# CLASSIFICATION OF

# ADEQUATE IMPACT PROTECTION FOR HANDS

by

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ABSTRACT

# CLASSIFICATION OF ADEQUATE IMPACT PROTECTION FOR HANDS

by

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Historically, hand injuries have been a large burden for the manufacturing, construction, mining, oil and gas industries. Specially designed gloves are commonly used in industry today to protect hands from impacts. These gloves are designed to reduce hand injuries by absorbing the impact forces workers may encounter due to objects striking the hand. However, to date, there is no standard for the testing of these gloves and quantifying the force reduction a user would experience when wearing these gloves during an impact. Therefore this research focused on developing and implementing a testing protocol.

The goal of this research was twofold: i) to quantify the hand fracture tolerance limit in five zones (1: the phalanges, 2: metacarpal-phalangeal joint, 3: the metacarpals, 4: first proximal phalange and 5: distal radius and ulna) of the hand, and ii) to test a variety of commercially available gloves claiming impact resistance.

Cadaveric hands were used to establish the tolerance limits, and manikin hands were used for glove testing. Throughout testing the resultant force (from a force plate under the specimen) and the peak force (from force sensors on top of the specimen) were recorded. Gloves were considered to provide adequate protection if the applied impact force was reduced by 50% or more of the mean fracture force for the hand zone.

The specimens were impacted using a guillotine style impact fixture. The drop height was selected to provide a similar force to the reported fracture force of the radius. The impact force was increased until fracture was observed in all zones.

The average hand facture tolerance limit (SD) from the cadaveric hand specimens by zone were found as follows: zone 1 - 3673 (1335) N, zone 2 - 2672 (655) N, zone 3 - 2957 (1321) N, zone 4 - 1439 (355) N, zone 5 - 2399 (1022) N. The facture force was correlated with BMC and BMD independently.

The resultant force measurements revealed that 10%, 100%, 0%, and 89% of the impact resistant gloves met the adequate protection criteria for zones 1, 2, 3, and 4 respectively. The peak force measurements revealed that 0%, 100%, 0%, and 100% of the impact resistant gloves met the adequate protection criteria for zones 1, 2, 3, and 4 respectively. Zone 5 was not tested, as the gloves did not provide protection to the ulnar region. The resultant force provided a more consistent measure of performance compared to the peak force sensor measurement.

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# Chapter 1: Introduction

Historically, injuries have been a large burden for all sectors of industries. In particular the manufacturing, construction, mining, oil and gas industries have large numbers of employees completing manual tasks with high risk factors. In 2012, manufacturing and construction were numbers one and two respectively for the highest number of injuries in private industries (BLS, 2012 b). The top three events leading to injuries are "overexertion and bodily reaction", "falls, slips, trips", and "contact with object, equipment" in successive order based on incident rate (BLS, 2012 b). It was reported that contact with objects had reached an incident rate of 25.5 in private industries and government in 2012 (BLS, 2012b). State and local government rank higher than private industries in nonfatal occupational injury (BLS, 2012a).

Upper extremities are the most common body part affected by injury in these industries, accounting for over 30% of total private and government injuries; hand and wrist accounted for more than 53% of the 347,590 injuries to the upper extremities in 2012 (BLS, 2012b). According to WorkSafe BC 2014, hands and wrists accounted for 20% of the body parts injured in the petroleum industry. Hand and wrist injuries also account for over 6% of all emergency room visits (Hill, 1998; Angermann, 2003). Fractures accounted for over 21% of occupational injuries for private and government sectors in 2012 (BLS, 2013b) and fractures of the hand accounted for 42% of all hand injuries (Angermann, 2003; Trybus, 2005).

Fractures of the hand in the manufacturing, construction, and petroleum industries typically have a high level of severity resulting in high costs. In the petroleum industry, fractures accounted for 17% of the total injury claim numbers (WorkSafe BC, 2014), while these same claims accounted for 32% of the industry's total claim cost. When looking at serious injury claims (recovery periods of 50+ days paid, and all death claims) "struck by" were 38% of accident types and of those claims 47% were fractures. While all of these "struck by" incidents may not all be attributed to hand fracture, the hand fracture problem cannot be overstated.

Specially designed gloves are commonly used in industry today to prevent hand fractures. These gloves are designed to reduce hand injuries by absorbing the impacts workers may encounter. Some of them have been shown to absorb up to 90% of the impact force for some areas of the hand. To conduct glove testing one manufacturer utilizes the ASTM D2632 modified to test the gloves. This test uses vertical rebound to measure material elasticity, which can be described as a materials ability to absorb energy (i.e. impacts). However ASTM states, "This test method is used for development and comparison of materials. It may not directly relate to end-use performance" (ASTM, 2014). The ASTM D2632 is acceptable for material testing, but it is not appropriate for determining the force reduction provided by a glove. The protocol must be capable of quantifying the force reduction the glove provides under dynamic loading.

The goal of this research was to quantify the hand fracture tolerance limits of the hand and to determine if impact resistant gloves provide adequate protection under dynamic loading. Two specific aims were developed to assess the fracture forces and protection provided. These specific aims are:

1. Determine the fracture tolerance limit of the fives zones of the hand under dynamic impact.
    a. Measure the fracture force during testing of each zone. The peak force obtained from the dynamic impact will be utilized to determine the tolerance limit. Fractures were defined by visible separation and classified by OTA standard (Marsh, 2007).

H01A - The zones of the hand will have different fracture tolerance limits.

H01B – Bone Mineral Content (BMC) will correlate with hand fracture in each zone.

H01C – Bone Mineral Density (BMD) will correlate with hand fracture in each zone.

2. Quantify the force reduction provided by impact resistant gloves in four zones of the hand under dynamic loading.
    a. The peak forces obtained from glove and no-glove conditions will be utilized to determine the force reduction in terms of:
        i. Percent force reduction provided by the gloves.
        ii. Total force reduction (N).

H02 - Impact resistant gloves will provide adequate protection in each zone of the hand.

To achieve these goals, specialized methodologies were utilized to quantify the fracture tolerance limit of the phalanges, metacarpal-phalangeal joint, the metacarpals, and the distal radius and ulna under impact loading. Since the fracture tolerance limit cannot be tested *in-vivo*, cadaveric hands were used to investigate the tolerance limits. The cadaveric hands were imaged using the pilot 2D images from a micro CT scanner. The pilot 2D images of the hand were used to identify fractures pre and post testing. To quantify fracture force, a multi-axis force plate was placed below the guillotine-like fixture and used to measure the force "transferred" through the cadaveric hand during impact. A force senor was placed on the top of the hand to quantify the force actually experienced by the hand.

Ballistic gel manikin hands with plastic anatomical skeletons were created and used for the testing of impact resistant gloves. Nineteen different commercially available impact resistant gloves were obtained from nine different manufacturers. Ballistic gel manikin hands with and without impact resistant gloves were impacted. The reduction in force due to glove protection was calculated as the difference in resultant force (force plate) between the glove and no-glove conditions of the ballistic manikin hands. The reduction in peak force (force sensor) for each glove, in four zones was analyzed and classified based on force reduction.

# Chapter 2: Background

## 2.1 Literature introduction

To begin the development of the new protocol capable of representing end use performance over 30 articles were reviewed. Many of the articles are directly related to hand and wrist fracture, while others were selected due to their relevance to other aspects of the study. Specifically, these articles discussed the locations of hand and wrist fracture, occupational injuries, quasi-static testing, dynamic testing, bone mineral density (BMD), bone mineral content (BMC), and the classification of fractures. These articles provided insight for the development of the methodology used in this study, including the impacting method.

Ten of these articles investigated the cause and prevalence of hand and wrist fractures. These articles discussed the average age, place of accident, and the anatomical location of fracture. However most articles don't describe how the fracture took place (i.e. fall, pinched hand, or impact by an object). Five of these articles investigated the fracture force of the wrist under quasi-static and impact loading. However some of the techniques were not directly applicable to dorsal hand impact testing. The fracture forces of these studies were also not directly related to the hand since they deal with different bones and tissue. One article investigated the risk factors for occupational hand fractures and found gloves reduced the risk of injury by 60 %. However this study did not examine the different types of gloves in use.

### 2.1.1 Location of fractures

The most common locations of hand fractures were identified from previous studies. Based on the prospective study conducted by Stanton (2007), 1444 cases were investigated over a 6-month period and the pattern of fracture was analyzed. Of these cases, 653 involved fracture or dislocation of the metacarpal or phalanges. The metacarpal was the most common bone fractured, accounting for 44% of all fractures. Fractures of the distal phalanx accounted for 24% of all fractures, and 29% were the proximal and distal phalanges.

Chung et al. (2001) analyzed hospital visits from the 1998 National Hospital Ambulatory Medical Care Survey (NHAMCS). In the NHAMCS population samples, there were 352 cases of hand or forearm fracture. This figure was used to estimate that 1,465,874 cases occur annually, equal to 1.5% of all hospital visits. The estimate was similar to 1997 NHAMCS, which had a value of 1.6% of all hospital visits. The study revealed that the radius or ulna accounted for 44% of all hand and forearm fractures. Phalanges were second with 23% followed by metacarpal 18%, carpal 14%, and multiple hand fractures 0.6%. The summary of this study and others are displayed in Table 1.

**Table 1: Prevalence studies fracture location percentages.**

| Study | Stanton et al., 2007 | Chung et al., 2001 | Van onselen et al., 2003 |
|---|---|---|---|
| **Anatomical location** | **Fracture location (%)** | | |
| phalange | 35 | 23 | 37 |
| Phalange-metacarpal joint | 8 | | 22 |
| Metacarpal | 44 | 18 | 33 |
| Thumb | 13 | X | X |
| Radius and/or ulna | X | 44 | X |
| Carpals | X | 14 | 8 |

Based on this research, the hand was divided into five zones for this project; zone 1 phalanges, zone 2 metacarpal-phalangeal joint, zone 3 metacarpals two through five, zone 4 the thumb, and zone 5 carpals, distal radius and ulna as shown in Figure 1.

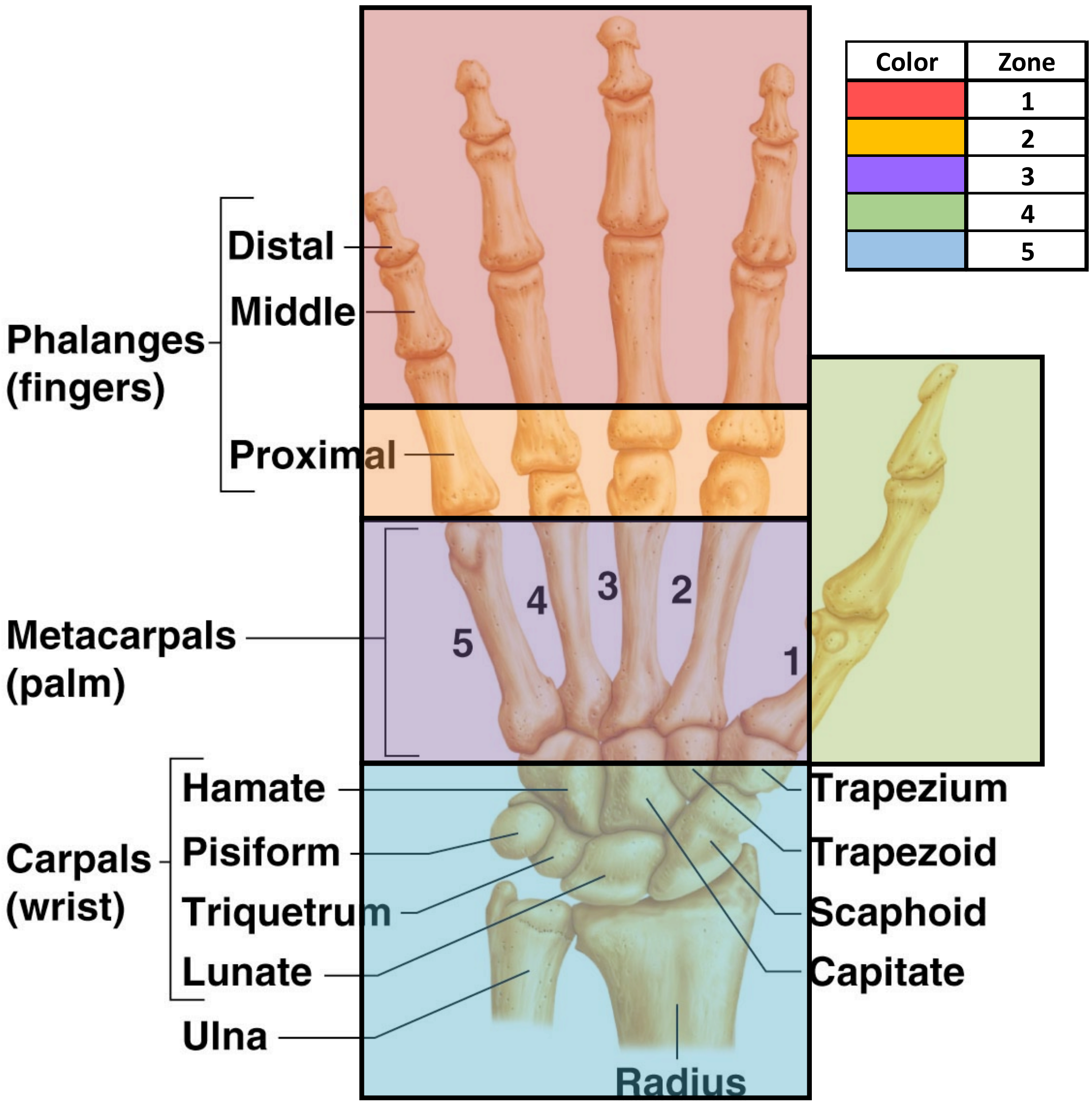




**Figure 1: Hand zone divisions: zone 1 phalanges, zone 2 metacarpal-phalangeal joint, zone 3 metacarpals, zone 4 thumb, zone 5 distal radius and ulna.**

2.1.2 Experimental testing

Current research related to the testing of hand and wrist fracture has been focused primarily on the radius and ulna (Greenwald, 1998; Muller, 2002; Njeh, 2001; Reeves, 2014). This topic has been researched to analyze risk factors associated with falls. Two types of testing were most commonly used: quasi-static and dynamic testing (See Table 2).

Muller, 2002 examined the distal radius in order to evaluate which bone assessment technique best predicted failure load. Thirty-eight forearms were measured using five different methods: Dual-energy X-ray absorptiometry (DXA) of the distal radius, DXA of the phalanges, peripheral quantitative computed tomography (pQCT) of the distal radius, quantitative ultrasound (QUS) at the distal radius, and digital X-ray radiogrammetry (DXR) of the forearm and hand. Following the measurements the radii were compressed quasi-statically at a rate of 100 mm/s, recording displacement and force data. The average failure load (SD) was 2642(397) N for females and 3673(792) N for males. The best predictor of failure was the pQCT measure of cortical bone mineral content (BMC). BMC measured by DXA or pQCT were better predictors of failure than their corresponding bone mineral density (BMD) measurements.

Njeh et al., (2001) evaluated the ability of the speed of sound (SOS) measured at the phalanges to estimate wrist fracture force. Twenty-eight cadaver forearms were used to determine the SOS, BMD, and the combined cortical thickness (CCT) at the phalanges. The BMD of the radius was measured using DXA and pQCT. The radii were then removed and compressed quasi-statically to failure at a rate 75 mm/s. The displacement and load were recorded. BMD, SOS, and CCT were all predictors of fracture load. Cortical area and BMC of the radius were consistently higher predictors of fracture load than BMD. The average fracture load (SD) was found to be 2648 (1489) N.

Greenwald et al. (1998) studied the dynamic impact response of braced and un-braced cadaveric wrists. The vertical force and time were recorded for the tests. The peak fracture load was found to be higher for braced versus un-braced forearms (3808 (271) N versus 2821 (763) N).

Reeves et al. (2014) examined the effect of muscle forces on the fracture strength of an intact distal radius. Twelve paired cadaveric forearms were mounted onto an impact apparatus, which was driven into a force plate. Steel tension cables were attached to the tendons of the forearms to simulate muscle forces prior to impact. The mean (SD) resultant fracture forces for the simulated muscle force and no force conditions were 6565 (866) N and 8665 (5133) N respectively. The difference in resultant fracture force between the simulated muscle force and no force conditions was not statistically significant.

**Table 2: In-Vitro testing studies summary.**

| Study | Testing method | Fracture force (N) | Bone quality |
|---|---|---|---|
| Njeh et al., 2001 | Quasi-static | 2648 (1489) | DXA: BMC and BMD |
| Muller et al., 2002 | Quasi-static | 3673 (792) | DXA: BMC and BMD |
| Greenwald et al., 1998 | Dynamic | 2821 (763) | Radiographs |
| Reeves et al., 2014 | Dynamic | 8665 (5133) | Pre-screened |

### 2.1.3 BMC and BMD failure prediction

The experimental testing of the radius and ulna above demonstrated the strong correlation of BMC and BMD with bone fracture. These studies also consistently found that BMC was a more accurate predictor of fracture than BMD using the same measuring equipment. Verstraeten (1986) and Peel (2005) observed similar correlation.

In order to identify variations in DXA measurements of BMC and BMD Deodhar (1994) conducted a comparative study. Ninety-five healthy subjects and fifty-six patients with rheumatoid arthritis (RA) had both hands scanned. The variation of BMC measurement between repeated scans was found to be 2.3% with no added variation due to curling of hands due to RA. BMD measurements were found to have a variation of 1.3% for non-arthritic hands, which increased by an average of 13.1% for RA hands (curling of fingers). This measure of BMD variation was similar to the findings by Peel (2005). These findings demonstrated the influence changing of hand area has on BMD, while not affecting BMC. The total hand BMC for healthy males was 90.9 grams, while RA males had a BMC of 81.7 grams. Healthy females had a BMC of 62.2 grams, while RA subjects had average of 52.3 grams.

### 2.1.4 Fracture criteria

The Orthopaedic Trauma Association (OTA) fracture and dislocation compendium is the standard for comparing fractures in clinical research (Marsh, 2007). The OTA allows all researchers to use the same terminology. The sections of Metacarpals, Phalanx – Hand, and Hand and Carpus in the OTA contain the detailed descriptions of all hand fractures.

Swiontkowski, (2007) evaluated the inter-observer variation for the AO/OTA fracture classification system. Five evaluators of varying knowledge and skill set independently classified eighty-four radiographs. When analyzing agreement between the evaluators they received a moderate agreement score. A Kappa statistic was used to determine the evaluator's difficulty with any specific category of the classification system. The agreement between observers was considered to be adequate.

Swiontkowski, (2000) also conducted a study of two hundred patients with lower extremity fractures to determine whether a greater severity of injury as classified by AO/OTA correlated with poor scores of impairment, and function. The classification correlation between severity of injury and impairment was significant for Type C and Type B fractures.

## 2.2 Literature gaps

Table 3 contains as summary of the articles reviewed for this study. Hand and wrist fractures have been studied extensively. The primary area studied is prevalence of hand and wrist fractures. Several authors have tested the wrist fracture tolerance limits using varying methodologies. Wrist fracture has been correlated with hand BMC and BMD, however hand fracture has not. The testing methodology with the greatest uniformity has been quasi-static testing with varying rates. Dynamic testing of the wrist has been conducted using vertical and horizontal impact. Concurrently with the fracture testing, BMC and BMD were measured and have been correlated with the fracture of the wrist but not hand fracture. The OTA fracture classification system has been studied with acceptable repeatability between observers.

Based on the conducted literature review there were several gaps identified in the following areas:

- To our knowledge, the fracture tolerance limits of the phalanges, metacarpal-phalangeal joint, the metacarpals, and the thumb under dynamic loading has not been reported to date; without the fracture tolerance limits no threshold value can be established for protection.
- There is no established correlation between BMD and BMC and hand fracture tolerance. The research correlating BMD and BMC with fracture has been focused on wrist fracture rather than hand fracture. The correlation of BMC and BMD with hand fracture is necessary for future biomechanical modeling and the identification of workers who may require additional protection. The effect of BMD and BMC has been reported and has become a key component in the measurements and analysis of cadaveric specimens.
- There are no established guidelines or a standard for testing of hand personal protective equipment (PPE) for impact resistance. Therefore workers are unable to select gloves based on the protection required for a specific task.

Currently there are no standards for the testing and classification of impact resistant gloves. The occupational safety and health administration (OSHA) currently has no requirements for employers specifically on impact resistant personal protective equipment (PPE). OSHA states “Selection. Employers shall base the selection of the appropriate hand protection on an evaluation of the performance characteristics of the hand protection relative to the task(s) to be performed, conditions present, duration of use, and the hazards and potential hazards identified” (OSHA 1910.138(b), 2015). Without a standard for testing, consistently quantifying “appropriate” or adequate protection is problematic.

**Table 3: Articles reviewed for the current study with a description of the topics covered.**

| Article Information | | | Article Topics | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Authors | Year | Wrist fracture | Hand fracture | Dynamic testing | Quasi-static testing | Hand pressure | Fracture incidents | Occupational hand injuries | BMD | BMC | Fracture type classification | DXA |
| 1 | Al-Qattan | 2008 | | X | | | | | | | | | |
| 2 | Angermann et al. | 1993 | X | X | | | | | | | | | |
| 3 | Carter et al. | 1992 | | | | | | | | X | | | |
| 4 | Choi et al. | 2011 | | | X | | X | X | | | | | |
| 5 | Chung et al. | 2001 | X | X | | | | X | | | | | |
| 6 | Degoede et al. | 2002 | | X | | | X | | | | | | |
| 7 | De Jonge et al. | 1994 | X | X | | | | X | | | | | |
| 8 | Deodhar et al. | 1994 | | | | | | | | X | X | | X |
| 9 | Devlin et al. | 1996 | | | | | | | | X | | | X |
| 10 | Fransson-Hall et al. | 1993 | | | | | X | | | | | | |
| 12 | Goulding et al. | 2001 | | | | | | | | X | X | | X |
| 13 | Greenwald et al. | 1998 | X | | X | | | | | | | | |
| 14 | Hill et al. | 1998 | X | X | | | | X | X | | | | |
| 15 | Kröger et al. | 1995 | | | | | | | | X | X | | X |
| 16 | LU et al. | 1996 | | | | | | | | X | X | | X |
| 17 | Marsh et al. | 2007 | | | | | | | | | | X | |
| 18 | Muller et al. | 2003 | X | | | X | | | | X | | | |
| 19 | Myers et al. | 1993 | X | | | X | | | | X | | | X |
| 20 | Njeh et al. | 2000 | X | | | X | | X | | X | | | |
| 21 | Oleske et al. | 1992 | | X | | | | | X | | | | |
| 22 | Peel et al. | 1994 | | | | | | | | X | X | | X |
| 23 | Reeves et al. | 2014 | X | | X | | | | | X | | | |
| 24 | Schuit et al. | 2004 | X | | | | | | | X | | | X |
| 25 | Sievänen | 2000 | | | | | | | | X | | | |
| 26 | Sorock et al. | 2002 | | X | | | | | X | | | | |
| 27 | Stanton et al. | 2007 | | X | | | | | | | | | |
| 28 | Swiontkowski et al. | 2000 | | | | | | | | | X | X | |
| 29 | Swiontkowski et al. | 2007 | | | | | | | | | X | X | |
| 30 | Trybus et al. | 2006 | | X | | | | | | | | | |
| 31 | Van Onselen et al. | 2003 | | X | | | | X | X | | | | |
| 32 | Verstraeten et al. | 1986 | | | | | | X | | | X | | X |

# Chapter 3: Materials and Methods

## 3.1 Materials

### 3.1.1 Test specimen

Six fresh cadaveric hands (4 male, 2 female) with an average age (SD) of 87(11) years were received from the Medical College of Wisconsin. The hand and forearms were removed from the human cadaver at approximately 30% of radius and ulna length. The bone quality of the specimen was measured in terms of Bone Mineral Density (BMD) and Bone Mineral Content (BMC) using a DXA scanner (Lunar Prodigy, GE Healthcare). The cadaveric hands were scanned in the proximal-distal direction. The hand measurement data for the six cadaveric hands are shown below in Table 4.

The cadaveric hands were imaged using the pilot 2D images of the micro CT scanner ZEISS Xradia 410 Versa (ZEISS, CA) before testing to verify no previous fracture as shown in Figure 2. The images were captured to allow for the identification of fractures post testing. The 6 cadaveric hands were stored at 2.2 °C until testing which was conducted within 14 days. The equipment and respective methods are described below.

**Table 4: Specimen age, number, BMC, and BMD measurements.**

| Cadaver 1 | | | | | | |
|---|---|---|---|---|---|---|
| | Specimen 1 | | | Specimen 2 | | |
| Age | Condition | BMD ($g/cm^2$) | BMC (g) | Condition | BMD ($g/cm^2$) | BMC (g) |
| 87 | 6 cm rice | 0.33 | 28.45 | 6 cm rice | 0.35 | 29.54 |
| Cadaver 2 | | | | | | |
| | Specimen 3 | | | Specimen 4 | | |
| Age | Condition | BMD ($g/cm^2$) | BMC (g) | Condition | BMD ($g/cm^2$) | BMC (g) |
| 76 | 6 cm rice | 0.52 | 53.70 | 6 cm rice | 0.52 | 52.83 |
| Cadaver 3 | | | | | | |
| | Specimen 5 | | | Specimen 6 | | |
| Age | Condition | BMD ($g/cm^2$) | BMC (g) | Condition | BMD ($g/cm^2$) | BMC (g) |
| 98 | 6 cm rice | 0.29 | 20.68 | 6 cm rice | 0.32 | 23.49 |

**Figure 2: 2D CT image of cadaver three right hand metacarpal-phalangeal joints 3-5 (pre-testing).**

### 3.1.2 Manikin hands

Manikin hands were prepared for the glove impact testing to simulate human hands. Molds of a human hand were created and used to fabricate all manikin hands. The molds were split into two pieces; a plastic anatomical skeleton was placed inside a nitrile glove and inserted into the mold. The nitrile glove served as the epidermis of the manikin hand. Ballistic gelatin was poured into the glove filling the mold. The ballistic gel hand was placed in a refrigerator for a minimum of 24 hours to allow the gel to cure. The hands were stored at 4.4 °C until the time of testing. For detailed manikin hand fabrication instructions see Appendix A.

### 3.1.3 Gloves

Nineteen different impact resistant gloves were collected from manufacturers for testing (See Figure 3). The gloves were selected based on being the largest selling brands in the impact resistant glove market. Nine different manufacturers were chosen for the study. Five of the manufacturers had a minimum of two different pairs tested, and one manufacturer had six different pairs of gloves in the study. The remaining manufacturers each had 1 pair used in the study. The order of glove testing was based on a random number generator in EXCEL to reduce bias and the effect of external variables (Microsoft, WA).


**Figure 3: Impact resistant gloves selected for study.**

## 3.2 Experimental Design

### 3.2.1 Hand fracture testing protocol

Six cadaveric hands were tested independently. All hands were tested in zones 1, 4, and 5. In order to maximize the number of test that could be performed per hand, zone1 and zone 3 were tested on the same hand. Zone 2 was then tested on the other hand of the pair. The testing was conducted in this manner to minimize the number of repeated impacts in the zones. After each round of testing the hands were imaged to identify fractures. If fracture did not occur the drop height was increased by 0.1 m. Where possible the hands were rotated to minimize the number of impact in any one zone. The testing continued until all tested zones on each hand had fractures. The fracture tolerance limits were measured as the lowest resultant force required to cause fracture in the zone. The testing protocol diagram is shown in Figure 4.

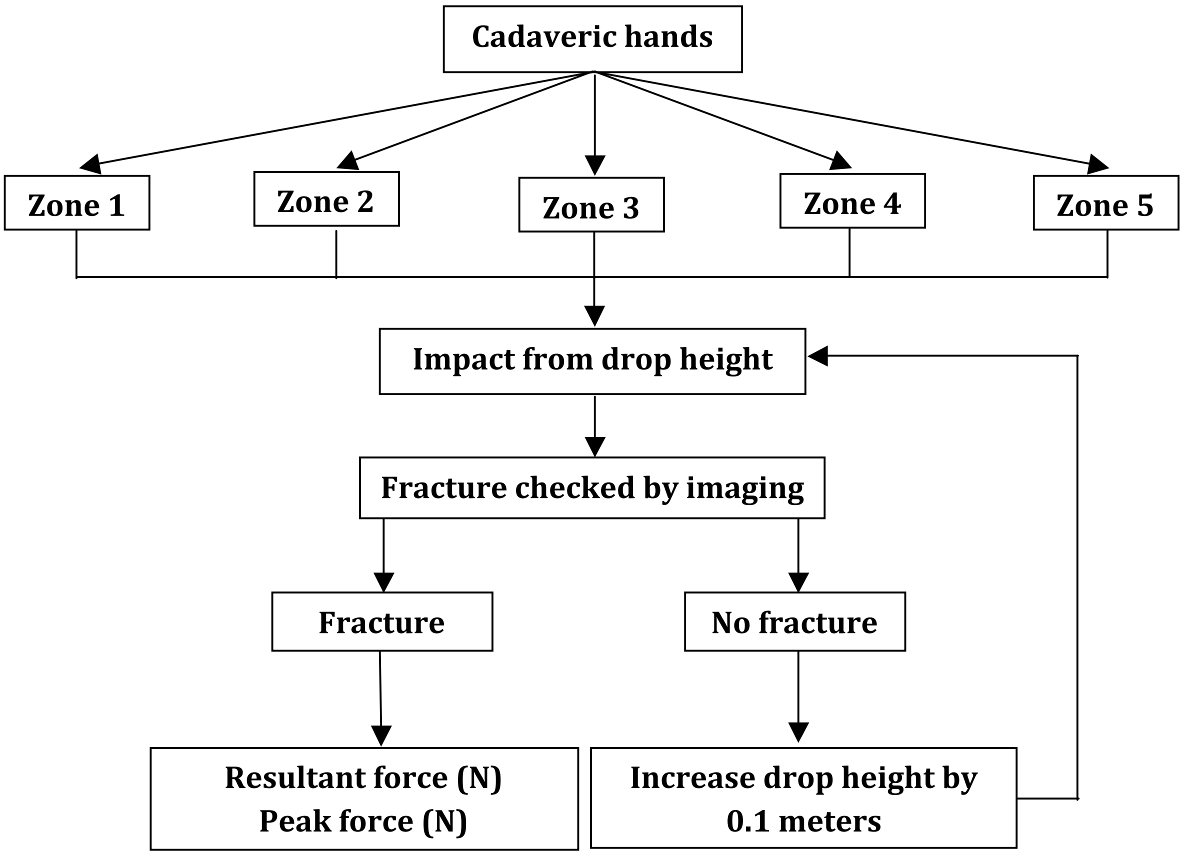


**Figure 4: Cadaveric hand testing experimental protocol.**

Following the completion of all testing and imaging of the cadaveric hands, the hands were dissected to verify fractures observed from imaging. A trained faculty member completed the dissection. The dissection was used for secondary confirmation of the fractures found by the imaging of the hands (See results and Appendix C). The process also aided in the identification of dislocation of joints in the hand. The hand fractures were then classified using the OTA fracture criteria.

3.2.2 Glove testing protocol

Manikin hands with and without impact resistant gloves were impacted at the hand fracture tolerance limits (HFTL) for cadaveric specimens 3 and 4. Specimens 3 and 4 were selected for the target impact force due to their total hand BMC similar to the normal values reported in the literature.

The appropriate drop height for the testing of the gloves was assessed by comparing the average HFTLs for zones 1 through 3 and with the impact force for no-glove manikin hands. A drop height of 0.2 meters was used for zones 1 through 3 and a drop height of 0.1 meters was used for zone 4. Manikin hands impacted without impact resistant gloves were tested to ensure the target impact force was met and reported as Peak Force No-Glove (PFNG). A sample of four hands were tested for the initial baseline, and one sample from each batch of new manikin hands was tested without a glove to address any batch variation.

Nineteen different impact resistant gloves were then tested in zones one through four with manikin hands inside. Zone 5 was not tested because the gloves are designed to protect just the first four zones. The nineteen gloves were tested three different times in a random order. The schematic block diagram shown in Figure 5 represents the study design.

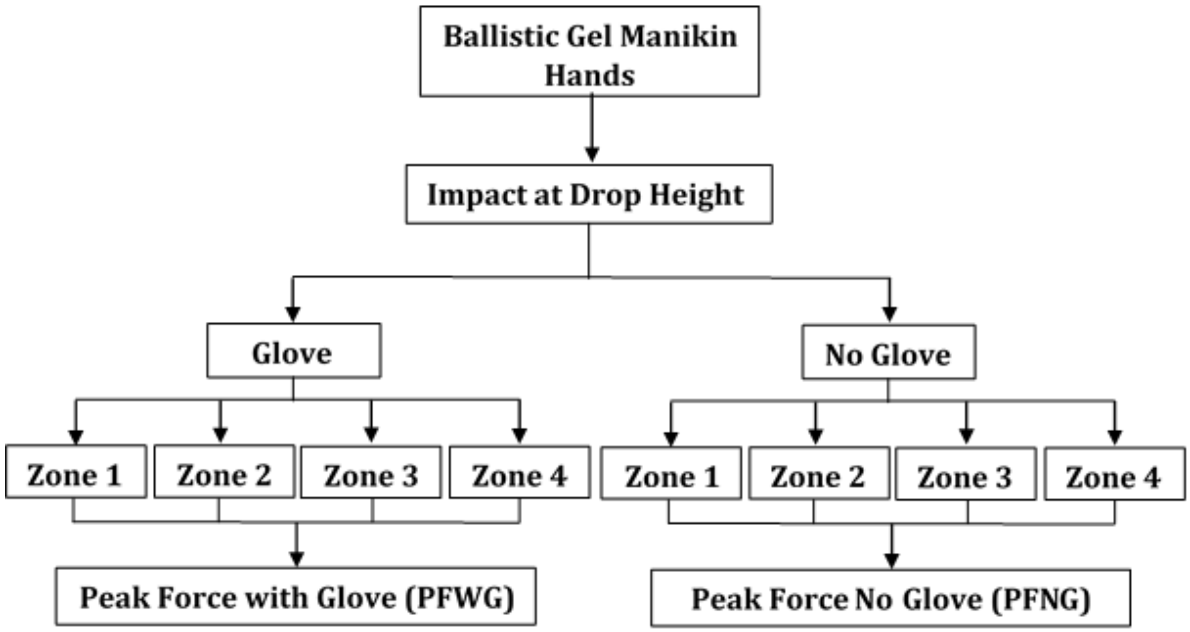


**Figure 5: Impact resistant glove testing experimental protocol.**

3.2.3 Testing procedure

Step-by-step procedures for conducting Cadaveric Hand Fracture Testing Protocol (CHFTP) and the Impact Resistant Glove Testing Protocol (IRGTP) are shown below.

Initial setup (All tests)

1. The hand was carefully removed from the refrigerator.
2. The hand was marked in the test location with a marker for sensor placement.
3. The specimen marking was aligned with force plate marking and visually verified for impact location.
4. The specimen was secured using vinyl adhesive strip (3M, MN).
5. The FlexiForce sensor was secured to top of the hand in the corresponding zone using double-sided adhesive vinyl strip. (3M, MN).

6. The impact mass was secured in the snap-shackle at desired drop height.
7. The AMTI force plate hardware was zeroed before each test.
8. Begin video recording.

Cadaveric hand fracture testing

1. The drop height was set to 0.2 m.
    a. The drop height was increased by 0.1 m until fracture was observed.
2. The impact mass was released.
3. Peak force on the top of the cadaveric hand (N) was measured with the FlexiForce sensor constantly recorded at a sampling rate of 980 Hz.
4. Peak resultant force from the impact (N) was measured with the AMTI force plate constantly recorded at 1200 Hz.
5. The displacement of the impact mass (m) was constantly recorded at a sampling rate of 1000 Hz.

Impact resistant glove testing

1. The manikin hand was inserted into the impact resistant glove.
    a. The FlexiForce sensor was placed inside of the glove for testing.
2. The drop height was set to 0.2 m for zones 1-3.
    a. The drop height was set to 0.1 m for zone 4 thumb testing.
3. The impact mass was released.
4. Peak force on the top of the cadaveric hand (N) was measured with the FlexiForce sensor constantly recorded at a sampling rate of 980 Hz.

5. Peak resultant force from the impact (N) was measured with the AMTI force plate constantly recorded at 1200 Hz.
6. The displacement of the impact mass (m) was constantly recorded at a sampling rate of 1000Hz.

### 3.3 Equipment

A guillotine style impact fixture was custom built with cues taken from case studies of accident descriptions. The impact fixture consisted of a mass with two flange-mount linear sleeve bearings riding on steel rods. A pull-wire potentiometer (Micro-Epsilon, Germany) attached to the impact mass was used to determine the velocity of the impact. The peak forces on top of the hands were recorded using a FlexiForce ELF® system (Tekscan, MA). The peak resultant forces under the hands were recorded using an AMTI Force plate (AMTI, MA). The entire impact was recorded using a Sony Handycam (Sony Electronics Inc., CA).

#### 3.3.1 Impact fixture

An impact fixture was specifically designed for this study (Figure 6). The fixture consists of two main parts: frame and impact mass. The frame was constructed of extruded aluminum with a base of 0.685 m by 0.914 m, and the vertical supports of the frame were 2.29 m tall. The vertical rails on which the impact mass rode are 2.29 m tall and 0.0124 m in diameter. The impact mass was 7.63 kg and had an impact head with a width of 0.127 m and cross-section of 0.037 m.

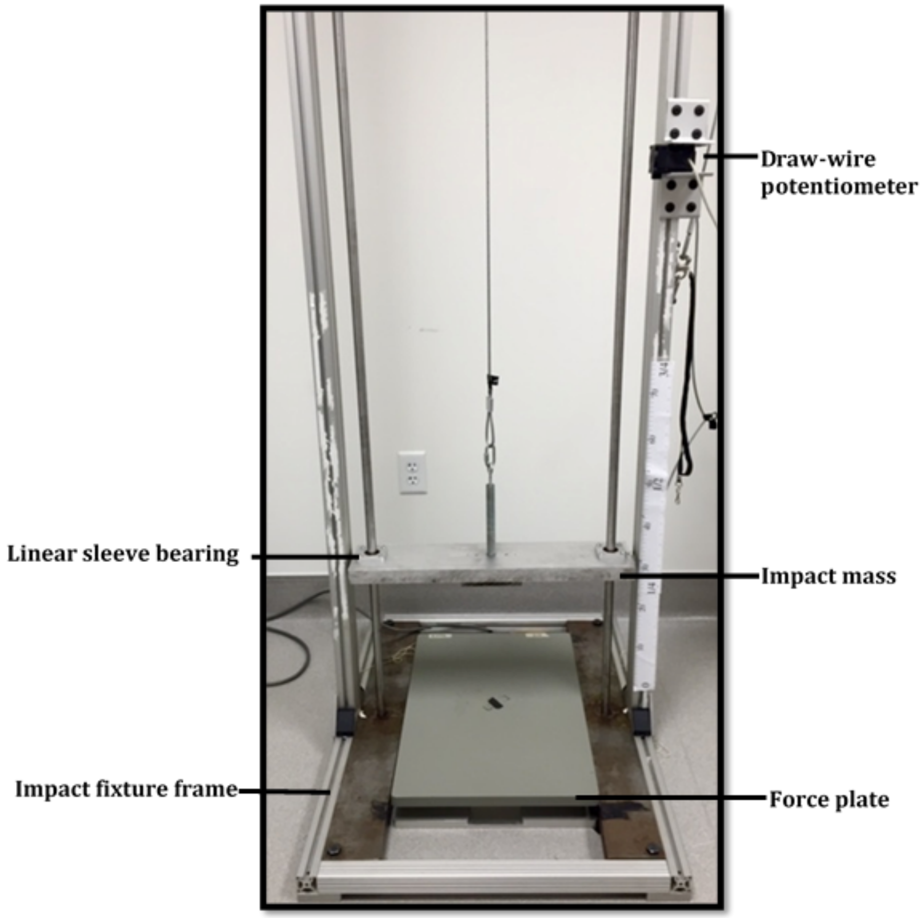


**Figure 6: Custom built impact fixture with annotation**

### 3.3.2 Pull-wire potentiometer

The pull-wire potentiometer (Micro-Epsilon, Germany) was attached to the impact fixture 1 m above the ground. The wire from the potentiometer was attached to the top of the impact mass. The potentiometer was scaled from voltage to output displacement using a linear relationship. This scaling was created using LabView 2009 (National Instruments, TX) software and a National Instruments USB-6218.

3.3.3 FlexiForce ELF® System

The FlexiForce ELF® system (Tekscan, MA) consists of a compact force sensor that was placed on the top of the cadaver and ballistic manikin hands in the zone of the test (Figure 7). The sensor is 1 cm in diameter. The peak force experienced on the top of the hand was recorded using ELF® (Tekscan, MA) standalone software.


**Figure 7: FlexiForce sensor place in zone 2 with markings for all zones.**

The FlexiForce sensors (Tekscan, MA) were calibrated for each specimen using a Material Test System (MTS) (MTS Corp., MN) loading frame. The sensor was place between the ram and base of the MTS and loaded to 3300 N. The sensors were loaded to 3300 N because they require being loaded to 110% of the testing maximum force for calibration purposes. The sensors were loaded to 3300 N and the force was completely removed (ram height 4 mm) five times. Using the force controls of the MTS, the sensor was then loaded to 100 N, 300N, 500 N, 750 N, 1000 N, 1500 N, 2000 N, 2500 N, and 3000 N successively. The load was removed (ram height 4 mm) between each step. The MTS load value fluctuates about the desired value. To minimize error, the data point was collected when the force values from the MTS were within 5 N of the desired value. A piece-wise linear calibration was chosen over a linear best-fit calibration because of its ability to accurately represent low and high forces. Calibration was then verified by setting a known force on the FlexiForce sensor. The readings discrepancy was typically within the manufacturer's claim of 5 percent.

### 3.3.4 DXA scanning

Bone mineral density (BMD) and bone mineral content (BMC) were recorded by DXA scanning (Lunar Prodigy, GE Healthcare) the cadaveric hands in the proximal-distal direction. A 6 cm rice bed was used to provide sufficient attenuation, required due to the cadaver's lack of mass. The proximal-distal direction was set by the scanning enCORE protocol. The analysis of the scans and determination of BMD and BMC utilized enCORE software (GE Healthcare).

### 3.3.5 Imaging

After removal from the cadaver, the cadaveric hands were imaged using the 2D pilot imaging capability of the microCT ZEISS Xraidia 410 Versa (ZEISS, CA). Images of the hand from the distal radius and ulna to the distal phalanges were collected to ensure no previous fracture, and for comparison after impact testing.

## 3.4 Positioning of specimen

Positioning the specimen hands was completed using repeated visual inspection. For zone 1 an 'X' was placed on the medial and proximal phalangeal joint of the $2^{nd}$ phalange. Zone 2 an 'X' was place on the metacarpal-phalangeal joint of the $2^{nd}$ phalange. Zone 3 an 'X' was placed in the center of the $2^{nd}$ metacarpal. Zone 4 an 'X' was placed in the center of the 1st phalange. Zone 5 an 'X' was placed between the distal radius and ulna (Figure 8). The hand was placed so that the targeted 'X' was at the center of the force plate. A FlexiForce sensor was then placed on the 'X' of the hand. The impact mass was then lowered to 1 cm above the specimen to visually confirm correct impact location. After the specimen location was confirmed, clear vinyl adhesive strips (3M, MN) were used to secure the specimen to the force plate.

**Figure 8: Cadaver 2 right hand with 'X' in zones 2 and 3.**

## 3.5 Data analysis

### 3.5.1 Cadaveric hand analysis

Raw data files from the FlexiForce sensor for all of the cadaveric tests were imported into Excel. The maximum force recorded by the ELF® System was reported as the peak force on the top of the hand for each specimen. The maximum peak force for each cadaveric specimen was reported as the Peak Hand Fracture Force (PHFF) for each zone.

The raw data files from the AMTI force plate were imported into Excel. The maximum force value in the Z-direction and the corresponding X and Y were recorded. The X and Y forces were used in calculating the resultant force which reduces the variation due to specimen alignment and zonal differences. The 3-axis forces were used to calculate the peak resultant force as shown in equation 1. The minimum peak resultant force recorded from fracture for each of the cadaveric specimen was reported as the Hand Fracture Tolerance Limit (HFTL) for each zone.

$$(1)\quad Peak\ resultant\ force = \sqrt{F_x^2 + F_y^2 + F_z^2}$$

### 3.5.2 BMC, BMD correlation

The correlation of BMC with resultant fracture force for each zone was completed. A linear best fit for each zone was created and the correlation coefficient recorded. The process was repeated for BMD and resultant fracture force to compare correlation values for each zone.

### 3.5.3 Impact protection

The impact protection from the use of gloves was calculated in terms of: total force reduction (N), and percent force reduction between glove and no-glove conditions (%). The impact protection was evaluated by examining both the force sensor and force plate measurements. The Total Peak Force Reduction (TPFR) and Percent Peak Force Reduction (PPFR) were calculated using equation 2 and 3 respectively. The Total Resultant Force Reduction (TRFR) and the Percent Resultant Force Reduction (PRFR) were calculated using equations 4 and 5 respectively.

$$(2)\ Total\ peak\ force\ reduction_{\,Zone_i\,,Glove_j} = PFG_{i,j} - PFNG_{i,No\ glove}$$

$$(3)\ \%\ Peak\ force\ reduction_{Zone_i,Glove_j} = \frac{PFG_{i,j} - PFNG_{i,No\ glove}}{HFTL_{i,No\ glove}} \times 100$$

$$(4)\ Total\ resultant\ force\ reduction_{\,Zone_i\,,Glove_j} = PRFG_{Zone_i\,,Glove_j} - PRFNG_{Zone_i\,,No\ glove}$$

$$(5)\ \%\ Peak\ resultant\ force\ reduction_{Zone_i,Glove_j} = \frac{PRFG_{i,j} - PRFNG_{i,No\ glove}}{HFTL_{i,No\ glove}} \times 100$$

The HFTL limit was used for the calculations using the force sensor because forces measured using the force plate are the same when the force applied is directly over the sensor.

### 3.5.4 Statistical analysis

Statistical analysis was used to test HO1A, HO1B, and HO1C. A general linear model ANOVA was used to determine if there was a statistical difference between the HFTLs. An alpha value of 0.05 was used for testing. A simple linear regression was used to test for statistical significance in the correlation of BMC and BMD with resultant fracture forces. An alpha value 0.05 was used for testing.

### 3.5.5 Adequate protection

Adequate protection from impact was defined as a force reduction of fifty percent or greater reduction of the HFTLs of specimens 3 & 4 resulting from the use of the gloves in each zone. Specimens 3 & 4 were selected based on their bone quality, as measured by BMC, best representing a normal population. The HFTLs from specimens 3 &4 were used to determine the appropriate impact force. Adequate protection was assessed from the glove testing measurements of percent peak force reduction and the percent peak resultant force reduction. These two measures were compared to confirm agreement between the measuring devices of adequate protection provided by the gloves.

## 3.6 Reproducibility

A test method will only have value if the results are reproducible. The uncertainty of a test must be quantified to validate the test method. Reproducibility was addressed by comparing four ballistic gel hands to each other. The ballistic gel hands were impacted in the four zones of the hand, and the resultant forces recorded for each zone were compared between the samples. These maximums served as the peak force for each zone by which the glove reduction in force was calculated. This same procedure was followed for the glove testing.

# Chapter 4: Results

## 4.1 Cadaveric Hand Fracture Tests

### 4.1.1 Cadaveric hand fracture classification

The hand fractures were observed using the 2D CT imaging and then verified by dissection of the hands. The fractures were classified using the OTA classification system and the results are shown in Table 5. In zone 1, complex comminuted fractures were present in all but one specimen. A zone 1 complex comminuted fracture is shown in Figure 9. This type of fracture was expected due to the crushing nature of the impact. Fractures in specimens 1, 2, and 4 which were used for classification of the hands are illustrated in Figures 9, 10, and 11. Zone 2 fractures were typically oblique or simple non-comminuted fractures. In zone 3, all cadaveric specimens fractured in a unique manner. In zone 4, oblique and transverse were the most common types of fracture. All cadaveric specimens had different types of fractures and dislocations in zone 5.

**Table 5: Cadaveric specimen fracture classification.**

| Cadaver 1 | |
|---|---|
| **Zone** | **Fracture types** |
| **1** | Complex comminuted (78.C2.2) |
| **2** | Comminuted (77-A1.2) |
| **3** | Oblique (77-A2.2) |
| **4** | Complex comminuted (78.C2.2) |
| **4** | Oblique (78-A2.2) |
| **5** | Simple (23-B2.1) |
| **5** | Extending into Diaphysis (23-C3.3) |
| **Cadaver 2** | |
| **Zone** | **Fracture types** |
| **1** | Complex comminuted (78.C2.2) |
| **2** | Non-comminuted (77-A1.1) |
| **3** | Transverse (77-A2.3) |
| **4** | Complex comminuted (78.C2.2) |
| **4** | Transverse (78-A2.3) |
| **5** | Dislocation |
| **5** | Dislocation |
| **Cadaver 3** | |
| **Zone** | **Fracture types** |
| **1** | Complex comminuted (78.C2.2) |
| **2** | Non-comminuted (77-A1.1) |
| **3** | Spiral (77-A2.1) |
| **4** | Oblique (78-A2.2) |
| **4** | Transverse (78-A2.3) |
| **5** | Complex (23-A3.3) |
| **5** | Transverse, no tilt, but may be actually shortened (23-A2.1) |

**Figure 9: Cadaveric specimen 1 zone 1 proximal phalange complex comminuted fracture (Left: 2D pilot image Right: Dissection photograph).**

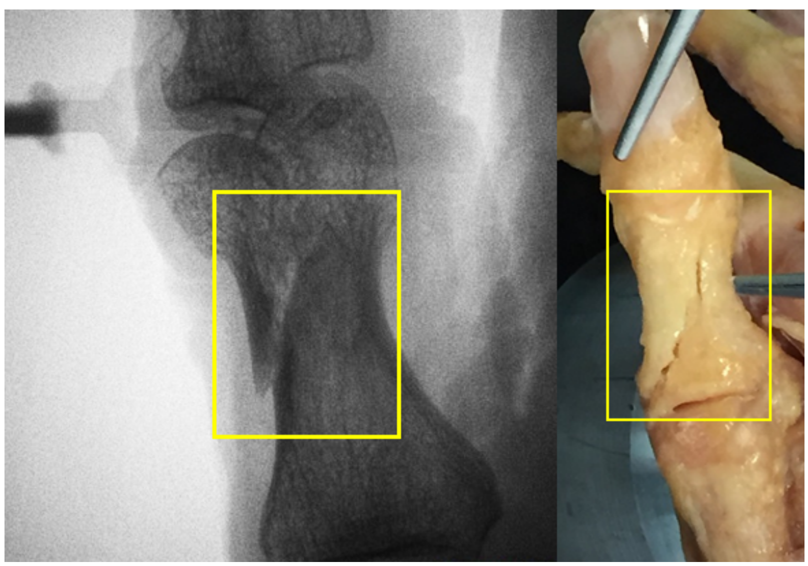

**Figure 10: Cadaveric specimen 2 zone 4 proximal phalange (Left: 2D pilot image Right: Dissection photograph).**

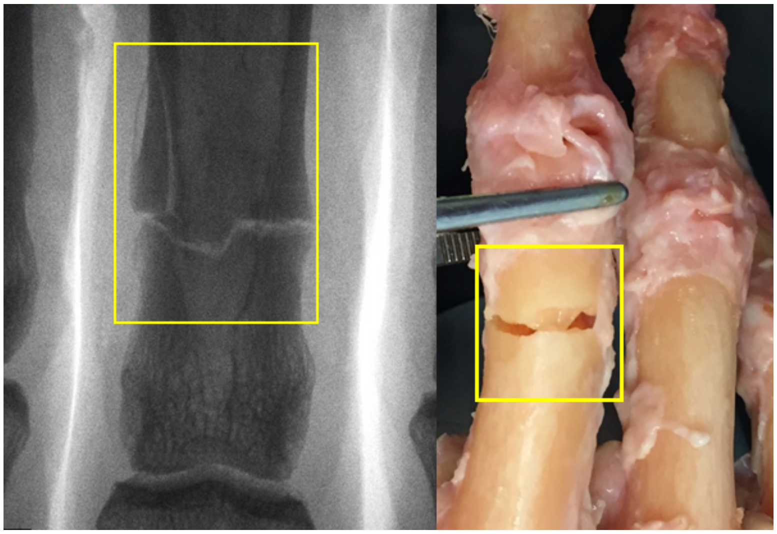

**Figure 11: Cadaveric specimen 4 zone 1 proximal phalange fracture (Left: 2D pilot image Right: Dissection photograph).**

4.1.2 Cadaveric hand fracture forces

Cadaveric hand fracture resultant forces measured using the force plate are illustrated in Figure 12. The average HFTLs (SD) for zones 1 through five are 3673 (1335) N, 2672 (655) N, 2957 (1321) N, 1439 (355), and 2399 (1022) N respectively. Cadaveric hand fracture peak forces measured using the FlexiForce sensor are illustrated in Figure 13. The data from both measuring devices is summarized in Table 6. FlexiForce data collection errors occurred during some tests and are labeled in Table 6 as 'n/a'.

In Table 6, under the Pre-fracture column, any previous impact force which did not cause fracture in that zone are recorded. In specimens 2 and 3, the previous impact may have weakened the zone prior to the test that resulted in a fracture. In specimen 2, the pre-facture force was 1352 N while the fracture force was 1260 N.

In specimen 3 the pre-fracture force recorded was 4057 N while the fracture force was 3890 N.

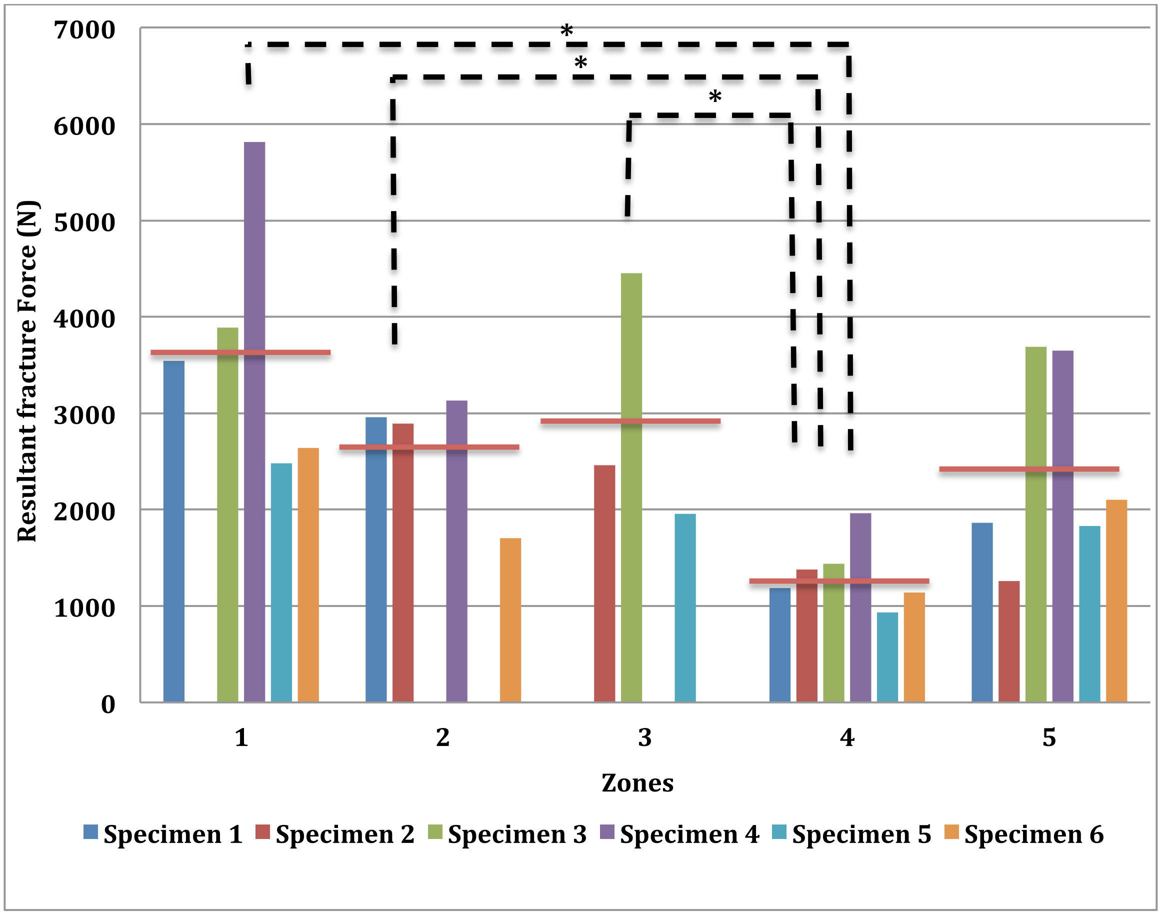


**Figure 12: Cadaveric specimen resultant fracture forces (N) by zone with significant difference between zones shown (dashed line and asterisks) and averages represented by red bars.**

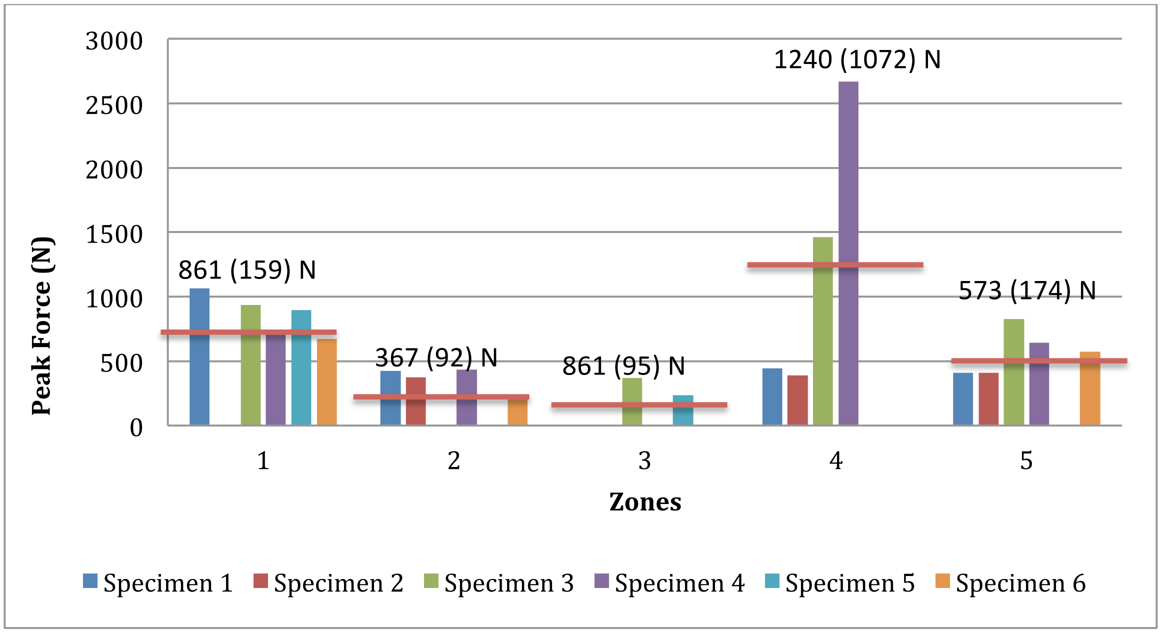


**Figure 13: Cadaveric specimen peak force recorded using the FlexiForce sensor with averages shown.**

**Table 6: Peak resultant fracture force (force plate) and peak force (force sensor).**

| Specimen 1 | | | | |
|---|---|---|---|---|
| | | Peak Resultant Fracture Force (N) | | Peak Force (N) |
| **Zone** | **Drop height (m)** | **Pre-fracture** | **Fracture** | **Force Sensor** |
| **1** | 0.3 | 2878 | 3543 | 1066 |
| **2** | 0.3 | 2884 | 2962 | 424 |
| **3** | | | | |
| **4** | 0.2 | | 1185 | 443 |
| **5** | 0.3 | 1224 | 1864 | 410 |
| **Specimen 2** | | | | |
| | | Peak Resultant Fracture Force (N) | | Peak Force (N) |
| **Zone** | **Drop height (m)** | **Pre-fracture** | **Fracture** | **Force Sensor** |
| **1** | 0.2 | | | |
| **2** | 0.3 | | 2894 | 373 |
| **3** | 0.2 | | 2461 | n/a |
| **4** | 0.2 | | 1382 | 387 |
| **5** | 0.3 | 1352 | 1260 | 410 |
| **Specimen 3** | | | | |
| | | Peak Resultant Fracture Force (N) | | Peak Force (N) |
| **Zone** | **Drop height (m)** | **Pre-fracture** | **Fracture** | **Force Sensor** |
| **1** | 0.4 | 4057 | 3890 | 936 |
| **2** | 0.2 | | | |
| **3** | 0.2 | 3077 | 4454 | 370 |
| **4** | 0.2 | | 1441 | 1463 |
| **5** | 0.5 | 2829 | 3689 | 824 |
| **Specimen 4** | | | | |
| | | Peak Resultant Fracture Force (N) | | Peak Force (N) |
| **Zone** | **Drop height (m)** | **Pre-fracture** | **Fracture** | **Force Sensor** |
| **1** | 0.4 | 2999 | 5812 | 735 |
| **2** | 0.3 | | 3132 | 436 |
| **3** | 0.2 | 2688 | | |
| **4** | 0.2 | | 1963 | 2667 |
| **5** | 0.5 | 2853 | 3650 | 644 |
| **Specimen 5** | | | | |
| | | Peak Resultant Fracture Force (N) | | Peak Force (N) |
| **Zone** | **Drop height (m)** | **Pre-fracture** | **Fracture** | **Force Sensor** |
| **1** | 0.2 | | 2482 | 896 |
| **2** | | | | |
| **3** | 0.2 | | 1955 | 235 |
| **4** | 0.1 | | 932 | n/a |
| **5** | 0.3 | 1427 | 1828 | n/a |
| **Specimen 6** | | | | |
| | | Peak Resultant Fracture Force (N) | | Peak Force (N) |
| **Zone** | **Drop height (m)** | **Pre-fracture** | **Fracture** | **Force Sensor** |
| **1** | 0.2 | | 2640 | 670 |
| **2** | 0.2 | | 1701 | 235 |
| **3** | | | | |
| **4** | 0.1 | | 1138 | n/a |
| **5** | 0.3 | 969 | 2105 | 575 |

Statistical significance was observed for the differences between zone 4, and zones 1, 2, and 3 (See Figure 12). Zone 4's HFTL was not statistically different from zone 5. No other statistical significance was found when comparing zone fracture forces. When analyzing BMD and BMC a linear best fit was selected. The positive correlation of hand resultant fracture forces and BMD had coefficients of 0.6681, 0.3007, 0.9962, 0.7216, and 0.8378 for zones 1 through 5 respectively (See Figure 14). The BMD's positive correlation with fracture force in zones 3 and 5 was significant with $p= 0.039$ and $p=0.010$ respectively. The resultant fracture force positively correlated with BMC with coefficients of 0.6964, 0.3990, 0.9952, 0.7082, and 0.8143 for zones 1 through 5 respectively (See Figure 15). The correlation of BMC with the hand fracture forces for all specimens in each zone was tested using linear regression and was statistically significant ($p=0.014$, and $p=0.044$) in zones 3 and 5 respectively.

On average BMC had a slightly higher correlation of 0.7226 versus BMD's average correlation value of 0.7089. These findings are in agreement with other observers that BMC is a more accurate predictor of failure compared to BMD using the same measuring equipment (Verstraeten et al., 1986; Peel et al., 2005; Njeh et al., 2001; Muller et al., 2002). In Figure 16, the resultant fracture forces are illustrated for each specimen based on zone and sorted by increasing BMC. From this illustration, zones 1, 2, and 4 demonstrate the positive correlation of BMC and resultant fracture force.