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# Energy-based safety risk assessment: does magnitude and intensity of energy predict injury severity?

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**ABSTRACT**

Although the quantity and quality of safety risk data have improved in recent years, available data do not link directly to natural principles and are, therefore, limited in their application and scientific extension. The present study aims to test the hypothesis that the quantity and intensity of energy observable prior to an incident predicts the severity of the incident. The hypothesis is built upon the theory that energy is translated to an injury through uncontrolled release of the energy, transfer of the energy to the human body and the vulnerability of the body and associated protective equipment. To test the hypothesis, a multi-phase experiment was conducted. First, over 500 injury reports were gathered from national databases and private companies. For each report, the leading information describing the work operations and environment and the lagging information describing the injury were extracted, separated and isolated. Second, the magnitude of the energy was estimated using only leading information. Once energy magnitude was quantified, the distribution was compared across injury severity levels using analysis of variance tests. As hypothesized, energy magnitude is a strong predictor of injury severity. Although computationally intensive, energy intensity, defined as the magnitude of energy divided by the area of contact between an object and the human body, showed strong predictive validity. This research indicates that energy-based safety risk analysis has predictive validity and is a promising line of scientific inquiry with the potential to increase our understanding of the natural phenomena that contribute to injuries.

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Accident; injury; occupational health and safety; risk analysis; safety

## Introduction

To reduce the frequency of injuries and fatalities, a plethora of programmes have been introduced such as project-specific training and safety meetings, frequent worksite inspections and worker safety and health orientation. However, the effectiveness of these traditional injury prevention approaches is limited due to their reactive and regulatory-based nature (Hallowell and Gambatese 2009a). Additionally, most existing strategies have reached saturation in terms of new adoption, suggesting that new, perhaps untraditional, avenues of research and development for construction safety is critical for future improvement (Esmaeili and Hallowell 2012). In response to these limitations and trends, researchers have begun to explore risk-based practices as a means for safety innovation.

Safety risk researchers have used a variety of data sources and theoretical perspectives on what constitutes risk. Based on the generally acceptable definition, a safety risk is considered to be the likelihood of an injury or illness of a given severity level (Baradan and Usmen 2006). When modelling the safety risk of a work environment, risk is quantified by finding the product of the frequency or probability of an incident (i.e. likelihood) and the expected severity of that incident (Jannadi and Almishari 2003). Although most research acknowledges that the likelihood and severity components of risk are equally important in the quantification of risk, the focus of most research is on likelihood. In fact, recent researchers have recently made significant progress in measuring the probability that an injury will occur based upon the observable attributes of a particular work environment (Tixier *et al*. 2016). However, attempts to predict severity using empirical data have failed (Esmaeili *et al*. 2015, Tixier et al. 2016).

Society would benefit from the ability to view a work environment and accurately forecast the severity of a potential injury. At present, the severity component of risk is empirically considered only when using retrospective analyses; i.e. when the distribution of injuries of particular severity levels are known from past incidents. There is no present method for observing the characteristics of a new work environment and making an accurate prediction of the severity of an injury if one were to occur. This limitation

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has stifled empirical risk analysis, predictive analytics and the practical assessment of the criticality of work. If a predictive method were available, researchers could pair existing probabilistic assessment methods with severity forecasts to model risk empirically for a unique environment for the first time. Additionally, severity forecasts would allow practitioners to identify near-miss situations with the potential for high impact. This would enable the justification for resource-intensive near-miss investigations that are required for learning.

The objective of this study is to address the current limitations in safety risk analysis by offering and testing a new, energy-based approach to predicting the potential severity of injuries. The specific goal is to test the hypothesis that *the quantity and intensity of energy observable prior to an incident predicts the severity of the incident*. If this hypothesis is correct, an elegant and scientific method for assessing the severity component of safety risk may emerge that may be operationalized as a more robust safety risk assessment technique for industry.

Applying the concept of energy to explain variability in the severity of construction injuries requires a description of our epistemological positions on both safety risk analysis and safety energy. Also, we must explain the scientific basis for our proposed extension of the energy theory first proposed by Haddon (1968). Thus, we dedicate this background to reviewing perspectives of and approaches to safety risk analysis, the concept of "safety energy", extant methods of explaining accident propagation and comparable scientific approaches to risk modelling from the field of natural disaster research. We use this background to frame our theoretical point of departure and our contributions to the body of knowledge.

## Safety risk analysis background

At its essence, risk can be defined as a potential event that results in an outcome that is different from what is planned. Researchers have consistently calculated safety risk using Equation (1), which expresses the quantity of safety risk as the product of injury frequency and severity (e.g. Jannadi and Almishari 2003, Baradan and Usmen 2006, Hallowell and Gambatese 2009b). Unfortunately, traditional safety risk analysis techniques are severely limited because of bias towards the frequency component of risk, inadequate data sources and units of analysis that compromise generalizability (Hallowell *et al*. 2011).

$$\text{Unit risk} = (\text{frequency}) \times (\text{severity}) \quad (1)$$

### Approaches to safety risk quantification

Most safety risk analyses have focused exclusively on quantifying the frequency or likelihood of particular injuries. For example, Huang and Hinze (2003) quantified the rate of fall incidents using statistical data from OSHA and the Bureau of Labor Statistics (BLS 2014) and Everett (1999) quantified the risk of overexertion injuries for various trades by computing the rate at which they occur. Researchers have focused on frequency because the data are typically accessible through databases such as the BLS. Although the severity component of risk is equally important in a mathematical sense, its quantification has received comparatively little attention potentially due to reliance on the widely used *Safety Pyramid* (Heinrich 1931) assumption to explain injury severity distribution.

In contrast to advances achieved in risk analyses for other project management functions like cost control, the development of safety risk analysis has lagged because of inadequate data sources. Since it is challenging to access large volumes of sensitive empirical safety data, many researchers have resorted to opinion-based ratings of safety risk (Everett 1999, Jannadi and Almishari 2003, Brauer 2005, Hallowell *et al*. 2011). Unfortunately, human ratings of risk are vulnerable to biases in judgement that often render the data invalid (Gustafson 1998, Kahneman and Tversky 1982, Sjöberg 2000). Fortunately, recent advancements in injury reporting and data collection have enabled researchers to leverage high quantities of data from private companies to perform empirical risk analyses (Esmaeili *et al*. 2015a, 2015b). These studies involved forecasting likelihood of various injury types based upon the physical attributes of the work environment. Although physical attributes of the work environment can be used to assess the likelihood component of risk, they do not predict the severity of an injury better than random (Tixier *et al.* 2016). Although this is consistent with Heinrich's (1950) axiom that the severity of an injury is largely fortuitous, we challenge this assumption with a new scientific method of severity prediction.

### Units of safety risk analysis

Past safety risk studies vary in the units of analysis, which have a great impact on the generalizability and practicality of the risk ratings. All past safety risk researchers have assumed that the work can be decomposed into its constituent parts to address the variability of work activities and environments (Lingard 2013). The decomposition has resulted in a great variety of units ranging from high-level studies that compare risk among trades (Baradan and Usmen 2006, Fung *et al*. 2010) and injury types (Hinze *et al*. 2005) to detailed studies looking at specific work activities and the risk associated with specific tasks (Everett 1999, Jannadi and Almishari 2003, Hallowell and Gambatese 2009b). The limitations arise from the fact that the units either so overly broad that they have limited

application to individual projects or are so specific that any new work methods or variation upon existing methods requires a laborious research process to collect new data. Very recently, Esmaeili *et al*. (2015a) introduced attribute level risk analysis, which focuses on elemental characteristics of the work that are independent of any task or environment (e.g. uneven surfaces, work at height, etc.). Although this new framework allows researchers to quantify the risk of injury for virtually any environment, risk forecasts have shown to only have moderate validity (Esmaeili *et al*. 2015b).

To address limitations associated with data source and unit of analysis, the present study introduces and tests a new means to predict severity for safety risk analysis based on a theory that all injuries are caused by the unwanted release of energy. The relationship between energy and severity is independent of any work environment and focuses on a fundamental natural condition. If true, the relationship may prove to be a basic method for predicting injury severity and conceptualizing safety risk.

## Energy release theory

The inspiration for an energy-based approach to safety risk analysis originated with Haddon's (1968) aetiologic basis for describing injury severity. Using medical diseases and symptoms as an analogy, Haddon (1968) argued that injuries are not caused by the seemingly infinite and random collaboration of causal factors that describe the specific circumstances of the accident (i.e. symptoms). Rather, he claims that injuries should be defined by their fundamental cause, hazard energy (i.e. disease), or more specifically, the release of hazard energy and contact by an individual. Under this aetiologic explanation, there must be a form of energy exchange in excess of the body's vulnerability in order for an injury to be sustained. Approximately ten years later, Haddon (1980) further expanded upon this aetiological theory by introducing the concept that injury prevention should focus on the removal, reduction, isolation, or control of hazard energy.

Fleming (2009) contributed to Haddon's energy release theory by defining various energy sources that cause injury. His argument was that industry application of the energy theory requires focus on the management of specific types of hazard energy sources (e.g. gravity, motion, electrical). Most recently, principles of the energy release theory were organized into a ten-energy-source mnemonic, which was then field-tested in an effort to measure its impact on hazard recognition skills (Albert *et al*. 2014). The results of the multiple baseline test indicate that the mnemonic-based learning increases hazard recognition skills by approximately 30% when compared with traditional safety planning activities alone (e.g. job safety analyses and checklists). Despite these significant advancements, there is still a dearth of research that investigates the scientific extension and practical application of hazard energy within occupational safety.

### *Comparison to extant methods of injury propagation*

The energy release theory is different from more traditional methods of explaining accident propagation. There is a relatively large body of knowledge related to accident causation, which aims to explain the reasons *why* injuries occur. In the form of risk analysis, some researchers have begun to adopt a position that the risk of injury is related to the physical characteristics of the work environment and tasks (e.g. Esmaeili *et al*. 2015, Tixier et al. 2016). Others have focused on the role that specific entities play in accident causation like designers (e.g. Gambatese *et al*. 2008), clients (e.g. Huang and Hinze 2006), supervisors (e.g. Hardison *et al*. 2014) and workers (e.g. Rasmussen *et al*. 1990). In a more inclusive epistemological position, accident causation researchers agree that injuries are the result of the confluence of system failures (Suraji *et al*. 2001, Haslam *et al*. 2005). This position emanates from theories like the *Swiss Cheese Model* (Reason 1990). This entire body of knowledge focuses on what causes an injury to occur rather than how severe the injury might be if one were to occur. Here, we focus exclusively on predicting and explaining injury severity. This defines our theoretical point of departure.

It should be noted that there have been a few studies that aimed to predict injury severity. For example, Esmaeili *et al*. (2015) attempted to predict injury severity using the presence or absence of fundamental attributes of the work environment and a generalized linear model. Their position as that injury severity could be predicted by the tools, equipment, tasks, environmental conditions and other physical attributes of the workspace. The results indicated that the model was able to predict the type of injury (e.g. fall or struck by) but was not significantly better than random at predicting injury severity. Tixier et al. (2016) confirmed these results using similar data and machine learning techniques. We offer an alternative approach to severity prediction using a scientifically fundamental position that the quantity and magnitude of energy is the true predictor. This position was inspired by the fields of disaster research as discussed below.

## Parallels between energy release theory and natural disaster research

Our concept of energy-based safety risk analysis parallels modern theory of natural hazard risk assessment

techniques. In essence, predicting the impact of a natural hazard relies on three fundamental factors: (1) the potential for a natural hazard; (2) the natural hazard's impact intensity; (3) and the vulnerability of the affected community (Lindell and Prater 2003). Similar to occupational injuries, the impact (severity) of a natural hazard is very difficult to predict because it may be comprised of several hazards that may inflict damage on a particular area (Lindell and Prater 2003). For example, one agent, such as a hurricane, may inflict casualties and damage through wind, rain, storm range and inland flooding (Bryant 1991). For this reason, the impact intensity of a natural hazard can generally be defined in terms of the physical materials involved (i.e. liquid in a flood or solid material in a landslide) and the energy these material impart (Lindell and Prater 2003). Whether the goal is to predict the potential impact of landslides using the mass and velocity of a potential landslide area (Cardinali *et al*. 2002) or predict the potential impact of a hurricane by measuring wind speed (Moon *et al*. 2007), using a natural hazard's energy allows the potential impact of various natural hazards to be expressed in one universally relatable metric (Lindell and Prater 2003). We postulate that the same theory holds true for safety, where many sources of energy can contribute to the potential severity of an event.

The second portion of any natural hazard risk assessment is the vulnerability of an affected community and the community's ability to withstand a natural hazard. The majority of natural hazard risk analysis research involves the study of vulnerability. For example, several studies have created models to assess the vulnerability of potentially affected areas based on variables ranging from a country's Gross Domestic Product (Kahn 2005), the money invested in mitigation and emergency practices in the area (Lindell and Prater 2003), the density of population and complexity of commercial infrastructure (Wei, Fan, Lu, and Tsai 2004), or the area's reliance on the surrounding ecosystem (Tang, Li, Lei, Wang, and Shen 2015).

## Proposed new energy-based safety risk analysis

From elemental concepts of energy release theory, we postulate that: *the severity of a potential injury is determined by the ratio of energy intensity and the vulnerability of the human body part to which the energy is transferred*. Furthermore, a hazard's energy intensity is defined *as the ratio of the hazard's energy magnitude and the mechanism by which energy contacts the human body*. The likelihood component of risk is, in turn, defined as the human, managerial, political, social and stochastic factors that define the probability that energy will be released and will contact a worker. Figure 1 illustrates the proposed relationships among these factors organized in to parallel prevailing natural disaster models presented by Lindell and Prater (2003). Here, the energy transfer mechanics refer to the shape and size of the object possessing energy, which may contact the human body (e.g. a sack of concrete, tape measure, mobile equipment).

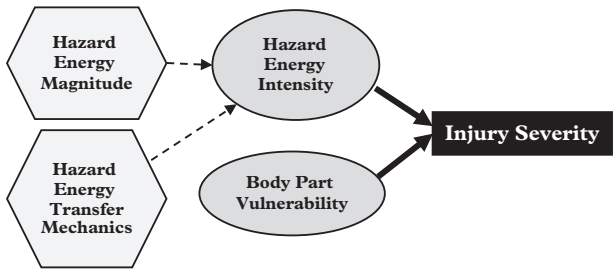



**Figure 1.** Proposed energy-based occupational safety risk analysis framework.

Because the vulnerability of the human body is highly variable among subjects and difficult to observe in a leading manner, the focus of this paper will be on hazard energy magnitude and intensity. Specifically, we aim to assess the extent to which energy magnitude and energy intensity predicts injury severity. Since we postulate that energy intensity is a better predictor of injury severity, we show this relationship in Figure 1.

### *Hazard energy magnitude*

In order to compute energy intensity, one must first measure *energy magnitude*. Since a variety of energy sources exist in occupational environments (e.g. gravitational, kinetic, radiation), there are various methods of computing energy magnitude. For example, using basic physics, gravitational potential energy (*PE*) can be directly measured by finding the product of the mass of an elevated object, the height of the object and the gravitational constant (Equation (2)).

$$PE = mgh \tag{2}$$

where $m$ = mass; $g$ = gravitational constant; and $h$ = height that the object or subject could fall.

In a practical sense, the computation of *PE* is quite simple as it only requires the measurement of height and mass along with the knowledge that when either increases, the quantity of *PE* increases proportionally. However, translating energy magnitude to potential injury severity can be abstract without formal analysis.

Take, for example, the conditions where both a 0.5 kg tape measure and a 7 kg sledgehammer are dropped from a height of 2 metres. It is obvious that, due to the difference in mass, the sledgehammer possesses a greater quantity of energy than the tape measure. Also, it may seem intuitive that the sledgehammer has the potential to inflict greater

damage and result in a more severe injury. However, it becomes comparatively difficult to intuit energy magnitude and make comparisons in extremes when more than one variable changes at a time or when different energy types are compared. For example, assessing the comparative energy between a 0.5 kg tape measure dropped from 10 metres and a 7 kg sledgehammer dropped from 2 metres is not as easy. In such cases, formal energy computations with consistent units and reliable predictive models could allow for an objective assessment of risk. In other words, formal analyses would help a person to evaluate the quantity of the energy and interpret the risk associated with the energy without relying on judgement that is subject to cognitive biases.

### *Hazard energy intensity*

Synonymous with natural hazard risk analysis, we postulate that the actual danger associated with a hazard energy source depends not only on energy magnitude but also on the physical characteristics of the hazard itself. In order to be theoretically transferable to any hazard energy source, the term "relation" used within the definition of energy intensity references two scenarios: (1) a scenario in which a greater transfer mechanism value will increase the likelihood an individual is severely injured and be expressed in a unit of time (i.e. radiation, sound and chemical); (2) and a scenario in which a smaller energy transfer mechanism value will result in a more severe injury and be expressed in a unit of area (i.e. pressure, gravity and motion). Equations (3) and (4) present the respective relationships above scenarios, respectively. From a scientific standpoint, the second scenario is analogous to pressure and the translation of energy to force through Newton's Second Law of Motion. The second scenario will be the focus of the experimental portion of this study; however, the proposed theory can apply to any hazardous energy source.

$$\text{Hazard intensity} = (\text{Energy magnitude}) \times (\text{energy transfer period}) \tag{3}$$

$$\text{Hazard intensity} = \frac{\text{Energy magnitude}}{\text{energy transfer area}} \tag{4}$$

To better illustrate the relationship between energy intensity and the severity of a sustained injury for the second scenario (Equation (4)), a comparison between a 0.5 kg tape measure and a 0.5 kg concrete chisel dropped from 3 metres provides a compelling example. The concrete chisel has a minimum contact area at its tip of approximately 0.6 $cm^2$ while a standard tape measure on its smallest edge is approximately 12.9 $cm^2$. Assuming that both objects strike a person with the identical impact duration and velocity (i.e. 0.05 s and 7.67 m/s, respectively), the pressure of the tape measure and concrete chisel are 59.5 and 1279 kPa, respectively. Although the tape measure and concrete chisel possess an equivalent amount of potential gravitational energy (14.7 joules), the disparity in impact area between the objects causes dramatic differences in pressure and injury.

Because the impact duration needed to calculate the rate of force transfer (i.e. impulse) cannot be readily measured in a leading fashion, we simplify the computation to energy intensity, which, for the example, would be 1.14 joules/$cm^2$ for the tape measure and 24.5 joules/$cm^2$ for the concrete chisel. The concept of energy intensity provides a reasonable compromise between the scientific validity and practicality, using variables that are readily observed in the field.

### *Vulnerability of the human body*

Returning to the analogy of natural hazard modelling, the magnitude of a natural disaster, such as a hurricane, does not fully predict the magnitude of damage. For example, due to differences in infrastructure, a hurricane striking the coast developing country would presumably inflict more human casualties than a hurricane of the same magnitude striking a developed country. This concept, referred to as vulnerability, also applies in the context of energy-based safety risk where the extent of injury caused by a particular hazard varies depending upon the vulnerability of a particular body part to which the energy is transferred. For example, in the unfortunate case of the New Jersey construction worker being struck by a falling tape measure (Santora 2014), the injury most likely would have not been fatal had the tape measure stuck the worker in the shoulder rather than his head. Additionally, personal protective equipment (PPE) items, such as a hard hat or padded gloves, can improve the body's resistance to injury and reduce vulnerability to impact by dispersing the energy across its surface. Although we theorize that the vulnerability of the impacted body part heavily influences the severity of injury suffered, it is difficult to evaluate this factor in a predictive sense due to the speculative nature of estimating variables such as the variations in worker actions and body position. These values are often impossible to quantify accurately from second-hand accounts in injury reports. For these reasons, vulnerability was omitted from analysis with the caveat that inclusion of this variable in future research may improve overall scientific validity.

## Hypotheses

Based upon the proposed energy-based safety risk analysis discussed above, we formed the following two priori null hypotheses:

*Null Hypothesis* 1: Energy magnitude measureable prior to an incident does not predict variability in injury severity better than random.

*Null Hypothesis* 2: Energy intensity measureable prior to an incident does not predict variability in injury severity better than random.

In order to test these two null hypotheses, the leading information describing the circumstances on an injury from which energy magnitude and intensity could be computed was decoupled from the lagging information regarding the severity of each injury. In addition to testing the two primary hypotheses, we aimed to measure the extent to which energy magnitude and energy intensity distinguish between low severity injuries (i.e. non-fatal injury) and high severity injuries (i.e. fatalities) in an effort to define a "high energy" threshold. This was important from a practical perspective because industry practitioners are beginning to use the term "high energy" without a precise definition or threshold.

## Computing energy magnitude and energy intensity

In this study, motion and gravity hazards were analysed. We restricted our scope to these energy sources because they contribute to three of the four leading classified types of construction injuries (BLS 2015). Additionally, these two energy sources proved to be readily available for robust statistical hypothesis testing. As shown in Equations (5) and (6), we needed the following independent variables to compute energy magnitude and energy intensity: the weight, height, speed and contact area of an object or person possessing the energy. These variables are leading in that they are observable prior to an incident and objectively measurable.

Although we hypothesize that energy intensity has stronger predictive validity than energy magnitude, we recognize that, in practice, the probabilistic assessments of contact area are abstract and unrealistic. Energy magnitude, however, only requires the observation of height, weight and velocity, which are easily estimated. Table 1 illustrates several case examples of the data needed to compute energy magnitude and energy intensity from gravity and motion.

$$\text{Energy magnitude} = mgh = \frac{1}{2}mv^2$$

$$\text{Energy intensity} = \frac{\text{Energy magnitude}}{\text{contact area}} = \frac{mgh}{A} = \frac{\frac{1}{2}mv^2}{A} \quad (6)$$

where $m$ = hazard mass; $g$ = gravitational acceleration constant; $h$ = height of the hazard; $v$ = velocity of hazard; and $A$ = contact area (i.e. "sharpness" of hazard).

## Research methods

The proposed hypotheses were tested by investigating the relationship between the severity of worker injury and the characteristics of the energy present before the injury was sustained. Energy magnitude and energy intensity were computed from information contained in detailed accounts of past injuries. The severity of each injury was entered into an event management system and classified according to the guidance provided by Hallowell and Gambatese (2009b). The injury severity classifications are listed in Table 2 along with their respective definitions.

Injury reports were obtained from three databases: (1) donation by a consortium of 281 private multi-national construction organizations over a three year span; (2) the Fatality Assessment and Control Evaluation (FACE) reports provided by the National Institute for Occupational Safety and Health (NIOSH) in the United States; (3) and

**Table 1.** Proposed energy-based safety risk analysis computational framework with examples.

| | Input variables | | | | Output variables | |
|---|---|---|---|---|---|---|
| | Weight (kg) | Height (m) | Speed (m/s) | Contact area ($cm^2$) | Energy magnitude (joules) | Energy intensity $\left(\frac{\text{Joules}}{cm^2}\right)$ |
| Computation | $A$ | $B$ | $C$ | $D$ | $A \times B$ or $\frac{1}{2} \times \left(\frac{A}{g}\right) \times C^2$ | $(A \times B)/D$ or $\left(\frac{1}{2} \times \left(\frac{A}{g}\right) \times C^2\right)/D$ |
| Tape measure dropped from 50 stories | 0.5 | 152.4 | – | 12.9 | 747.5 | 57.9 |
| Bag of cement mix dropped from 1 storey | 22.7 | 3.0 | – | 232.3 | 668.1 | 2.88 |
| Tape measure dropped from 1 storey | 0.5 | 3.0 | – | 12.9 | 14.7 | 1.14 |
| Concrete chisel dropped from 1 storey | 0.5 | 3.0 | – | 0.65 | 14.7 | 22.6 |
| Nail fired from pneumatic nail gun | 0.001 | – | 30.5 | 0.008 | 0.47 | 58.14 |

**Table 2.** Injury classification system used during data analysis.

| Classification | Definition | Reports analysed |
|---|---|---|
| 1st aid | Any treatment of minor scratches, cuts, burns, etc. where the worker is able to return to work the same day following first-aid treatment | 55 |
| Medical case | Any work-related injury or illness requiring medical care or treatment beyond first-aid where the worker is able to return to work the following day | 113 |
| Lost work time | Any work-related injury or illness that prevents the worker from returning to work the following day | 280 |
| Permanent disability | Any work-related injury or illness that results in permanent aliment | |
| Fatality | Any work-related injury or illness that results in death | 57 |

the Worker's Compensation Board of British Columbia (WorkSafeBC). In total, 505 reports of injuries related to gravity and motion energy sources were obtained. The distribution of injury reports within each injury classification can be viewed in Table 2.

Processing the injury report data first involved decoupling the independent predicting variables, *hazard energy magnitude* and *hazard energy intensity*, from the dependent variable, *injury severity*. Using only descriptions contained within the written injury reports, a team of three engineering students with training in Newtonian energy principles computed hazard energy magnitude and hazard energy intensity by estimating height, weight, speed and physical characteristics of the equipment, tools, material and workers. Importantly, the estimation of the independent variables was performed without knowing the outcome of each case. Then, statistics were applied in order to test our hypotheses. Figure 2 illustrates the described research process.

## Results and analysis

### *Testing statistical significance among all injury severity levels*

The goal of the analysis was to measure the extent to which energy magnitude and energy intensity predicts injury severity better than random. In other words, we aimed to answer the question: *does magnitude and intensity of energy predict injury severity?* To make this assessment, the distribution of energy magnitude for each severity level was first plotted and compared statistically. In order to visualize the distributions across the severity levels, a series of boxplots were created. In addition, approximate probability density functions (PDF's) were mapped with respect to each injury classification to visually represent the distributions of each boxplot.

It is apparent from examination of Table 3 and Figure 3 that the distribution of energy magnitude is starkly different across the severity levels (note the log scales). Because injury severity is typically observed and quantified as a step function rather than a continuous scale, the presentation of the data and the statistical metrics used to compare the groups were categorical. Furthermore, a logarithmic scale was used to facilitate visual comparison among the injury severity levels. The high energy threshold is depicted in Figure 3; however, the underlying rationale to determine the threshold will be explained in subsequent sections.

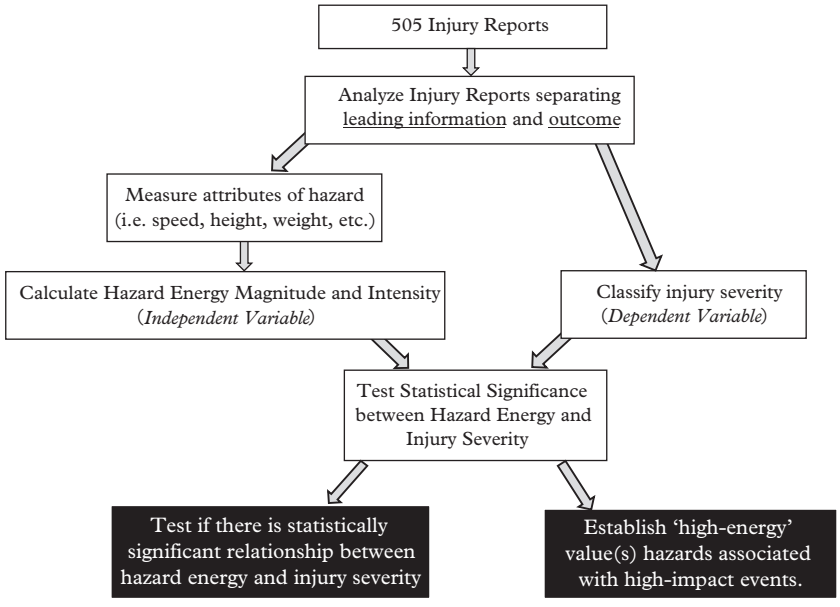



**Figure 2.** Diagram of research and analysis process.

**Table 3.** Demographic statistics for energy magnitude.

| | Fatality | Lost work and permanent disability | Medical case | First aid |
|---|---|---|---|---|
| Number of reports | 57 | 288 | 134 | 57 |
| Min. (joules) | 590 | 5 | 6 | 1 |
| Quarter 1 (joules) | 3580 | 1952 | 162 | 32 |
| Median (joules) | 5859 | 2645 | 1587 | 103 |
| Quarter 3 (joules) | 40,689 | 3967 | 2116 | 1058 |
| Max (joules) | 4,433,408 | 85,853 | 22,652 | 2121 |

Note: ANOVA (single factor) $p$-value < 0.01.

To test for differences in the energy magnitudes across severity classifications, a single-factor analysis of variance (ANOVA) test was performed. As one can see, the assumptions of approximately normally distributed data to use the ANOVA test were met. The ANOVA test indicates, and the distributions suggest, there is a significant statistical difference across all severity levels ($p$-value < 0.01). These results indicate that null hypothesis 1 should be rejected.

The same analyses were performed using energy intensity values for each injury classification. A similar boxplot format was employed to graphically compare the energy intensity distributions (see Figure 4). The salient values are shown in Table 4. Again, the high energy threshold is shown in Figure 4 but will be explained in following sections. When compared with the distributions for energy magnitude, energy intensity showed significantly less variability among the severity groups (i.e. the variability decreased significantly by adding the variable contact area). Accounting for contact area reduced both the variance within each severity level and overlap among severity levels. This indicates that energy intensity predicts injury severity better than energy magnitude. Similar to the analysis performed with energy magnitude, a single-factor ANOVA statistical test was performed, yielding

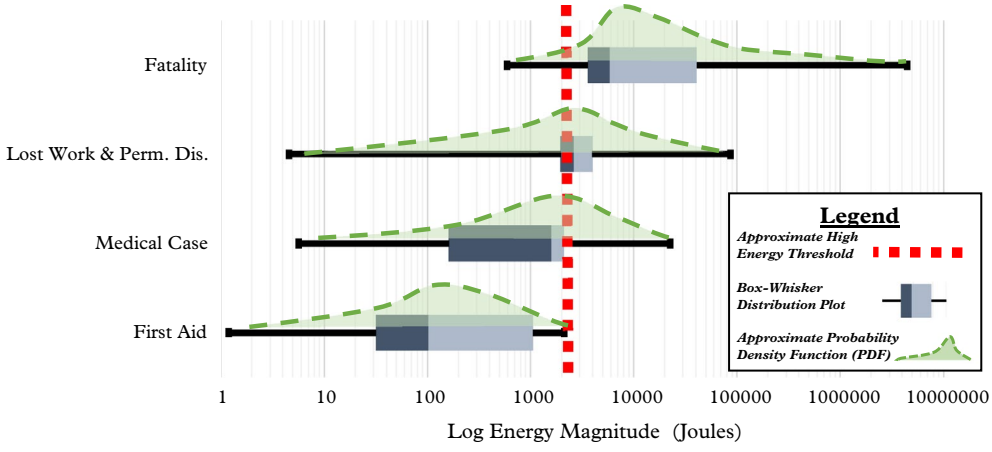



**Figure 3.** Boxplot distributions of energy magnitude with respect to injury severity.

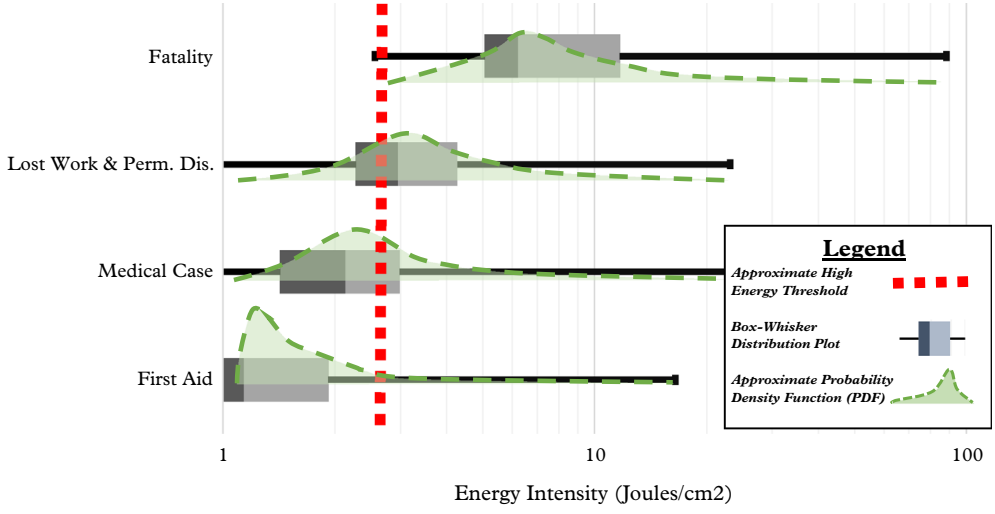



**Figure 4.** Boxplot distributions of energy intensity with respect to injury severity.

**Table 4.** Demographic statistics for energy intensity.

| | Fatality | Lost work and permanent disability | Medical case | First aid |
|---|---|---|---|---|
| Number of reports | 56 | 280 | 113 | 55 |
| Min. (joules/cm$^2$) | 2.6 | 0.35 | 0.27 | 0.092 |
| Quarter 1 (joules/cm$^2$) | 5.1 | 2.3 | 1.4 | 0.60 |
| Median (joules/cm$^2$) | 6.2 | 3.0 | 2.1 | 1.1 |
| Quarter 3 (joules/cm$^2$) | 11.7 | 4.3 | 3.0 | 1.9 |
| Max (joules/cm$^2$) | 88.3 | 23.2 | 22.9 | 16.5 |

Note: ANOVA (single factor) $p$-value < 0.01.

a $p$-value < 0.01. These results indicate that null hypothesis 2 should also be rejected.

### *Defining a "high energy" threshold*

As previously indicated, one goal of our analysis was to help practitioners to distinguish conditions that may lead to a fatality from non-fatal events. In other words, we aimed to define the "high-energy" threshold. The implication is that, if the potentially fatal conditions can be identified before an event occurs, targeted and potentially costly prevention efforts can be implemented with confidence grounded in empirical evidence.

To measure this threshold, a standard $t$-test was performed comparing energy magnitude and intensity for fatal and non-fatal events. The results indicate very strong differences in energy between fatal and non-fatal events ($p$-values for hazard energy magnitude and hazard energy intensity of 0.06 and 0.00007, respectively). Figures 5 and 6 present the distribution of hazard energy of high impact events and low impact events for both hazard energy metrics.

## Discussion and interpretation

### *Explaining the variability and extreme values*

Wide variability within each injury classification causes modest overlap between the differing injury severity

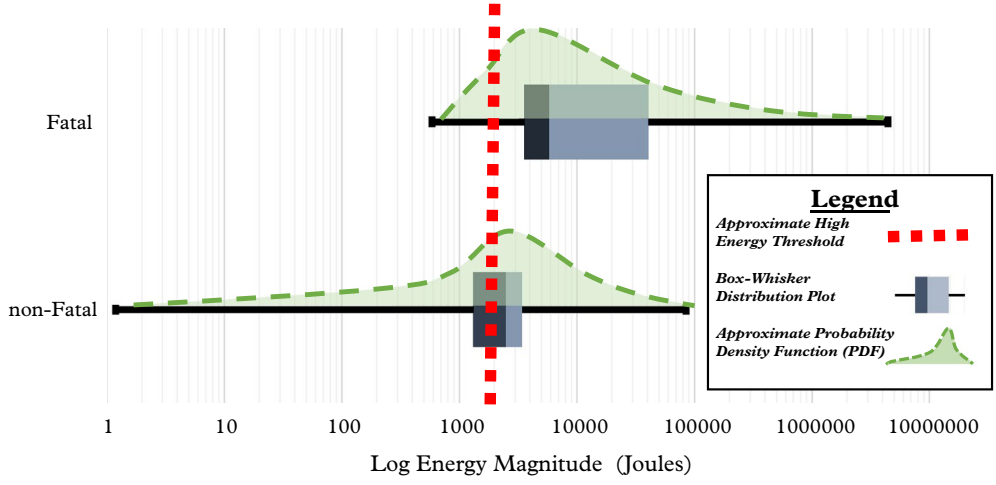



**Figure 5.** High and low impact event energy distributions for hazard energy magnitude.

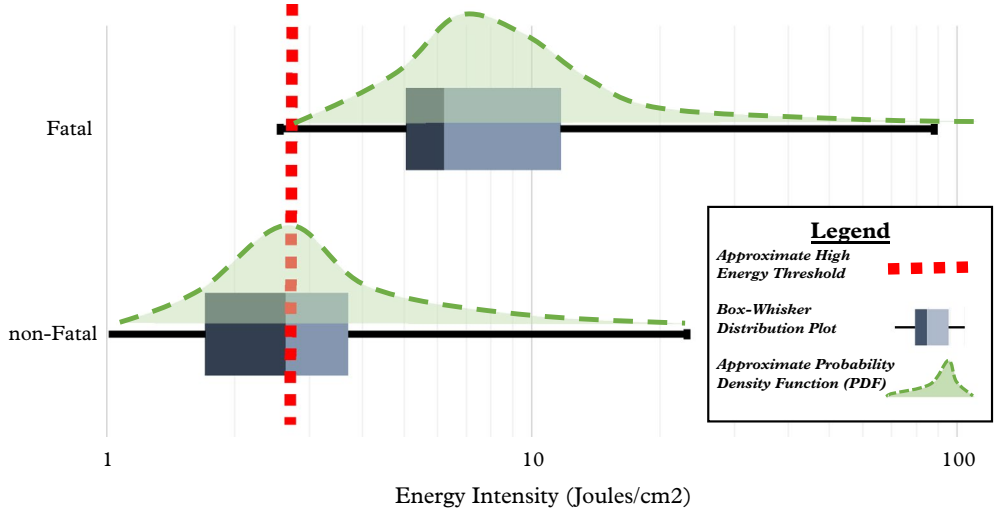



**Figure 6.** High and low impact event energy distribution for hazard energy intensity.

**Table 5.** Examples of injury reports in which contact area affected the severity of injury sustained.

| Injury Severity | Verbatim injury report (described units converted to metric) | Impact area ($cm^2$) | Approximate energy magnitude (joules) | Approximate energy intensity (joules/$cm^2$) |
|---|---|---|---|---|
| Fatality | A worker was crushed by a lift of OSB sheathing when it slipped off the forks of a skid steer loader, falling approximately 8 feet | ~29 | 590 | 21.8 |
| Permanent disability or lost work time | A worker was on the third rung of a 6-foot stepladder that was set up leaning against the side of a flatbed trailer. The worker slipped off the ladder and fell to the ground (about 3 feet) | ~155 | 790 | 5.13 |
| Medical case | The turned on the foot bridge and walked off into the excavation (3–4 feet) where the worker struck his head and shoulder on some wooden forming materials | ~465 | 793s | 1.70 |
| First aid | A worker fell 3 feet from an aluminium sawhorse, landing squarely on his back | ~929 | 793 | 0.84 |

distributions. To study this variability, extreme cases were examined. This examination also provided insight as to why energy intensity was, indeed, a better predictor of injury severity than energy magnitude. Extreme cases revealed that much of the variability can be explained using the previously explained concepts of impact area (i.e. "sharpness") and the vulnerability of the affected body part. When computing energy magnitude alone, the impact area is neglected, which does not account for sharp objects that cause a plethora of injuries. For example, one injury involved a worker who fell 0.7 metre and landed on a flat surface on his back and another report described a worker being struck in the head by a corner of oriented strand board (OSB) sheathing panel. Both incidents involved approximately 600 joules of energy; however, the worker who fell on his back sustained only minor contusions (first aid) while the worker who was struck by OSB sheathing was killed. The worker struck by the OSB sheathing unfortunately sustained fatal injuries despite the relatively low magnitude of energy because he was struck by a sharp object at a vulnerable part of his body. In contrast, the other worker sustained only minor injuries because he fell on a flat surface and contacted a more resilient part of his body.

In order to better understand the role that impact area and body resilience affect injury severity, these variables were isolated and anomalous conditions (e.g. cases in the overlap among distributions) were studied. Table 5 provides several example injury reports of similar *energy magnitude* where the injury severity varied greatly. For each case, the estimated contact area of the object-person interaction is provided. One can easily see from these cases why energy intensity was a better predictor of injury severity than energy magnitude alone. It should be noted that these cases were used because they represent situations where the various distributions shown in Figure 3 overlap.

As expected, the energy intensity values for the examples listed in Table 5 appear to appropriately predict the severity of injury sustained due to the fact that energy intensity accounts for the impact area of a hazard. Consequently, the inclusion of impact area resulted in less variability and overlap between injury severity distributions within the energy intensity data. However, despite the increase in accuracy, the energy intensity distributions still overlap to a modest extent (see Figure 4). This residual variability can be primarily attributed to the vulnerability of the body part affected. For example, one injury classified as Permanent Disability involved a worker falling 2.4 metres (8 feet) off of a stepladder, which had approximately the same level of energy intensity as a Medical Case injury that involved a non-structural steel member falling 3 metres (10 feet). The disparity in injury severity can be explained when one considers the vulnerability of the body part impacted. In the medical case injury the beam struck the worker's shoulder, arm and hand whereas the more serious injury involved an impact to the head and back. Table 6 lists example injury reports in which body vulnerability had an effect on the injury severity. Looking at the listed injury report examples in addition to the analysis results, it appears that energy magnitude and energy intensity are equally susceptible to inaccuracies due to body vulnerability.

### *Defining "high energy" hazards*

The comparisons between serious injuries and less serious injuries using the high and low thresholds were performed with the ultimate goal of identifying values for energy magnitude and energy intensity that distinguish high-impact events (i.e. fatal injury) from low-impact events (i.e. non-fatal). Unfortunately, due to the explained variability within each severity classification, a clear and distinctive value did not arise from the data. Therefore, values using deterministic and probabilistic logic for each metric are presented below.

**Table 6.** Examples of injury reports in which body vulnerability impacted injury severity.

| Injury severity | Injury report | Impact area ($cm^2$) | Body part impacted | Approximate energy magnitude (joules) | Approximate energy intensity (joules/$cm^2$) |
|---|---|---|---|---|---|
| Fatality | A 37-year-old male labourer fell approximately 13.5 feet from a residential roof to a concrete driveway; he died immediately from his injuries | ~929 | Head and back | 3580 | 3.85 |
| Permanent disability or lost work time | A worker was standing on an 8-foot stepladder while installing a vent in an 11-foot ceiling. The worker fell to the ground | ~929 | Head and back | 2117 | 2.27 |
| Medical case | … The clamp supporting the beam slipped and the beam fell about 3 metres, striking the worker at ground level | ~929 | Shoulder, arm and hand | 2592 | 13.3 |
| First aid | Employee received a contusion to the left foot after a belly liner weighing approximately 300 pounds fell approximately one foot striking the employee on the left foot | ~155 | Foot | 407 | 2.63 |

**Table 7.** Deterministic high energy criteria with approximate examples.

| | High energy criterion | Example 1 | Example 2 |
|---|---|---|---|
| Energy magnitude | 2000 joules | A worker falling from a height of 2.4 metres | A standard scaffolding board (approximately 20 kg) falling 3 stories |
| Energy intensity | 2.56 joules/$cm^2$ | A worker falling 2.4 metres and landing on back | A framing hammer being dropped from a height of 2.4 metres |

Note: Contact area was estimated for energy intensity values; the high energy criterion is not absolute.

### *Deterministic "high energy" threshold*

Initially, the high energy criterion was chosen to be the minimum *energy magnitude* and *energy intensity* values for high impact events (i.e. fatal and disabling injuries). These values were 590 joules and 2.56 joules/$cm^2$, respectively. Although the 2.56 joules/$cm^2$ high energy threshold includes approximately 50% non-fatal injuries, this value appears to be a reasonable threshold. In assessing the low-impact injuries that contained an *energy intensity* greater than 2.56 joules/$cm^2$, it was determined using the judgement of the researchers that most of these injuries could have reasonably resulted in a fatality with only slight changes in space and time (e.g. several falls from 6 metres or higher, 24″ concrete pipe weighing 318 kg landing on a worker's leg and a nail fired from a pneumatic nail gun into a worker's leg).

Contrarily, the use of the minimum *energy magnitude* value to establish the high energy criteria proved to be of limited value. As one can see in Figures 3 and 5, the high energy threshold of 590 joules overlaps an even larger portion of less severe injuries (e.g. low-impact injuries). One of the primary flaws in using *energy magnitude* was the notable inaccuracies implicated with smaller hazards. For instance, the value of 590 joules initially chosen to be a criterion for high energy represents the minimum value evaluated for a fatality and involved an OSB board striking a worker's skull. In a different context, the *energy magnitude* present within this fatality is roughly equivalent to a worker falling from a height of 0.7 metres. Taken literally, using 590 joules as the criterion indicates any work being performed where a worker is located 0.7 metres above the ground is high energy and has potential to be fatal. Certainly this is not the case and the *energy magnitude* threshold of 590 joules needed adjustment.

During analysis, *energy magnitude* proved to be an accurate predictor of hazards that were neither sharp nor small, such as falls from height or impacts from large vehicles. Therefore, in order to establish a more accurate criterion for high energy using hazard *energy magnitude*, only the injuries that could be accurately depicted were considered. Following this realization, the new high energy criterion for energy magnitude became approximately 2000 joules (e.g. a fall from a height of 2.44 metres). Although the new high energy criterion for *energy magnitude* does not include all high-impact injuries, it provides a more practical and useful threshold. Table 7 lists examples of hazards evaluated in the data that contained roughly equivalent *energy magnitude* and *energy intensity* values to the established high energy criteria. The high energy criteria for each metric has also been marked and labelled on Figures 3, 4 and 5 as well.

### *Probabilistic "high energy" assessment*

Similar to techniques used in fields such as earthquake engineering that utilize deterministic and probabilistic approaches to hazard assessment (Villaverde 2009), a

probabilistic approach to evaluating hazard risk was used to compliment the deterministically established high energy criterion of 2000 joules and 2.56 joules/cm$^2$. To accomplish this task, *logit* regression models were fit to the data using each respective hazard energy metric as the predicting variable and the injury severity (fatal or non-fatal) as the dependent variable. The resulting regression equations are provided below for each hazard energy metric using two arrangements and provide a means to predict the probability of a high-impact event's occurrence. Equations (8) and (10) will output the probability of a high-impact, fatal event occurring for any given hazard energy value, *X*. For example, a hazard possessing 2000 joules would have a 6% chance of resulting in a fatal injury. Equations (9) and (11) allows for the reverse calculation to take place in which a desired probability for high-impact injury, in decimal format, could be inputted for *P* to calculate a resulting hazard energy threshold. This would allow a user to set a desired high energy criterion based on probabilistic data in place of the deterministic value of 2000 joules or 2.56 joules/cm$^2$. These equations are far more precise than a single, deterministic threshold but they require computation, which can be unrealistic in the field.

*Hazard energy magnitude probabilistic equations*

$$P(x = \text{Energy}) = \frac{e^{-2.9768+0.00016(X)}}{e^{-2.9768+0.00016(X)} + 1} \tag{8}$$

$$X_{\text{Energy}} = \frac{\ln\left(\frac{P}{1-P}\right) + 2.9768}{0.00016} \tag{9}$$

*Hazard Energy Intensity Probabilistic Equations*

$$P(x = \text{Energy}) = \frac{e^{-3.9065+0.386(X)}}{e^{-3.9065+0.386(X)} + 1} \tag{10}$$

$$X_{\text{Energy}} = \frac{\ln\left(\frac{P}{1-P}\right) + 3.96065}{0.386} \tag{11}$$

## Proposed directions

The premise that the quantity of energy observable during work strongly predicts injury severity was supported. This theoretical and practical advancement may catalyse future research. Future researchers may wish to test this relationship with energy sources beyond motion and gravity and examine extreme cases. Our work had a limited focus on motion and gravitational energy. Other energy sources may require a different approach. For example, chemical and biological energy may need to be classified rather than quantified on a continuous scale. Similarly, electrical and radiation energy may involve a dichotomous threshold because of how they exist in the natural world.

The established relationship between energy and injury severity has potential applications to technology and Building Information Modelling (BIM) and Advanced Work Packaging (AWP) in particular. If a user can adequately characterize the height, weight, speed or other basic characteristics of the work environment, the potential severity (i.e. seriousness) of the work can be empirically forecasted. Such information could be useful in visual form such as a heat map to show sources of high energy. Such maps would be tremendously valuable during pre-job planning, and perhaps lead to an "energy leveling" process to strategically manage the day-to-day level of energy exposure on a project to positively affect worker safety.

## Conclusion

The fundamental purpose of the research was to test the hypothesis that the energy magnitude and intensity predict the severity of an injury better than random. In testing the null hypothesis, a relationship between energy and severity was presented based on the concepts of energy, pressure and body vulnerability. This relationship, leading to energy-based safety risk assessment, was inspired by natural hazards research. The relationship was tested using data from 505 information-rich injury reports gathered from multiple data sources. Two metrics were successfully used to represent hazard energy: magnitude and intensity. Energy magnitude offers a simplistic evaluation of safety risk at the expense of certain inaccuracies; in particular, inaccuracies involving sharp or small hazards. These inaccuracies ultimately led to large data variability that, at times, compromised the predictive value of energy magnitude. Energy intensity proved to be a better predictor of injury severity but is also more burdensome and computationally intensive. Thus, practitioners must weigh the benefits of increased accuracy against the drawbacks of additional computation.

Although the concept of predicting injury severity from energy may seem logical and obvious, this concept has never been formally defined or analysed. The lack of formal investigation corresponds with inconsistent and unscientific use of the term energy as it applies to safety. There was a lack of knowledge of what constitutes high energy (i.e. enough energy to cause serious or fatal injuries). The implication of a formal analysis of energy magnitude and energy intensity is that these variables can be measured and tracked as projects progress and worksites are designed to identify and empirically analyse vulnerability. Such analysis offers the opportunity to identify and monitor energy sources in design, model energy in technological systems like Building Information Models and alert workers using proximity sensing technology. Simply, the relationship between energy and severity

and the associated analysis offers a new way of empirical measurement of workplace hazards and risks.

Albert *et al*. (2014), who utilized the concept of hazard energy, was able to improve deficiencies in worker hazard recognition by creating a universally applicable mnemonic system that is independent of any specific work scenario. The proposed energy-risk based risk analysis technique would enjoy similar benefits within the context of safety risk analysis, advancing the practical application of Haddon's (1968) original aetiological approach to injury prevention. Hazards can be dissected to their most elemental form that, when combined with probability, can be theoretically applied with relative ease to nearly every construction project or activity and addresses a significant limitation in the current state of safety risk analysis within construction safety. Initial data presented in this study demonstrate that energy-based safety risk analysis possesses significant promise in becoming a much improved and more universally accessible technique for safety risk analysis.

To the knowledge of the authors, this is the first significant study relating injury severity to hazard energy and, as expected, initial limitations were revealed. Most notably, it was discovered that the energy intensity metric could not accurately depict mechanical hazard energy sources (i.e. saws, grinders, etc.). Mechanical hazards resulted in outlying values for energy intensity predicting much higher injury severity than what actually resulted. As anticipated, the explanation for this discrepancy relies on the concept of body vulnerability. Similar issues were encountered for biological and chemical hazards where severity seems to be predicted in a more dichotomous fashion. For example, a particular biological agent like a bee or a snake either causes great harm in normally encountered situations or causes little to no harm, depending on the agent. These other forms of energy offer opportunity for future research.

This study has advanced knowledge and formalized the theory of energy transfer. Just as researchers in natural hazard prediction have become adept in natural hazard risk analysis due to an energy-based approach for natural hazard modelling, a similar understanding from the perspective of safety can improve proficiency in safety risk analysis. To build upon our research we suggest three areas: (1) utilizing body vulnerability in predicting injury severity; (2) analysing other hazard energy forms; and (3) establishing a definitive set of computational values to be used in analysis to establish universal hazard energy values. Residual variability present within both metrics was, in large part, attributed to the body part where the injury was inflicted. Although implications were discussed, empirical investigation of injury severity in relation to body vulnerability remains to be extensively investigated. Also, supplementary exploration is needed regarding the other hazardous energy sources to further validation of this study's results.

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No potential conflict of interest was reported by the authors.

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