56.0 mm anteriorly to −46.5 mm posteriorly relative to the headform origin. Since these existing helmet systems have not been linked to short- or long-term issues, these measures provide a preliminary, conservative definition of a safe design envelope for evaluating for future developments. Further work is needed to expand the measurements to different headform sizes and helmet systems.

*Relevance to industry:* In the absence of rigorous guidelines, the mass and CG information from current systems define a safe design envelope for the development of new helmets and helmet systems.


## 1. Introduction

Helmets are used in a variety of contexts —leisure and sporting activities, military service, the workplace— to protect the head of the wearer. A great deal of design and research activity has focused on ensuring appropriate levels of protection and comfort (Proctor, 1982; Mills and Gilchrist, 1992; Bogerd et al., 2015). National and international standards have also been developed which codify the minimum acceptable level of protection for particular uses (ASTM, 2012; ANSI, 2009; ISO/DIS, 2015; Snell Memorial Foundation, 2015). For example, ANSI/ISEA standard Z89.1 (2009) prescribes the minimum behavior for industrial helmets in terms of their electrical insulation, flame retardance, and force attenuation capabilities.

Beyond simply protecting the wearer, helmets also serve as a platform for supporting additional modular equipment. Military helmets, for example, may be outfitted with communications equipment, night-vision goggles, and the batteries required to power these devices (Manoogian et al., 2005). While the mining industry is not yet as technically sophisticated as the military, the helmets of underground workers routinely support both ear protection and cap lamps.

The addition of these helmet accessories has two major effects. First, with each item added there is an increase in the total mass of the *helmet system* (i.e., the helmet plus accessories). This weight must be supported safely and comfortably by the wearer's head and neck. The second change is a potential shift in the effective center of gravity (CG) of the helmet system. For example, the addition of a cap lamp to the front of a helmet results in a more forward CG location than for the helmet alone. These changes can have negative effects on the wearer such as increased muscle fatigue (Gallagher et al., 2008).

Advances in communication and bio-monitoring technology mean that additional accessories are likely to be added to the helmets of underground workers. While existing standards prescribe

* Corresponding author. Bharti School of Engineering, Laurentian University, 935 Ramsey Lake Road, Sudbury, Ontario, Canada.
*E-mail address:* blievers@laurentian.ca (W.B. Lievers).

https://doi.org/10.1016/j.ergon.2017.10.001
0169-8141/

the necessary protective characteristics of an industrial helmet, there are no guidelines for the maximum mass or optimal mass distribution that may be supported on the head and neck. A great body of research has quantified the tolerance of the head and neck to axial forces and moments (Mertz and Patrick, 1971; Nightingale et al., 1997, 2015). Unfortunately, this work is focused on acute traumatic events that far exceed what is expected during routine helmet use.

Various military bodies have conducted extensive studies on the effects of head-supported masses, particular in aviators. For example, the "Knox-Box" criterion for helmet CG locations was developed to minimize head and neck injuries during ejection (Gaur et al., 2013). Unfortunately, the applicability of military guidelines to underground workers is unclear due to substantial differences in the two populations. Underground workers are, on average, much older than the average member of the military (43.3 vs. 28.6 years), and will also be very different in terms of fitness and training (U.S. Department of Defense, 2014; McWilliams et al., 2012). The types of activities performed by each group, the length of exposure, and other working conditions, are also expected to be very different.

Because there is a risk of negative short- and long-term effects from excessive or unbalanced head loads (Jäger et al., 1997; Knight and Baber, 2004; Forde et al., 2011; Ibrahim, 2015), care must be taken when designing helmets or accessories, or when prescribing equipment for employees. Poorly selected or poorly designed helmets can put manufacturers and employers at risk of litigation (Stanley, 2015). No comprehensive safety standards currently define safe maximum loading or load distribution for industrial workers and developing such standards is a long and difficult process. Yet one simple task within this larger work is simply to understand the effective masses and CGs currently supported by underground workers. Since no acute or chronic problems have been identified to date due to existing helmet systems, it follows that the current systems define a "safe" envelope for the development of any new helmets or helmet accessories.

The purpose of the current work is to measure the masses and CGs of selected helmet systems currently worn by underground workers. A custom test device was developed to measure the effective CG relative to a standard headform for a 50th percentile male (ASTM, 2014). Two different helmets were tested in combination with six different cap lamps (3 cordless, 3 corded) and ear protection in one of four potential orientations. By measuring a sample of existing systems, we can define a preliminary, conservative envelope of acceptable CGs which can then be used in the design or evaluation of new helmets and accessories.

## 2. Methods

### 2.1. Helmet measurement system design

A custom experimental device was developed to measure the center of gravity (CG) of helmet systems relative to the origin of a standard headform. The overall concept is based on the recognition that, for an object mounted to a load cell, the CG of that object relative to the load cell is determined by:

$$\mathbf{M} = \mathbf{X} \times \mathbf{F} \quad (1)$$

where **M** is the vector of the three (x, y, and z) moments, **F** is the vector of the three forces, and **X** is the vector location of the CG. All three terms are expressed in the coordinate system of the load cell. While there is no unique solution for a single pair of force–moment measurements, multiple measurements can be combined to calculate a least-squares fit of **X**. See Appendix A for more details.

It is important for reproducibility that the CG values be expressed in a form which is independent of the helmet being measured. ASTM standard F2220 (2014) provides mathematical descriptions for a number of headforms routinely used in helmet testing. The J-sized headform, which represents the 50th percentile male head, was selected to support the helmets being tested in this preliminary study. All CG measures are also expressed relative to the origin for that head.

The J-sized headform was modelled in three-dimensional (3D) computer aided design (CAD) software (SolidWorks; Dassault Systèmes; Paris, France). While the overall dimensions of the headform were preserved, several modifications were made for the purpose of this experiment. First, cylindrical pockets were added at the top of the headform so that calibration weights could be added in known locations. The entire inside of the headform model was then hollowed out so that reinforcements and cross-pieces could be added to interface the headform with the load cell. Portions of the face were removed to facilitate assembly of the final system; however, this was done below where the helmet head band would rest. The final headform model was exported to a stereolithograhy file and then manufactured using a 3D printer (Dimension SST 1200es; Stratasys Ltd.; Eden Prairie, MN).

Forces and moments were measured using a six-axis load cell (Gamma; ATI Industrial Automation; Apex, NC) attached to a National Instruments chassis (NI PXIe-1082) via a NI-PXIe-6358 acquisition card. Custom fixtures were designed to attach the headform to the load cell. The load cell and headform were then mounted on a Manfrotto 3046 camera tripod with a Bogen tilt tripod head which allowed the test fixture to be reoriented with respect to gravity. This set-up simplified the process of acquiring unique combinations of **F** and **M** measurements, all while keeping **X** constant relative to the load cell. Photographs of the system are given in Fig. 1.

### 2.2. Calculating CG using the helmet measurement system

In order to express the CG of the helmet system in the coordinate system of the headform, initialization and calibration steps were necessary. The purpose of the initialization is to determine the CG of the test fixture attached to the load cell. Force and moment measures were taken in five different positions: upright, tilted backward, tilted forward, tilted left, and tilted right. From these measures the mass and CG of the fixture could be determined as described in Appendix A.

The system was then calibrated by placing a 25.4 mm diameter steel cylinder of known height (97.3 mm) in one of the calibration pockets. The location of the CG of the calibration cylinder can then be calculated in the load cell coordinate system. By performing three such measurements with the cylinder in three different locations, a coordinate system for the helmet could be established. A translation and a rotation matrix could then be determined to convert any measurement from the load cell to the helmet coordinate systems. See Appendix B for more details.

### 2.3. Helmets, ear protection, and cap lamps tested

While it would be ideal to measure all possible combinations of helmets, ear protection, and cap lamps in order to define a comprehensive design envelope, it must be recognized that such an approach is infeasible. The total number of permutations is simply too large to be practical. Nor is such an exhaustive study needed. A carefully selected sample of existing devices should be sufficient to define a conservative design envelope. Subsequent testing of other device combinations may expand the safe zone; however, future experiments will not decrease its size.