

Performance under Impact Loads of Metacarpal Gloves used in the Mining Industry

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Abstract: Hand injuries are a significant problem in the mining industry. Even with the continuous advancements in the technology and the safety procedures for production and maintenance tasks, especially in the coal mining industry, there are still manual tasks with high-risk factors, including roof bolting tasks, handling of materials and others, that can produce hand injuries with varying degrees of severity. Between 2000 and 2018, there were nearly 42,000 reported accidents involving some part of the hands with different degrees of severity. These injuries often result in functional limitations or disabilities and have significant financial implications. Metacarpal gloves are used by the mining industry to protect their workers from hand injuries. However, there are multiple glove manufacturers with several options for metacarpal gloves currently in use. Despite the importance of injury prevention, the protection against impact loads is not well known. The mining industry lacks objective measures of performance of metacarpal gloves under impact loads. Current commercially available metacarpal gloves offer varying protection against impact loads depending on the position of the impact, the design, and materials of the glove. This work identifies the most commonly used metacarpal gloves and the characteristics of the object(s) and operation(s) that generate hand injury conditions of miners working in the Appalachian region. Controlled impact tests are conducted to quantify the impact forces for selected impactors. Impact tests are performed on artificial semi-rigid hands and semi-flexible hands manufactured from a medical grade synthetic gel and with 3D printed bone structures wearing different metacarpal gloves. An impact protection index that integrates the data obtained from the tests is proposed and implemented for comparison purposes and to establish a scale of performance.

Keywords: Metacarpal Gloves, Impact Test, Impact Protection Index

1. Introduction

Hand injuries have been and still are a significant problem in the mining industry. In spite of the continuous advancements in the technology and the safety procedures for production and maintenance tasks, there is still a significant number of employees completing manual tasks with high-risk factors (Pollard et al., 2014). According to the Accident Injuries Data Set published by MSHA (U.S. DOL, 2018), from January of 2000 to January of 2018, nearly 20% of the total number of reported accidents corresponded to injuries to the hands of the mine workers. Specifically, there were approximately 42,000 reported accidents involving “fingers/thumb” (76%) and “hand (not wrist or fingers)” (24%). Fracture or crushing occurred in nearly 30% of the accidents, and 41% of the injuries were produced by “struck of falling, flying and rolling object.” Within this last category, activities with higher incidence included accidents with non-powered hand tools (35%), machine maintenance (18%), handling supplies or material (15%) and activities that involved operations with a roof bolter machine (9%). Among the roof bolting tasks, bolting, handling materials and setting up temporary roof support (TRS) are activities with the highest risk indices (Sammarco, 2016). As expected, all these injuries led to thousands of days lost with the consequent burden for the injured and the resulting loss of productivity.

Because the relatively high incidence of injuries involving hands, mine workers are required to wear impact protective gloves (also known as metacarpal gloves) as personal protective equipment (PPE) to protect hands from impact injuries. Metacarpal gloves are typically bulkier than conventional gloves, and the hand function is decreased when the worker is wearing those gloves (Muralidhar and Bishu, 2000; Kinoshita, 1999; Tsousidis and Freivalds, 1998). Usually, when wearing metacarpal gloves, mine workers and machine operators experience decreased dexterity, less flexibility,

reduced tactile sensitivity as well as functional strength, which may lead to an increase in struck by or caught in injuries (Buhman et al., 2000). User acceptance is an essential consideration for the selection of PPE. Like any other industry, mine workers are less likely to wear PPE if it does not fit properly, is uncomfortable, or limits their dexterity, and therefore increasing their risk for injuries (Moore and Campbell, 2017).

There are at least forty five glove manufacturers operating in North-America that currently supply different types of industrial gloves (Dolez et al., 2010). Not all of them are suitable for mining applications. Many of those suppliers offer gloves with features designed to protect workers against individual or a combination of several hazards including mechanical protection (which requires cut resistance, puncture resistance, and abrasion resistance); chemical protection (requiring chemical permeation resistance, chemical degradation resistance and detection of holes); heat and flame protection (requiring flame resistance, heat degradation and conductive heat resistance) and protection from cold. Many models of metacarpal gloves currently available in the market are typically comprised of a fabric layer or set of fabric layers with external reinforcements of Thermo-Plastic Rubber (TPR). TPR is the molded material placed on top of the glove that provides impact protection. TPR reinforcements are typically placed in segments located on the top of the fingers and thumb, on top of the knuckles, or in the dorsal metacarpal region of the hand, or on a combination of these three positions. Other models only include thick pads placed all over the top and bottom surfaces of the glove. This diversity of designs and constructions make it difficult for the end users to select the most suitable glove for the task at hand.

The technical literature shows very few attempts to rationalize the evaluation of metacarpal gloves against impact loads. In one of the studies, the assessment included the measurement of the impact force to break bones of the hand using cadaver hands (Loshek, 2015). A limitation of this study is that the range of age of the cadaver hands was between 76 and 98 years of age with an average age of 87 years which can limit the validity of the reported results. Moreover, the same study shows significant variability in the results and only a minimal amount of detail regarding the methods implemented in the study are provided. The same study measured the reduction in hand impact force as a measure of performance of the glove against an impact and compared the performance of different gloves against no-glove testing (Loshek, 2015), but only a part of the results obtained is publically available.

Based on all the previous considerations as well as on the shortcomings seen in the published data and results, there is a clear need of carrying out an independent research effort to quantify the level of protection offered by the different types of metacarpal gloves currently in use in mining operations. This work presents an experimental setup for impact testing of metacarpal gloves as well as preliminary experimental evaluations carried out to assess the level of protection offered by the different types of metacarpal gloves currently in use in mining operations. The two main objectives of this research are: (a) evaluate the performance of safety gloves typically used in the coal mining industry under impact loads, and (b) establish a scale of performance based on the results of impact tests.

2. Materials and Methods

2.1 Impact Testing Machine

A guillotine-type impact testing machine was used for the evaluation of the performance of metacarpal gloves under impact loads. The testing apparatus consists of a vertically sliding mass attached to flange-mounted linear ball bearings. The sliding mass is released by the activation of a quick-release mechanical device connected to a holding cable. The weight of the sliding mass is 22 lbs. and is based on the weight of three 54" long Hex Tube typically used in roof bolting operations. The impact tests included two types of impactors that were attached to the sliding mass: 1) A rectangular impactor with a nominal impact area of 4.5 in²; 2) A hexagonal impactor derived from a Hex Tube with a nominal impact area of 0.45 in². An overview of the impact testing machine and the impactors are shown in Figure 1.

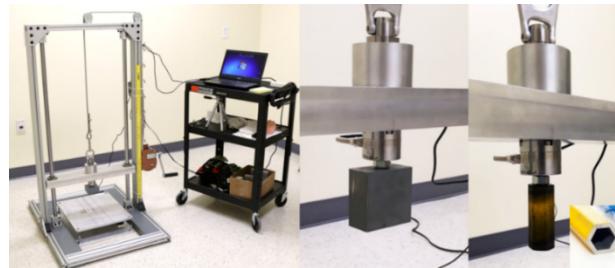


Figure 1. Overview of Impact Testing Machine (left) and rectangular (center) and hexagonal (right) impactors.

2.2 Surrogate Hands and Metacarpal Gloves

Two types of surrogate hands were implemented in this research: 1) a semi-rigid surrogate hand manufactured from segments of oak dowel rods that were sized and assembled to create a hand shape similar to a human hand. In this simplified initial model, no attempt to recreate the soft tissue of the hand was made other than using a nitrile glove to delimit the position of the fingers. The diameters of the dowel rods were kept constant, and the overall dimensions of the hand were representative of typical large-size hand; 2) the second model consisted of a semi-flexible surrogate hand comprised of a 3D printed bone structure and a medical grade ballistic gel hand representing the soft tissue of a typical large-size hand. This second model captured the features of a human hand better as the 3D-printed bone structure resembled the actual bone shape and distribution. These two types of hands are illustrated in Figure 2(a). A total of nine models of metacarpal gloves were selected for testing in this study. All gloves included different designs of thermo-plastic rubber reinforcements or pads placed along the fingers, knuckles, thumb, and metacarpal region. The different models were identified with letters A to I as shown in Figure 2(b). A large-size glove was adopted for all the tests.



Figure 2. Overview of: (a) Surrogate hands; (b) Metacarpal glove specimens used for testing.

2.4 Test Setup

Each hand specimen was divided into four zones for the tests. Impact tests were performed on fingers (p_1), on knuckles (p_2), on the metacarpal region (p_3), and the thumb (p_4). The different hand zones are illustrated in the diagram of Figure 3(a). The surrogate hands with and without gloves were placed on top of the force plate in a flat position as shown in Figure 3(b). For impact position p_1 and p_2 , the hexagonal impactor hit each finger individually at the middle of the length of each finger and each knuckle, respectively. Similarly, for position p_3 , the hexagonal impactor hit each metacarpal, and for position p_4 , the hexagonal impactor hit the middle point of the total length of the thumb. A total of 15 impacts were produced with the hexagonal impactor on each hand and glove specimen. In the case of the rectangular impactor, since the impactor contact area is larger than the contact area of the hexagonal impactor, only one impact was produced on each zone of the hand. In this case, a total of 4 impacts were produced per hand and glove specimen. Impact tests on each type of surrogate hand and type of metacarpal glove were repeated five times, and the average impact reaction forces were calculated for each position and each type of metacarpal glove being tested. Test repetitions were performed using a new surrogate hand and a new glove specimen for each repetition.

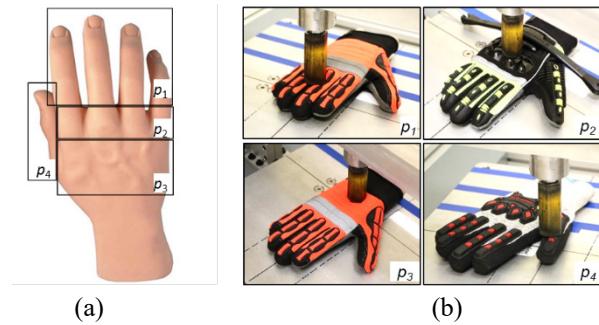


Figure 3. Overview of: (a) Impact zones; (b) Impact tests with the hexagonal impactor.

Impact reaction forces were measured with a force plate mounted at the base of the impact testing machine. The amount of reaction force transferred along the vertical direction (z-axis) to the impactor was measured with a load cell mounted between the impactor and the sliding mass. The bottom of the impactor was positioned at 4 inches (10 cm) from the surface of the force plate. This elevation was kept constant for all the tests. Both forces were measured at a frequency of 1 kHz to capture the dynamic effect caused by the impact. The peak reaction forces measured at the force plate and the impactor were used for the analysis. A diagram of the impact reaction forces and a typical force time history are illustrated in Figure 4.

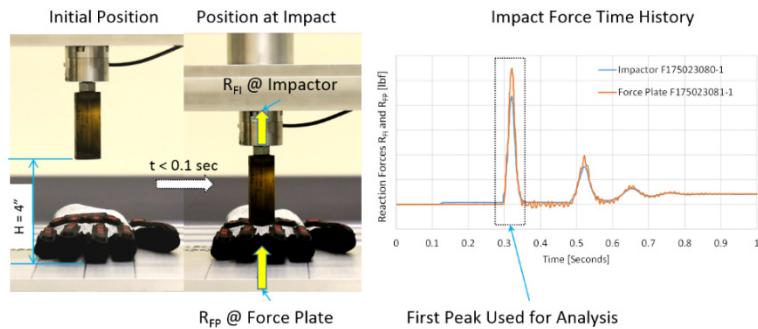


Figure 4. Diagram of impact reaction forces and time history captured during the tests.

2.5 Impact Protection Index (IPI)

An Impact Protection Index (*IPI*) was developed to quantify the performance of a particular glove G subject to impact forces. The index combines into a single number the impact forces measured at different positions of the hand. The *IPI* is calculated as follows:

$$IPI_G = \left[1 - \left(\sum_{p=1}^4 w_p \times \left(\frac{RF_{p(G)}}{RF_{p(\text{No-Glove})}} - FR_{p(\%)} \right) \right) \right] \times 100 \quad (1)$$

Where:

- IPI_G is the Impact Protection Index, a global indicator of the level of protection provided by a particular metacarpal glove G . The IPI_G ranges between 0 (no glove) and 100 (max protection level for a given glove G).
- w_p is a weighting factor selected based on the position p of impact (p_1 to p_4). The value of this factor is extracted from the percentage of accidents at hand position p obtained from accident reports.
- $RF_{p(G)}$ is the average reaction force measured by a force plate at hand position p for a particular glove G .
- $RF_{p(\text{No-Glove})}$ is the average reaction force measured by a force plate at hand position p for an unprotected hand (no glove).

- $FR_p(\%)$ is the percentage of force reduction calculated from the forces measured at the force plate and the impactor at hand position p for a particular glove G . This factor accounts for the energy dissipation provided by the materials (fabric and TPR) that comprise a specific glove G .

The weighting factors w_p corresponding to the different zones of the hand were obtained from historical data of accidents involving hands. Actual data provided by mine operator located in the Appalachian region indicated that during years 2014 to 2018, accidents involving hands were grouped into two major categories: “Fingers” (~61%) and “Hand” (~39%). With this information, the IPI_G was calculated using Equation (1) in which impact positions p_1 (four fingers) and p_4 (thumb) were grouped under “Fingers”, while impact positions p_2 (knuckles) and p_3 (metacarpals) were grouped under “Hand”.

3. Results

Nearly two hundred and fifty impacts were carried out with the test setup and the glove specimens described previously. Data analysis showed that for the semi-rigid surrogate hands tested without gloves, the average impact forces measured at the force plate were in the range of 966 lbf to 976 lbf for the hexagonal impactor, and in the range of 824 lbf to 1149 lbf for the rectangular impactor. For the semi-rigid hands wearing different gloves, the reaction impact forces measured at the force plate were in the range 158 lbf to 780 lbf for the hexagonal impactor, and in the range of 179 lbf to 773 lbf for the rectangular impactor. The difference between the force measured at the force plate and the impactor was in the range of 7% to 38%. For all the measurements the Coefficient of Variation (C.O.V), defined as the ratio between the average values and the standard deviation, was less than 5% for all the types of gloves used for testing.

On the other side, the semi-flexible surrogate hands were used for preliminary evaluation of gloves B, E, G and I only, and the results were compared to the no-glove configuration. For the semi-flexible hand without a glove, the impact forces measured at the force plate were in the range of 369 lbf to 771 lbf with a C.O.V of nearly 28% indicating a relatively scattering of the data. For the specimens wearing the selected gloves, the forces measured at the force plate were in the range of 162 lbf to 562 lbf. The difference between the force measured at the force plate and the impactor was in the range of 6% to 18% and the C.O.V. was in the range of 17% to 29%.

The results of the implementation of Equation (1) for both types of surrogate hands and the two types of impactors are illustrated in Figure 5. Figure 5(a) shows the IPI obtained for the semi-rigid surrogate hands arranged in decreasing order of performance for the two types of impactors. Figure 5(b) compares the IPI calculated for the selected gloves tested with the semi-flexible and semi-rigid surrogate hands and for the hexagonal impactor.

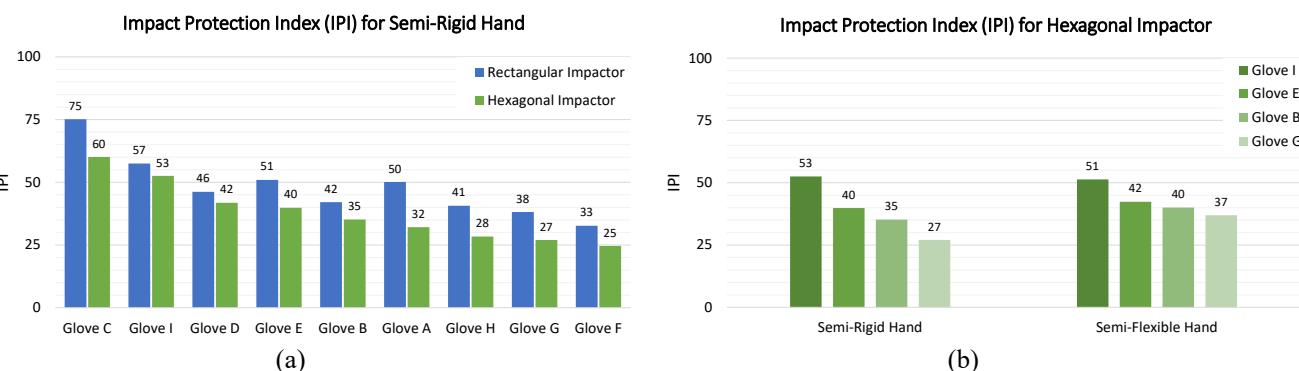


Figure 5. Impact Protection Index for: (a) Semi-rigid surrogate hand, rectangular and hexagonal impactor; (b) Semi-flexible vs. Semi-rigid surrogate hands for selected gloves and hexagonal impactor.

4. Discussion

The first important aspect of the test results is that the absolute magnitude of the impact forces must be taken with care because the impact force is proportional to the stiffness of the surrogate hand. A semi-rigid or stiffer surrogate hand,

such as a wooden hand, would be able to carry a higher impact force than a semi-flexible or softer gel hand. However, when different mean values of forces obtained from the various tests are plugged into Equation (1), the normalization with respect to the respective no glove configuration eliminates the magnitude and creates a relative index that can be used for comparison and classification purposes.

Results illustrated in Figure 5(a) show that for the semi-rigid surrogate hand, the proposed impact protection index (*IPI*) can capture the difference in the performance of the different gloves for the two types of impactors selected for the tests. The best performing glove (Glove C) obtained an index of 75 and 60 for the rectangular and hexagonal impactor, respectively, while the worst performing glove (Glove F) obtained an index of 33 and 25 for the rectangular and hexagonal impactor, respectively. These results are consistent with the level of thermo-plastic rubber and other reinforcements included in Glove C, which contributes to dissipate the impact force by deforming or dampening the effect of the impact. The lack of those reinforcements as well as the overall design of Glove F may have contributed to its low performance under impact loads.

Results illustrated in Figure 5(b) show a comparison of the *IPI* obtained for selected gloves (B, E, G and I) tested with two different surrogate hands (semi-rigid and semi-flexible), and the same impactor (hexagonal) indicate that the magnitude of the index changes slightly, but the tendency in the performance is the same. That is, Glove I performs better than Glove G, regardless of the type of hand used of the test. This is seen as an advantage of the normalization model proposed in Equation (1), which makes the evaluation of performance nearly independent of the type of surrogate hand used for the test, as long as the same type of surrogate hand is used for all the types of gloves and impactors under evaluation. Further tests are being conducted to confirm the validity of the proposed model.

Impact tests results showed that the variability of the impact force, reflected in a relatively low coefficient of variation, is smaller in the semi-rigid than in the semi-flexible hand. This is attributed to the constant section and relatively uniform material properties of the wooden segments that constitute the hand. The relatively large variability seen in the semi-flexible hands is attributed to the more realistic representation of the hand in which the cross-section of the bones is not constant, and distribution and thickness of the gel representative of the soft tissue vary with the position of the impact. Additional tests are being conducted to understand how the characteristics of the semi-flexible surrogate hand influence the performance of the different metacarpal gloves as well as their effect on the determination of the *IPI*.

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