

# Testing Setup for the Investigation of Bone Fractures due to the Impact of Hockey Pucks

BY

DARREN HART

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Department of Mechanical and Manufacturing Engineering

University of Manitoba

Winnipeg, Manitoba, Canada

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# Abstract

Bone fractures, mostly of the lower leg and foot, due to impact with hockey pucks are becoming a common injury in ice hockey. These injuries can take up to more than two months to heal and return to play. In the professional levels of play, these injuries cost the team in more than one way. Firstly, a member of the team cannot play for some time and secondly the team may continue to pay the player their salary even though they are injured and not providing their full services to the team. These injuries do not appear to be researched at this time and the current equipment options do not appear to provide adequate protection to prevent injury. This work attempts to develop a testing setup, which is composed to several components, to investigate the minimum requirements that lead to these injuries. A puck-shooting machine was used to impact composite tibias and the velocity at which they fractured was recorded. Other components were designed, built, and selected to comprise the testing setup. The results obtained with the testing setup presented in this work provided valuable insight on these injuries. The composite tibias fractured at impact velocities ranging from 28.83 – 31.25 m/s. Puck orientation at impact was captured with high-speed video. Slight improvements in the testing setup and methodology could provide even more valuable information that could lead to improvements in protective devices designed to prevent these injuries.



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# Dedication

This work is dedicated to my parents Bev and Robert.

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## **List of Abbreviations**

NHL National Hockey League

USD United States Dollars

PVC Polyvinyl Chloride

LED Light Emitting Diode



# Chapter 1

## Introduction

### 1.1 The Game of Ice Hockey

The sport of ice hockey is a fast paced game in which participants using a stick attempt to shoot a rubber projectile, known as a puck, past a goaltender and into a net. Much like soccer, the objective is to score as many goals as possible, and the team with the most goals at the end of the game wins. The game is played on an ice surface where all of the participants wear ice skates while playing the game. The origins of the game are disputed but the game has most fully developed and is most popular in Canada [1]. Some historians believe that the earliest forms of the game were present in the early nineteenth century [1]. As the game has evolved through the years and competition has increased in the elite leagues, the players have become bigger, faster and stronger. The National Hockey League (NHL) is widely regarded as the premier hockey league in the world with revenues estimated at \$3.7 billion in United States dollars (USD) for the 2013-14 season [2].

### 1.2 Injuries in Ice Hockey

A variety of injuries to different parts of the body can occur while playing ice hockey [3-4]. Certain physical contact, including body checking, is permitted in the advanced levels of play. Currently, head injuries, such as concussions, have been a major focus of ice hockey injury research. In addition to head injuries, soft tissue damage can also occur such as lacerations to

unprotected areas, tendon and ligament damage, and bone fractures [3-7]. The focus of this thesis is bone fracture. A common mechanism of bone fracture is impact with the puck. In elite levels of play the puck can travel at very high speeds. In a non-game event, puck speed has been recorded at 110.3 miles per hour [8]. Puck impact injuries can occur when a player makes a defensive play to purposely block the path of the travelling puck to prevent a scoring chance by the opposition, or inadvertently gets in the way of a fast moving puck. More serious injury, including death, has occurred due to impact with the puck [6-7].

## 1.3 Protective Equipment in Ice Hockey

The protective equipment worn by hockey players varies by position and level of play. A skater, forward or defenseman, will wear different equipment than a goaltender. A goaltender's equipment is bulkier and larger in surface area to protect against puck impacts and aid in making saves. A skater's equipment (Figure 1) is less bulky to allow the player to have increased mobility to skate about the playing surface. Of relevance to this thesis is the skater's equipment. In the past few decades hockey equipment has become lighter, most notably the hockey sticks and skates, and the performance benefits have increased. The main pieces of skater equipment consist of a helmet, shoulder pads, elbow pads, gloves, pants, shin guards, and skates. The shoulder pads protect not only the shoulder joint, but the chest and upper back as well. All of these pieces follow a similar form, a rigid plastic shell or insert with foam linings. Additional pieces such as neck and facial protection vary by organizational requirements.



Figure 1: The main pieces of a skater's protective equipment in ice hockey

## 1.4 The Puck

The puck is the object that both teams seek to possess in order to shoot into the opposing teams net. The puck is a circular disk that is made of vulcanized rubber [1]. The size of pucks can vary but in the NHL the pucks are 1 inch thick and 3 inches in diameter [9]. An image of a standard NHL game puck is shown in figure 2. The mass of the puck used in the NHL is between 5.5 and 6.0 ounces [9]. The coefficient of restitution of pucks is about 0.45-0.55 for room temperature

pucks and about 0.35 for a frozen puck [1]. Pucks are frozen for NHL games to reduce the bouncing of the puck and make it easier to handle [1, 9].



Figure 2: A standard NHL game puck

The decrease in coefficient of restitution suggests that the stiffness of the puck increases with decreasing temperature. Some have studied and highlighted this increase in stiffness in a dynamic setting [10]. It is unclear if or how the stiffness of the puck contributes to injury potential.

## 1.5 Purpose of Research

The defensive technique of shot blocking has become more popular in recent years. An unfortunate result of some of these plays is a bone fracture and over the past few years there have been increasing media reports of leg and foot injuries due to impact with the puck [11-18]. Bone fractures of the lower leg and feet have become more common areas of fracture. This is understandable as the feet and legs are the closest body parts to the ice surface where the puck is moving around the most frequently. In the case of leg fractures, these typically occur when a player is struck in an area of the leg that has little to no protection. The skaters wear protective pads on the lower legs called shin guards. These pads are constructed of a rigid plastic outer shell with a foam lining. The area of coverage is mainly the anterior of the lower leg and the knee joint. Some models have a smaller additional pad on the lateral side of the shin guard. These additional pads typically have thinner plastic and foam layers than the rest of the shin guard. It is not well understood how effective these lateral guards are in terms of protecting against bone fractures. Shin guards seem to be effective in protecting against lower leg fractures, in the area of coverage, when impacted by the puck.

In the case of the foot fracture, the equipment covering the foot is the skate. The skate is considered to be a performance piece rather than a protective piece. Over the years the skate boot has evolved from a leather boot to a lightweight carbon composite boot (Figure 3) weighing approximately 600-900 grams depending on the size of the skate. The internal layers of the skate contain foams in some areas including the ankle. The skate boot on current top of the line models is quite rigid and the internals contains foam lining much like other pieces of protective equipment in ice hockey. However, the protective capacity of the skate boot is unknown and the



performance aspects such as weight and mobility are the current standout design features. The objective of skate manufacturers over the past decade or so seemed to be focused on reducing the weight of the skate. It is possible that protection of the foot may have been affected by this trend. External protective devices that are worn over the skates exist, however, these devices add unwanted weight to the feet of the wearer and can potentially come unfastened during play and interfere with the skaters stride. The efficacy and impact attenuation ability of these external protects is not clear.



Figure 3: A current ice hockey skate with composite boot material

Only a few pieces of ice hockey equipment, mainly head and facial protection, are tested and certified by governing bodies. One of these pieces is the helmet and it is tested according to ASTM F1045 and CSA Z262.1 for player helmets, and ASTM F1587 for goalie helmets [19-21]. The testing in these standards involves drop testing of an instrumented headform fitted with a helmet [19-21]. The standards require that the peak acceleration of the impact testing not exceed 275 or 300 times gravity for all impacts depending upon which standard is used [19-21]. The peak values in helmet testing are based upon earlier work where the tolerance of the human skull to impacts was studied [22]. From the lack of literature on the subject, at the current time of this publication, it appears as though the injury tolerance of bones of the lower leg and feet when impacted by a hockey puck or other injury scenarios in ice hockey are not known. Determining information relevant to bone fracture due to puck impact may lead to interventions, in particular improved protective equipment, which may reduce the severity and occurrence of fractures.

A bone fracture due to puck impact can take 1-2 months to fully heal and allow a participant to return to play. In the professional leagues this missed time can be costly to the team due to missing a key player as well as economically as the injured player continues to be paid despite not being able to play. Donaldson, Li, and Cusimano investigated the economic costs to NHL teams due to players lost time because of injury [23]. It was found that leg/foot injury types cost the teams the most at \$68.2 million USD, which was just ahead of head/neck injuries at \$58.2 million USD [23]. The exact leg/foot injuries were not described but it is highly possible that bone fractures had a contribution. If leg and foot fractures are costing professional hockey teams large amounts of money, then it could be advantageous to investigate these injuries in the hopes of developing preventative measures.

The purpose of this research is to attempt to develop a test setup in the laboratory setting to investigate bone fractures due to impact by hockey pucks. The aim of the setup is to recreate and document the injury scenario by means of hockey pucks as projectiles impacting bone specimens as opposed to drop testing onto specimens.

## 1.6 Outline of Thesis

Chapter 1 contains the introduction to the subject of this thesis and the purpose of research.

Chapter 2 summarizes the literature regarding ice hockey puck impact and a brief summary of selected articles regarding bone fracture of the leg.

Chapter 3 outlines the materials and methods used in the experimentation phase of the thesis.

Chapter 4 outlines the results of the experimental trials.

Chapter 5 contains a discussion on the results of the experiment.

Chapter 6 contains the conclusions of the thesis.

Chapter 7 discusses recommendations for future work.



# Chapter 2

## Literature Review

As previously mentioned, it appears as though the literature on bone fractures due to ice hockey puck impacts is scarce. To the best of the authors' knowledge, it appears that there is no literature or comprehensive study involving an analysis of projectile ice hockey pucks impacting human tissues. However, there does exist literature on impact studies involving bone, literature involving impact of ice hockey pucks with other objects, and some literature on the evaluation of ice hockey protective equipment. This limited amount of literature will be presented later in this chapter. It is possible that the sporting equipment manufacturing companies conduct impact studies involving human tissues and choose not to publish their work in order to maintain or gain an edge over the other competing manufacturing companies.

Studies on bone fractures produced by high velocity projectiles appear to stem out of the research of bullet wounds. This literature started to appear as early as the late 1800s and studies involving in depth experimentation are present in the 1960s. In 1967 Huelke et al. studied fractures of the embalmed human femur produced by steel spheres [24]. A helium-operated gun was used to launch the steel spheres and impact velocities ranged from 500 to 1700 ft/s [24]. The size of the spheres used was  $\frac{1}{4}$  inch in diameter [24]. At an impact velocity of 500 ft/s not all spheres completely travelled through the bone and exited the other side, which the authors consider to be near the minimum for complete penetration [24]. As impact velocities increased, the damage became more extensive which ultimately lead to the separation of the distal end of the femur from the rest of the bone [24]. The target area for the projectiles in this study was the

popliteal surface [24]. Although this work was done over 40 years ago, Huelke et al. make some important observations. In this work Huelke et al. outlines four variables of note that influenced fracture. The first is “the total thickness of the bone at the impact point” [24]. The second is “the thickness of the cortical bone at the points of impact and exit” [24]. The third is “the density of the cortical bone and of the enclosed cancellous bone” [24]. The fourth is “the amount of marrow and/or embalming fluid within the cancellous spaces” [24]. These factors should be of consideration should a study take place that involves impact of ice hockey pucks with bone tissue. The makeup of the bones most commonly affected in fractures due to hockey puck impact should be taken into account.

In 1968 Huelke et al. published another study using similar methods this time with two different sized spheres, 0.25 inch and 0.406 inch diameter [25]. Impact velocities ranged from 200-2200 ft/s [25]. The impact location of the projectiles in this study was the posterior surface of the femur in the popliteal fossa [25]. This area of the femur is composed mostly of cancellous bone that is surrounded by a small amount of cortical bone [25]. It was found that the degree of calcification of the bones had an effect on the energy for fracture and penetration [25]. For either size of sphere it took more energy to fracture “normal” bones than mildly osteoporotic or osteoporotic bones [25]. The damage effects to the bones were similar to that of the previous work by Huelke et al. in 1967, however at impact velocities of 350 ft/s the 0.25 inch spheres began to completely penetrate the osteoporotic bones [25]. Complete penetration was seen at impact velocities of 400 ft/s when the 0.406 inch diameter spheres were fired [25]. Important findings of this study to consider for impact testing of bone specimens are the size of the projectile, mass of the projectile, and the amount of calcification of the bones.

A second study published later in 1968 by Huelke et al. focused this time on impacts to the shaft of the femur [26]. The shaft of the femur is composed of “a marrow filled cylinder of dense cortical bone” [26]. Impact velocities, sphere sizes, and methods were similar to the previous study in 1968 [26]. The impact location for the projectiles in this work was the anterior surface of the femur at the mid-length of the shaft [26]. It was observed that shaft impacts required more energy for fracture and penetration than the distal end in the previous work [26]. The type of bone, cancellous or cortical, is a factor that can be taken into consideration when observing for minimum energy required for fractures.

In 2001 Clasper reported on ballistic fractures [27]. Clasper mentions three factors that influence energy transfer and extent of wounding: the velocity of the projectile, the stability and geometry of the projectile, and the type of tissue impacted by the projectile [27]. Also mentioned are three potential mechanisms of energy transfer that can cause damage: cutting, overpressure, and cavitation [27]. Cutting is defined as a direct laceration as a result of projectile impact [27]. Overpressure is defined as tissue wounding caused by “compressive waves that radiate away from the projectile” [27]. Cavitation is described as a brief cavity that is formed behind the projectile and is considered to be the most significant factor in tissue damaged by the transfer of energy from the projectile [27]. Also mentioned by Clasper is the rigidity of bone being greater than skin and muscle tissue [27]. The fracture of bone is aided by the increased transfer of energy to a more rigid tissue [27]. Although these factors of injury are viewed from a ballistics point of bullets fully penetrating tissues they are similar to those described Huelke et al. and should still be considered when observing energy required for fracture in sporting events.

Quenneville et al. studied the impact testing of the human tibia using a custom built testing device [28]. This research was motivated by short duration impulse loading which is evident in

situations such as parachute landings, ejection seat systems, and antivehicle land mine blasts [28]. In this study human cadaver tibias were placed horizontally and in contact with an artificial talus that was machined out of polyethylene [28]. Projectiles were fired at the other end of the talus to provide axial loading to the tibia-talus joint [28]. Two different masses were used for projectiles to vary momentum and failure was defined as the separation of the tibia into at least two distinct pieces [28]. It was found that fracture occurred at 11.0 m/s for the smaller mass (3.9 kg) and 8.4 m/s for the larger mass (6.8 kg), which was statistically different [28]. Momentum was also found to be statistically different however kinetic energy (239 J for the small mass versus 241 J for the large mass) was not [28]. A load cell that was instrumented on the talus measured impact forces of the projectiles [28]. The average peak impact forces were measured at  $12,563 \pm 1,982$  N for the small mass and  $12,581 \pm 2,277$  N for the large mass and no statistical difference was found between the two forces [28]. Further statistical analysis showed that the natural log of axial force, kinetic energy, age in years of the specimen donor, and height of donor in centimeters were significant independent variables for injury risk [28]. There was no mention of the ability of the polyethylene, which is softer than bone, to absorb impact and the effect it had on the experiment. Although this study focused on axial impulses to the tibia, the experiment is similar in nature to that of this thesis, which will be presented in later chapters.

In a later study by Quenneville et al., synthetic composite bones were tested in a similar manner [29]. It was found that the synthetic composite bones failed at forces that were 37-45 percent of those in their previous cadaver study [29]. Kinetic energy was 26-31 percent of that seen in their previous cadaver study [29]. In the case of the synthetic composite tibias, average peak force was different for the smaller projectile mass than it was for the larger projectile mass however it was at the threshold of significance [29]. Impact velocity, momentum, and kinetic

energy were not parameters suggested to define the fracture tolerance [29]. It is suggested by Quenneville et al. that the difference in the geometry of the distal articular surface of the synthetic composite tibias could induce point loading by the artificial talus and reduce the resistance to failure [29]. The authors also suggest that due to the differing response of the synthetic composite tibia to axial impact loading compared to values in their previous cadaver study that the synthetic composite tibia is not recommended for investigations of this type [29]. It may be possible that the synthetic composite tibia could respond much like human bone when impacted perpendicular to the long axis of the bone, such as in this thesis. A reverse approach, testing synthetic bones followed by human bone, could be used to gain more insight on the suitability of using synthetic bones in hockey puck impact testing.

The literature involving impacts with an ice hockey puck also appears to be limited. One study involves the evaluation of the protective glass border of ice hockey rinks to sustain impact from a misplaced shot of a hockey puck. In this study Fam and Rizkalla used a drop test to observe the failure of different glass specimens proposed for ice hockey rinks [30]. Their method of impact was a drop test, which utilized a threaded rod that was placed through a puck [30]. The drop height was gradually increased until fracture of the glass occurred and when the fracture did not occur at the maximum height of the drop apparatus additional weight was added to the assembly [30]. Equivalent puck speed velocities were estimated from kinetic energy which was taken by the authors to be the potential energy at a given drop height [30]. It was found that as the thickness of the glass specimen increased so too did the equivalent puck velocity for fracture to occur [30]. The pucks in this study were kept frozen to simulate realistic conditions and it is unclear if this had an influence on the fracture tolerance of the glass. A drop test methodology of similar in nature to this study could be utilized in the laboratory setting for the testing of bone of

the lower leg and foot if projectile impact testing proves to be unfeasible. Kinetic energies of the puck at game speeds could be matched with a setup such as this, however it is unknown if a higher mass-low velocity impact as seen in drop tests will have the same damaging effects as a lower mass-high velocity impact such as that with projectiles.

In the evaluation of mouth guards, an ice hockey puck has been used as the impacting object [31,33-34]. A study by Oikarinen et al. used a modified hockey puck in a drop test to evaluate several mouth guard designs that were fitted onto plaster mouth models [31]. A drop test device was designed to drop the modified puck from a small height (24 cm) onto the mouth guard [31]. Additional weights were added to the modified puck as required to break the front teeth of the model [31]. It was found that the deciding factor for protecting the teeth was the soft layer of the labial plate [31]. This study highlights the importance of where material is placed in protective devices. In the optimization of sporting equipment where the trend seems to be leaning toward lighter and thinner pieces, a study of this nature can be consulted in order to still maintain protective qualities while still striving to meet the goals of developing a light, non-bulky protective piece.

Sim and Chao studied puck impact forces by dropping pucks from a height onto a force plate [32]. Various materials such as foam, rubber padding, corkwood tile, and plexiglass were placed onto the force plate to simulate human tissue and protective materials [32]. Forces were measured in the range of 150-250 lbs and the authors estimate that when the puck is travelling at game speeds the force could be as high as five times the measured values [32]. This type of experiment is limiting because of the need to continually drop from a greater height to increase the impact velocity. It may be difficult to get a puck to hit the force plate with the edge of the

puck consistently due the potential for the puck to wobble during its free fall. An experiment of this type may not be optimal for laboratory settings.

A thesis by Anderson illustrated puck impact forces as well [10]. In this work an air cannon was used to launch pucks at a strike plate equipped with load cells [10]. Pucks of two different manufacturers were compared to each other at room temperature and low temperature (72° F and 25° F respectively) [10]. It was found that at speeds above 55 mph with pucks at temperatures lower than 25° F, the peak impact force of the puck exceeded the load cell capacity [10]. Values for the coefficient of restitution for both puck manufacturers were found to be lower than those reported in literature for room temperature pucks (0.383 and 0.349 versus 0.45-0.55) [1][10]. Also investigated in this work was a concept used in evaluating softballs and baseballs known as dynamic stiffness [10]. The dynamic stiffness is a measure of the stiffness of the puck subjected to dynamic loading [10]. Dynamic stiffness is quantified in pounds per inch in the work presented by Anderson [10]. It was found that there was a dramatic increase in dynamic stiffness when comparing room temperature pucks to low temperature pucks [10]. A 626% increase in dynamic stiffness was seen in low temperature pucks produced by one of the manufacturers and a 488% increase in low temperature pucks produced by the other [10]. Considering that pucks are frozen in game play, it is not difficult to imagine that there could be implications on injury potential with a frozen or low temperature puck compared to those at room temperature.

Another mouth guard study used a pendulum impact device and load cell to observe dampening effect of mouth guards when impacted with different sports equipment [33]. Among the impacting objects that were attached to the pendulum were a steel ball, a baseball, softball, a field hockey ball, an ice hockey puck, a cricket ball, and a wooden bat [33]. The impacting objects all had similar masses [33]. An acrylic plate was placed over the load cell and the mouth

guard material was placed over the acrylic plate [33]. It was found that the steel ball had the highest forces detected by the load cell when there was no mouth guard material, as well as when the material was placed over the plate [33]. The hockey puck had the lowest peak forces of all impacting objects [33]. There was no mention of the temperature of the puck nor was it speculated what effect that it may have had on peak impact forces.

Duhaime et al. used a drop test to evaluate ethylene vinyl acetate (EVA) mouth guards [34]. A hockey puck that had a 1 inch flat area milled on the edge for the contact point of impact onto an acrylic dental cast with a mouth guard in place [34]. A load cell attached to the puck measured impact forces [34]. This study investigated the effect of thickness of EVA material of the mouth guard on transmitted force [34]. The analysis showed the potential to design mouth guards with desirable characteristics, such as comfort and thinness, which still provide adequate protection [34]. This finding may be of interest to designers of protective hockey equipment. In the pursuit of designing lighter protective pieces an experiment could first be designed to evaluate when a protective piece in question would be considered adequate for use.

In a more recent study of relevance, Ouckama and Pearsall performed projectile impact testing of ice hockey helmets and measured load distribution with flexible force sensors [35]. The authors highlight that the kinetic energy of a puck in motion most often can exceed the kinetic energy levels that are seen in helmet standards [35]. Five helmets of different materials and geometries were impacted at velocities corresponding to kinetic energies seen in helmet standards [35]. An air canon was used to accelerate the puck towards the helmets and laser light sensors were used to measure puck velocity [35]. The area of focus for this study was brain and head injury potential, however, this work is one of few involving puck impact and the methods



can potentially be expanded to testing of injury risk to other areas of the body. The use of flexible force sensors in puck impact testing could be of use in other tests.

Other sources of relevance to this thesis are the standards used in helmet testing. As mentioned previously one of the aspects of helmet standards involves impact testing by means of a drop test [19][20]. The standards for facial protection involve projectile impact testing [21][36]. The facial protection standards provide details on the parameters such as impact velocity and distances from the item under testing and the exit of the puck accelerator as well [21][36]. However, they do not specify details on the mechanics of the puck accelerator such as pressurized air, spring energy, etc. Also briefly described in the facial protection standards are the tolerances of the device used for measuring velocity [21][36]. The pass/fail criteria for facial protection are mainly a visual inspection of the integrity of the facial protection after impact rather than measured variables during the impact [21][36].

It appears as though that the literature regarding hockey puck impact is, at the current moment, limited. Adding to this small area of research provides motivation for the work of this thesis and will hopefully compel other researchers to add to the field as well. A summary of literature involving puck impact is shown in table 1.

**Table 1: Literature regarding hockey puck impact**

| Author             | Year | Method of Puck Acceleration | Emphasis of Study                                                      |
|--------------------|------|-----------------------------|------------------------------------------------------------------------|
| Sim & Chao         | 1978 | Drop Test (puck only)       | Injury Potential                                                       |
| Oikarinen et al.   | 1993 | Drop Test (assembly)        | Evaluation of Mouthguards                                              |
| Takeda et al.      | 2004 | Pendulum Device             | Evaluation of Mouthguard Material Impacted by Various Sports Equipment |
| Duhaime et al.     | 2006 | Drop Test (assembly)        | Evaluation of Mouthguards                                              |
| Fam & Rizkalla     | 2007 | Drop Test (assembly)        | Investigation of Protective Glass in Ice Hockey Arenas                 |
| Anderson           | 2008 | Air Cannon                  | Puck Characterization and Manufacturer Comparison                      |
| Ouckama & Pearsall | 2014 | Air Cannon                  | Head and Brain Injury                                                  |

# Chapter 3

## Materials and Methods

### 3.1 Overview

The first step in designing a system for the investigation of bone fracture due to puck impact was to define a model of the impact, and criteria at which fracture occurs. Analyzing an impact of this nature can be quite complex as in actuality the traveling puck has more than one component to its velocity and the force at impact likely has more than one component to it as well. The objective of this recreation was to keep variations and complications to a minimum. Therefore, a one-dimensional physical model was selected to analyze the impact. In a game scenario it is likely that when a player is struck by a puck, that the player is in motion. The target will be stationary to minimize varying parameters for this study. As previously mentioned, it is more common that a fracture of the foot occurs than fractures of the leg. It is unclear as to exactly which bones of the foot are fractured in puck impact injuries. It is not uncommon for professional sports teams to be vague when describing injuries to the press, and there does not seem to be any case reports of fractures of the leg or foot due to puck impact in the literature at this current time. The human foot is a complex structure composed of many bones and articulations. An unpredictable rebound trajectory due to the complex shape of the bones of the human foot makes it difficult to monitor the entire collision in the laboratory. In addition to the complex surfaces of the bones of the foot, the availability of suitable test specimens must also be considered. For the reasons mentioned the foot will not be the subject of impact investigation.

For the ease of testing purposes, the tibia, which is a large bone with a substantial flat surface on the medial side, is selected for the impact. The impact is approximated as a simple collision. A free body diagram of the collision is shown in figure 4. The puck travels toward the target and the impact is modeled an impulse after which the puck travels back in the opposite direction. Without measuring the force directly, it would not be known how the force changes throughout the impact duration. The linear impulse-momentum theorem can be used to approximate the average forces at impact in the x-direction by rearranging the linear impulse-momentum equation.

$$F_{x,avg} = \frac{m \times \Delta v_x}{t} \quad (\text{Eq. 1})$$

In this equation  $m$  is the mass of the puck,  $\Delta v_x$  is the change in velocity in the x-direction of the puck after impact, and  $t$  is the impact duration. Other criteria such as impact velocity, kinetic energy, and impact duration will also be considered and presented in the analysis. To achieve the recreation of a hockey puck impact with the tibia in the laboratory, several components that comprise the test setup will be implemented. These components are the test specimens, a rigid frame to hold the test specimens in place, a velocity measurement device, a puck accelerator, and a high-speed camera. These components will be described in detail in following sections of this thesis.

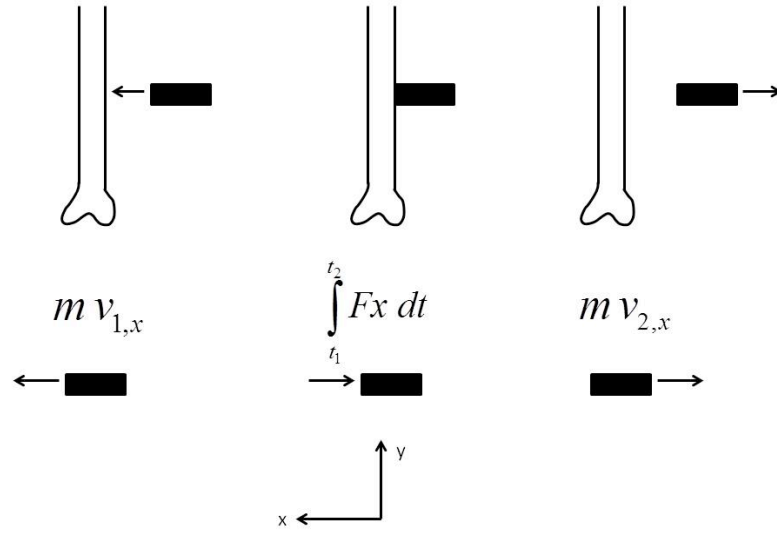


Figure 4: Free body diagram of the puck just before and after impact

## 3.2 Test Specimens

An important consideration is the availability of suitable test specimens. The use of real human bone would be beneficial, as the bone involved in the injury would be tested. However, the use of human bones introduces several complications such as ethics approval, bone quality, availability, cost, and variation in geometry from specimen to specimen. A substitute to human bone exists that is produced by Sawbones (Pacific Research Laboratories, Washington, USA). This analogue is known as the Fourth Generation Composite Bone. The composite bones are composed of a glass fiber and epoxy resin outer cortical shell, and polyurethane foam that serves as the cancellous bone core. The behavior of these composite bones is advertised to be similar to that of cadaveric specimens. As previously mentioned, axial impact testing of these composite bones has been performed in the past and was not recommended by the authors to be suitable for that type of testing [29]. The authors of that work had performed tests on cadavers prior to coming to that conclusion and were able to compare data between cadaveric and composite

bones. It may not be clear until future work using cadaver bones is performed with the test setup of this thesis, if the composite bones are an adequate substitute for real bone.

A total of 8 size large, left Fourth Generation Composite Tibias (Model #3402, Pacific Research Laboratories, Vashon Island, Washington) were selected for the experimentation of this thesis. The size large composite tibia measures 405 mm in length, 84 mm medial to lateral across the proximal end, and 54 mm across the distal end. A 9 mm canal runs from the distal end through the length of the shaft. A General Electric OEC 9800 Plus Mobile C-arm (General Electric Healthcare, United Kingdom) was used to image all of the specimens prior to testing to ensure that there were no pre-existing cracks. The tibias were potted in dental casting cement (Denstone Type III White, Modern Materials, Indiana, USA) on the proximal and distal ends. A 4 inch diameter Polyvinyl Chloride (PVC) pipe coupling served as a container on both ends of the specimens. An end cap was placed on the coupling to contain the casting cement until it had cured and was then removed. The casting cement was mixed using a ratio of 900 g of Denstone powder to 300 mL of water for each coupling. The target for puck impact was the medial surface of the tibia at mid-shaft height. To align the specimens, the tibial shaft was centered in the coupling and a level was placed against the medial surface and held perpendicular to the horizontal (Figure 5) until the cement was cured enough that the specimen could stand on its own. After the cement had cured the specimen was rotated and the same process was used on the other end. The prepared test specimen is shown in figure 6. The test specimen is then held in place during impact testing by a frame, which is described in the next section. In the preliminary testing sessions, which were mainly for the practice of operating the puck accelerator and alignment with the target, the Sawbones Solid Foam Tibia size large (Model #1125-21) were used. The cementing process for the foam tibia was the same as previously outlined.



Figure 5: The cementing process of the composite tibia specimen



Figure 6: A composite tibia specimen prepared for testing

### 3.3 Frame

A frame was designed to hold the specimens in place during impact testing. The frame was designed to hold a tibia specimen in an upright position. The desired position is to have the medial surface perpendicular to the horizontal. The frame must be rigid enough to withstand an impact with the puck at high speeds. Another consideration was that the frame be corrosion resistant. If in the future the frame is used with cadaveric specimens, the material of the frame must be able to withstand cleaning and disinfecting materials. For the reasons of rigidity and corrosion resistance, an all stainless steel construction was chosen. The frame consists of 4 main components: the base, flange, guide posts, and loading plate. The frame is shown in figure 7 and technical drawings can be found in Appendix A. The base is a 3 foot section of 1/4 inch thick rectangular tubing. The flange is a section of size 6 schedule 10 pipe welded to a square piece of 1/8<sup>th</sup> inch sheet. There are two flanges, one attached to the base and one directly above that is attached to the loading plate. The flanges hold the test specimens and they are secured with machine screws that feed through the wall of the pipe. The flanges are removable from the base and top plate to allow for customized fittings for different uses. The guide posts, as the name suggests, serve as a guide for the loading plate to travel up and down to accommodate different lengths of specimens and ensure that the flanges are aligned. The guide posts are composed of 2 inch schedule 40 pipe.

In determining a suitable member for the guide posts that would withstand a high velocity puck impact it was difficult to estimate loading as puck impact force data is limited at this point in time. In a study described earlier in this thesis, puck impact forces vary depending upon impact velocity and puck temperature [10]. However, structures that are subjected to high velocity puck impacts by low temperature pucks exist and have shown to withstand these



impacts. These structures are the goal nets. In the NHL, where puck velocities are of the highest in elite competition, the upright posts of the goal net are size 2 schedule 40 steel pipes [9]. This served as the rationale for the selection of size 2 schedule 40 pipe.

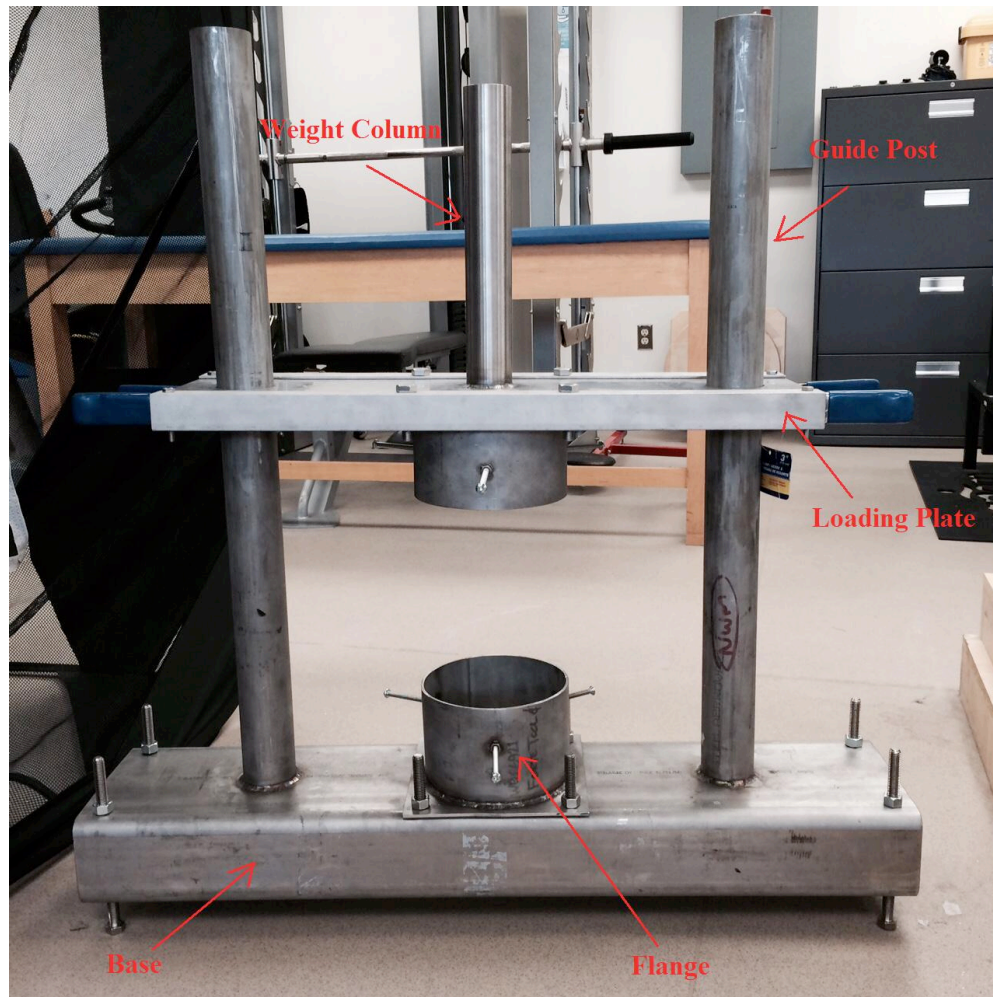


Figure 7: The components of the stainless steel impact frame

The loading plate consists of a  $1/8^{\text{th}}$  inch thick sheet with a 50 mm pipe welded to the center of the plate. The pipe served as a column to place additional weight onto to simulate different

axial loads on the tibia specimens. The length of the column allows for an additional 405 lbs (183.7 kg) axial load. The total mass of the frame is 105.5 lbs (47.8 kg).

### 3.4 Puck Accelerator

To accelerate the puck towards the target, a Porta-Puck shooting machine (Boni Goalie Trainers, Ontario, Canada) was used (Figure 8 and Figure 9). The Porta-Puck is similar to a baseball-pitching machine in that there are two wheels that are independently driven by electric motors that grip the puck and propel it through an exit port. The shooting speed is advertised to vary between 5 and 80 miles per hour. An actuator raises the exit port to vary the shooting angle. Pulling a lever that pushes the puck in between the two spinning wheels operates the machine. The pucks used for testing were produced by Lindsay Rubber (Ontario, Canada) and had an average mass of  $165.4 \pm 0.9$  g ( $5.8 \pm 0.03$  oz).



Figure 8: The Porta-Puck shooting machine

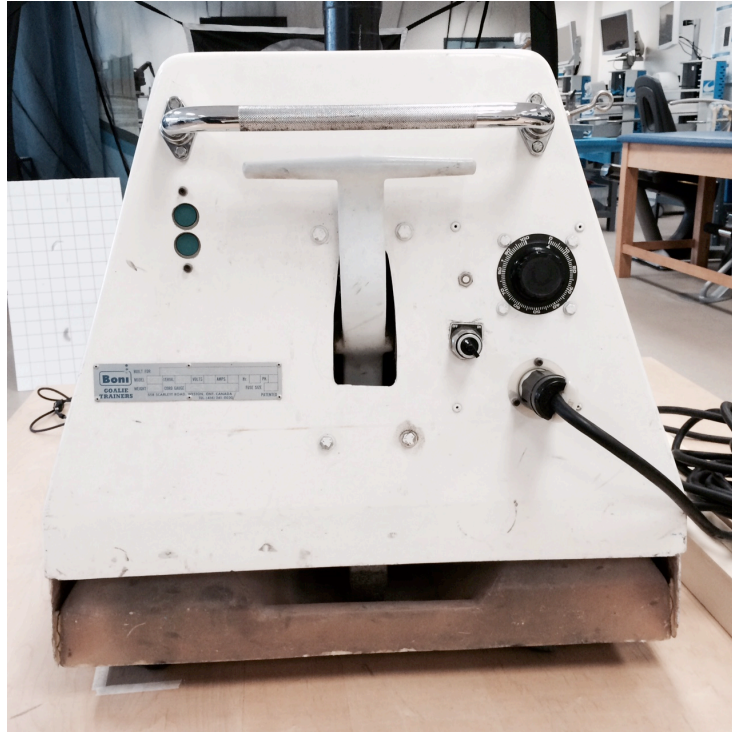


Figure 9: Controls of the Porta-Puck shooting machine

### 3.5 Velocity Measurement Device

An electronic device was built to measure the puck velocity after it left the exit port of the Porta-Puck. The device is similar to that described in a study on the coefficient of restitution of baseballs [37]. There are two components to this device, an emitter and a receiver. The emitter is a circuit of infrared light emitting diodes (LED) and the receiver is a circuit of phototransistors and indicator LEDs. Schematics of each circuit are shown in figure 10. In ambient light the resistance of the phototransistor component is high ( $\sim 100 \text{ k}\Omega$ ). When infrared light is aimed at the phototransistor, the resistance of the component drops and thus a change of voltage will occur. The emitter and receiver are aligned and together form a light screen. The device has two light screens that are spaced 0.25 m apart. When an object passes through the light screens the change in resistance of the phototransistors causes a momentary increase in voltage. The time it

takes the puck to travel through the light screens can be found by locating the increases in voltage with respect to time. The velocity can then be determined by dividing the distance between the light screens by the time it takes the puck to travel through the screens.

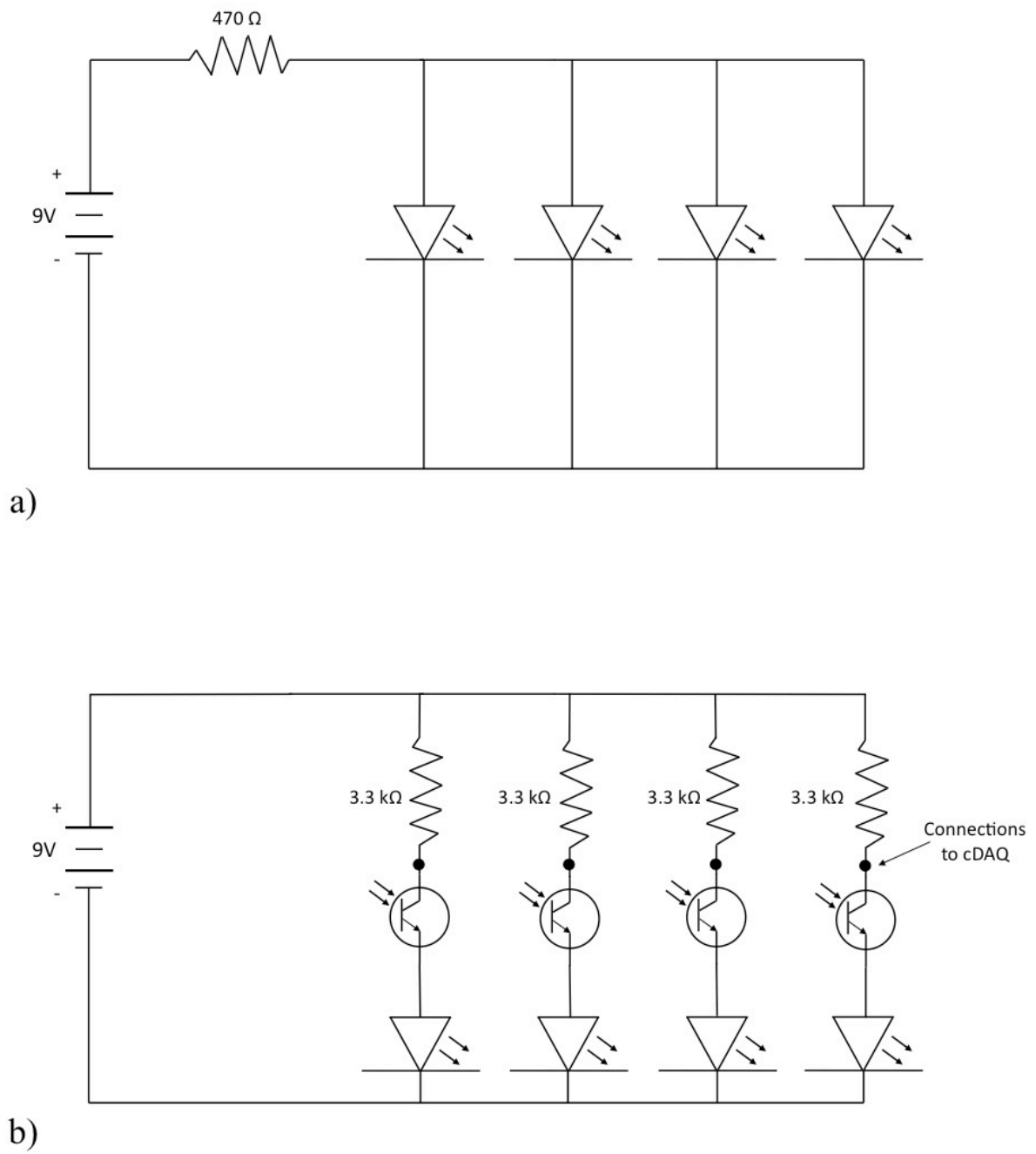


Figure 10: Schematics of the a) emitter circuit and b) receiver circuit of the velocity measurement device

To determine the time it takes the puck to travel through the light screens, an NI 9205 module that was connected to an NI cDAQ-9178 (National Instruments, Texas, USA) data acquisition unit logged voltages during testing. There were four phototransistors on each emitter and leads that were connected to the positive leg of the phototransistors and the NI 9205 were referenced to the ground terminal of the module. A total of 8 connections were logged by the cDAQ. National Instruments LabVIEW SignalExpress 2010 software was used to control the cDAQ, which was sampling at 3 kHz. The recorded data is exported to Microsoft Excel and a voltage-time plot of the 8 analog inputs is produced, an example of a typical recording is shown in figure 11.

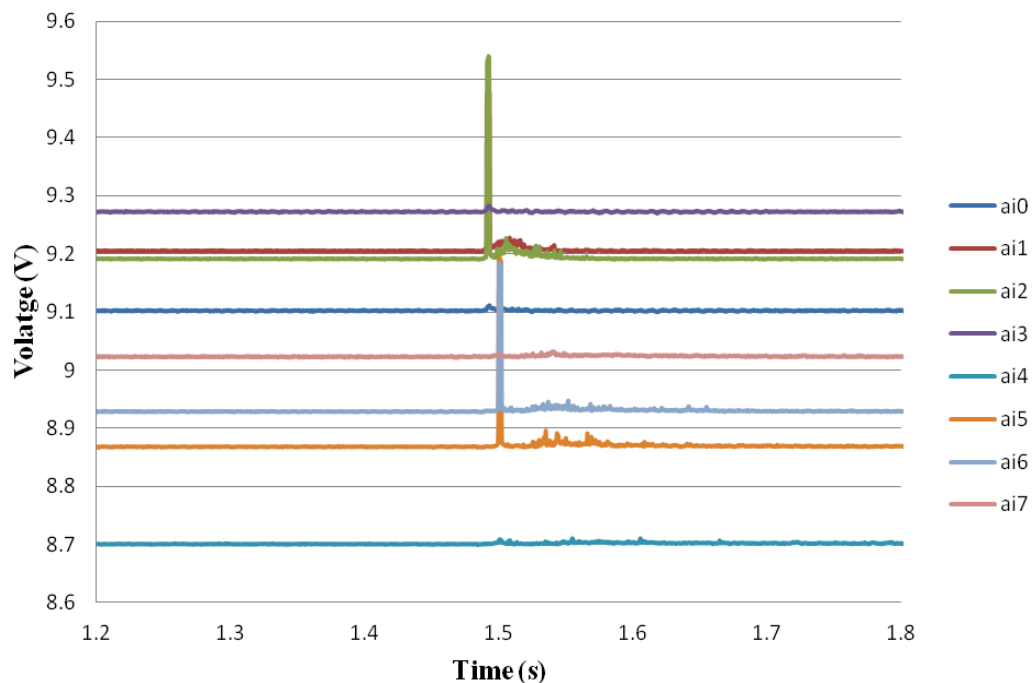


Figure 11: The voltage changes in the receiver circuits of the light screen as a puck passes through the velocity measurement device

The channels with the largest peak from each receiver are isolated and a threshold of half of the peak voltage is applied to the data. The first instance of the threshold value is located using a logic statement in Microsoft Excel and the time between these threshold values is used in

determining puck velocity. The velocity measurement device is shown in testing position in front of the Porta-Puck in figure 12.

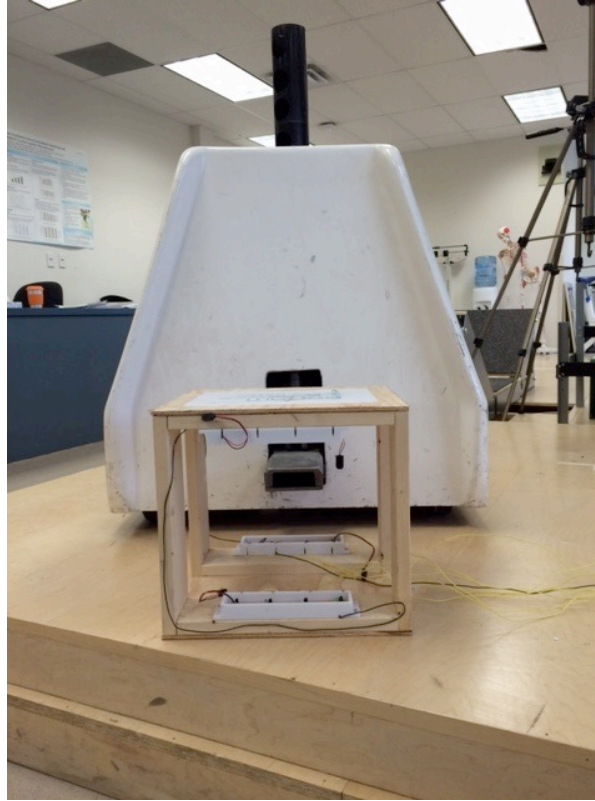


Figure 12: The positioning of the velocity measurement device

### 3.6 High Speed Imager

A high-speed camera was used to monitor the puck at impact. A FASTCAM MC1 (Photron USA Inc., California, USA) was focused on the test specimen and recorded the impact at 3000 frames per second in monochrome images. The Photron FASTCAM Viewer software was used to control the camera and to review recorded video. At a frame rate of 3000 frames per second the resolution of the images is 512 x 352 pixels. Analyzing the number of frames that the puck and test specimen are in contact will approximate the duration of impact.



### 3.7 Summary

As previously mentioned, the impact forces will be approximated using linear impulse-momentum. A Porta-Puck shooting machine will accelerate a puck towards the test specimen that is held in place by a custom designed impact frame. The custom-built velocity measurement device described in an earlier section will be used to determine the puck velocity. The high-speed camera will be used to approximate the duration of the impact. Using these components, the unknown variables required to compute equation 1 will be determined. A top view schematic of the test setup is illustrated in figure 13.

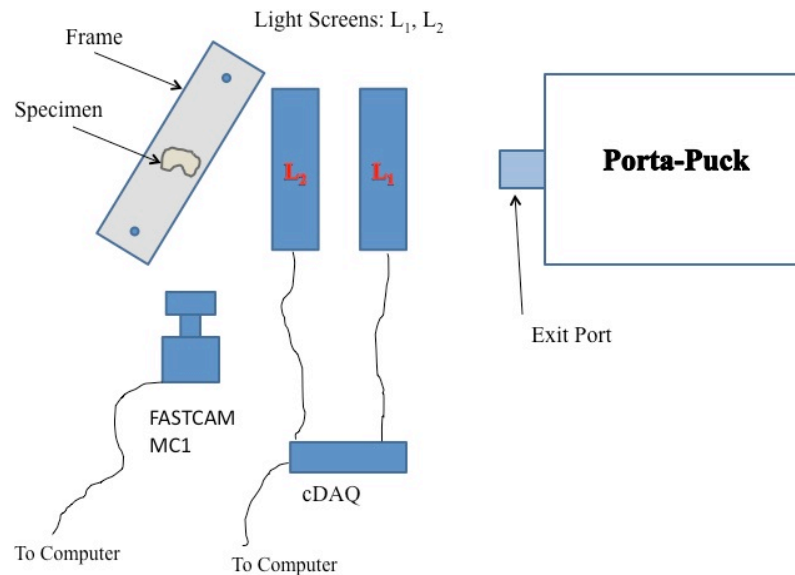


Figure 13: A top view of the arrangement of the test setup components



# Chapter 4

## Experimental Results

### 4.1 Performance of the Velocity Measurement Device

The accuracy and repeatability of the data produced by the velocity measurement device were examined prior to the testing of the composite bone specimens. As an initial test, the device was rotated 90° onto its side and a ball was dropped from two different heights to compare the time to travel between the light screens obtained from the device and calculated velocities of objects falling under gravity. The drop heights were 1.425 m and 2.672 m. The time for the ball to reach the light screens from the drop height was calculated using equation 2, where  $d$  is the distance from the drop height to the light screen and  $g$  is acceleration due to gravity. No opposing forces, such as drag or air resistance, were taken into account in this approximation.

$$t = \sqrt{\frac{2d}{g}} \quad (\text{Eq. 2})$$

The difference in time for the ball to cross the light screens was compared to the time between the voltage spikes in the output produced by the SignalExpress software. The results are presented in table 2.

**Table 2: Experimental and calculated times to travel between the light screens from different drop heights**

| Drop Height (m) | Experimental Average $\Delta t$ (s) | Standard Deviation (s) | Calculated $\Delta t$ (s) | Average % Error |
|-----------------|-------------------------------------|------------------------|---------------------------|-----------------|
| 1.425           | 0.0531                              | 0.000876               | 0.0519                    | 2.31            |
| 2.672           | 0.0383                              | 0.000675               | 0.037                     | 3.51            |

The sample rate of the cDAQ was set at 1 kHz. The corresponding velocities are obtained by dividing the light screen spacing of 0.25 m by the difference in time to travel between them. This data is presented in table 3. It can be seen that for an object falling due to gravity between the lights screens, the corresponding velocity is within 1 m/s, which is within the tolerance of velocity measurement as prescribed by standards for facial protection in hockey [21].

**Table 3: Experimental and calculated velocities of an object dropped from different heights**

| Drop Height (m) | Average $v$ (m/s) | Calculated $v$ (m/s) | Average % Error |
|-----------------|-------------------|----------------------|-----------------|
| 1.425           | 4.71              | 4.82                 | 2.28            |
| 2.672           | 6.53              | 6.76                 | 3.40            |

A session of shooting pucks with the Porta-Puck through the velocity measurement device was also performed. The Porta-Puck shooting machine has a variable speed control dial that is labeled 0 – 44.70 m/s (0 – 100 mph). Pucks were shot at several dial settings and the velocities obtained from the measurement device were compared to the setting on the Porta-Puck. Table 4 shows the average velocity of 10 shots for each of the various dial settings.

**Table 4: Average velocities of pucks at various dial settings**

| Dial Setting (m/s) | Average Velocity (m/s) | Standard Deviation (m/s) |
|--------------------|------------------------|--------------------------|
| 11.18              | 4.74                   | 1.10                     |
| 15.65              | 7.69                   | 0.52                     |
| 22.35              | 22.89                  | 1.25                     |
| 31.29              | 30.4                   | 1.44                     |

In another shooting session with the Porta-Puck, the data produced by the velocity measurement and the cDAQ were compared to the readings of a radar gun. A Bushnell Speed Radar Gun (Model # 10-1900, Bushnell Performance Optics, Kansas, USA) was aimed at the exit port of the Porta-Puck, inline with the path of the travelling puck, from approximately 4 m away to monitor the velocity of the puck as it was shot at various dial settings. This particular radar gun is advertised to have an accuracy of  $\pm 0.447$  m/s ( $\pm 1$  mph). The velocities obtained from the two devices are plotted in figure 14.

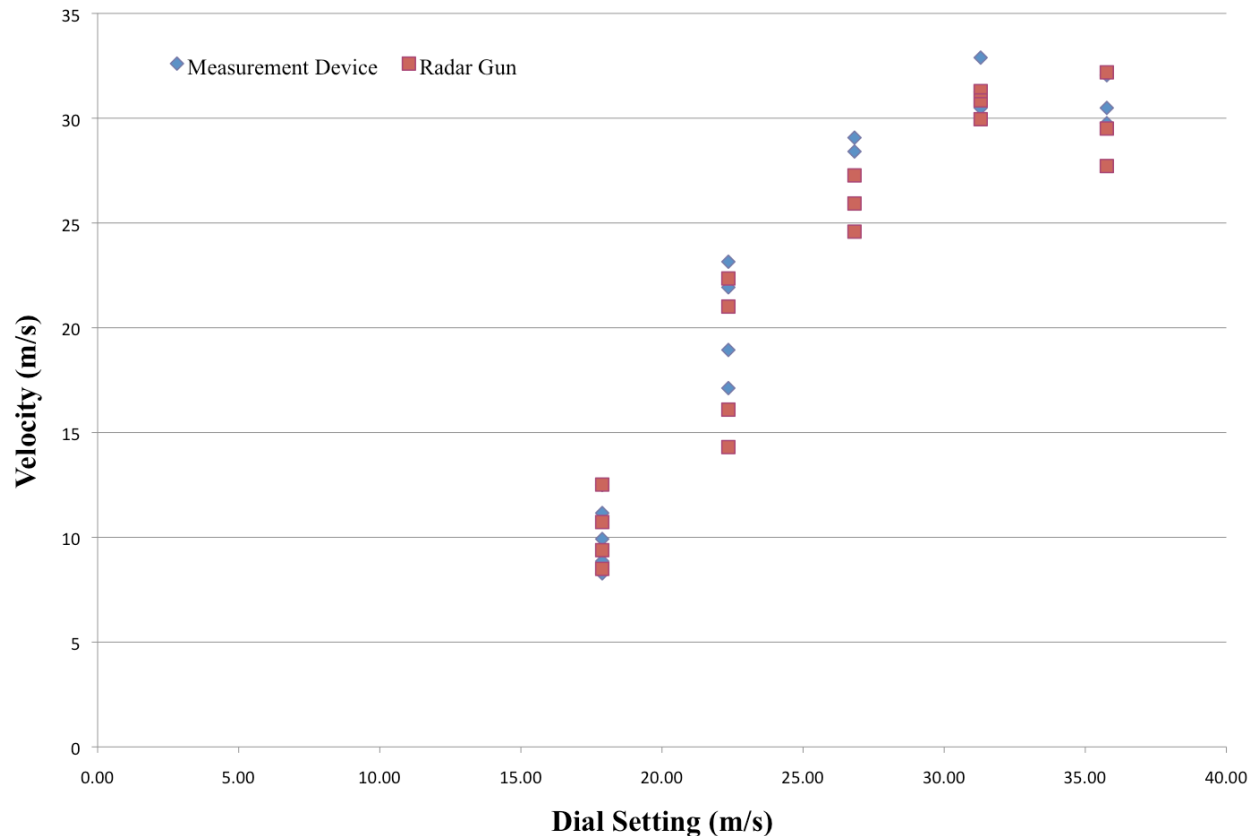


Figure 14: Comparison of velocities measured by the custom device and a radar gun

## 4.2 Preliminary Testing

As mentioned in a previous chapter, a preliminary test using a foam bone as a test specimen was performed to determine the appropriate alignment of the test setup components, namely the Porta-Puck and the impact frame. The distance from the medial surface of the test specimen to the exit port of the Porta-Puck was 75 cm and the distance from the light screen closest to the exit port to the exit port itself was 8 cm. These distances remained constant throughout future testing. An image of the testing setup can be seen in figure 15.

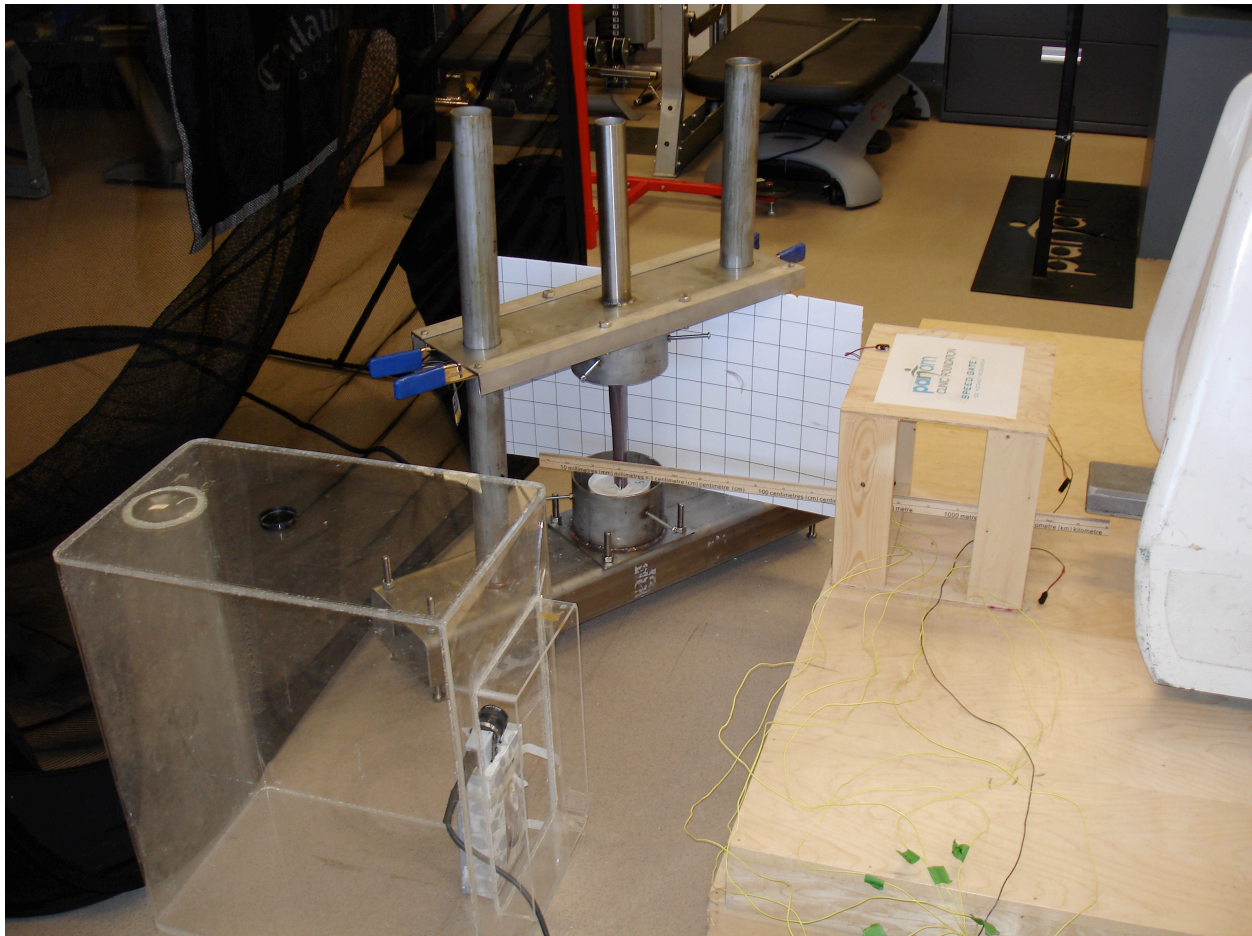


Figure 15: The testing setup used in hockey puck impact testing

Testing with the foam bone revealed that the mode of failure was shearing at the inferior portion of the shaft at the level of the cement (Figure 16) as opposed to a fracture near the impact site. This happened with the first foam bone specimen. The foam bone was under a compressive load of 9.6 kg, the mass of the loading plate. The compressive load was removed for another test with a foam bone by placing clamps onto the guide posts, the handles of which can be seen in figure 7. After removing the compressive load the foam bone had failed in bending at the level of puck impact at a velocity of 21.93 m/s. The clamps were left on the guide posts for all future tests.

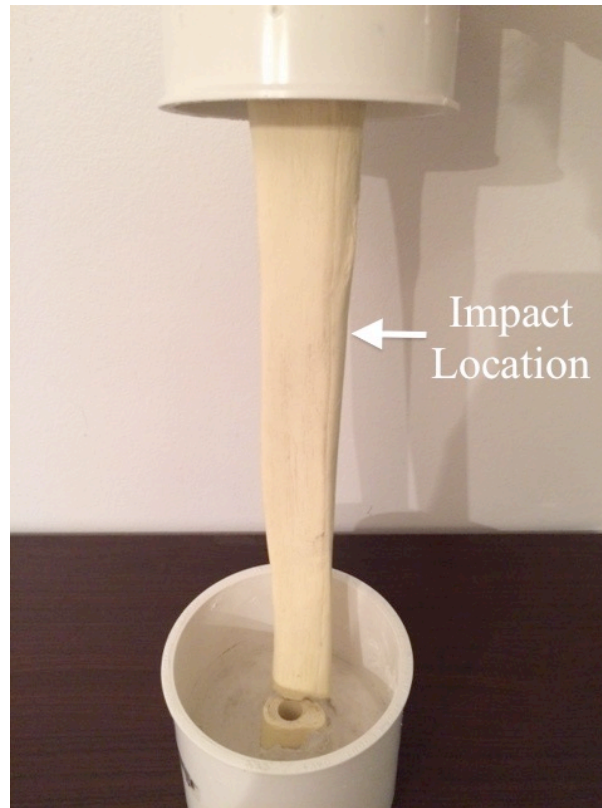


Figure 16: Fracture of foam bone in preliminary testing

An additional test, this time using a composite bone specimen, was performed to determine a starting point for impact velocity for the remainder of the testing. This test involved three

impacts and the puck velocity was increased for subsequent impacts. The dial settings on the Porta-Puck for these impacts were 22.35 m/s (50 mph), 26.82 m/s (60 mph), and 31.29 m/s (70 mph). There was no visible damage after the impacts at the first two dial settings. The specimen fractured at the 31.29 m/s dial setting. There was no high-speed imaging during the preliminary tests.

## 4.3 Composite Bone Impact Testing

Upon the beginning of the composite bone impact tests, it was observed that the puck did not consistently bounce back along the incident path. Also, the puck did not bounce far enough backward to travel through the velocity measurement device to measure the rebounding velocity. This unexpected result did not allow for the calculation of impact forces in the x-direction as described in equation 1. The impact velocities resulting in fracture will be presented later. The composite bone impact testing was performed in two sessions. The testing protocol involved impacting the test specimen and then increasing the velocity via the dial setting on the Porta-Puck in the event that the specimen did not fracture. However, turning the dial on the Porta-Puck did not always result in an increase in velocity according to the data obtained from the velocity measurement device. As previously mentioned, it was observed that the puck did not always rebound straight back and sometimes would bounce towards the camera. In these cases it appeared as though the puck did not hit the specimen squarely, hence the rebound angle, and an additional impact at the same dial setting would take place since the specimen did not fracture.

All specimens were impacted in the first session but not all were tested until fracture. It was suspected that some specimens might have sustained fractures that were not visible to the naked eye. Imaging with the General Electric OEC 9800 Plus in between testing sessions revealed that

no fractures had occurred due to impact during testing. After this finding and for the purposes of this testing, a fracture was defined as the complete separation of the test specimen.

The composite bone specimens were fractured in 1-4 impacts. The velocities at which the specimens fractured range from 28.83-31.25 m/s, as recorded by the velocity measurement device. The velocities and corresponding kinetic energies, where kinetic energy =  $\frac{1}{2}mv^2$ , for the impacts resulting in fracture are presented in table 5. The number of shots and velocity increases are presented in table 6. The cDAQ was sampling at a rate of 5 kHz in the first testing session. During this session the SignalExpress program malfunctioned several times and velocity measurements for some impacts were not recorded. The average of all shots at the same dial setting on the Porta-Puck was used to estimate how fast the puck may have been travelling in the missed recording and are highlighted with an asterisk.

**Table 5: Velocities and kinetic energy of impacts resulting in fracture**

| Composite Bone Specimen | Velocity (m/s) | Kinetic Energy (J) |
|-------------------------|----------------|--------------------|
| 1                       | 30.00          | 74.41              |
| 2                       | 31.25          | 80.75              |
| 3                       | 30.00          | 74.41              |
| 4                       | 30.49*         | 76.87              |
| 5                       | 31.25          | 80.75              |
| 6                       | 28.83          | 68.76              |
| 7                       | 31.25          | 80.75              |
| 8                       | 30.00          | 74.41              |
| Mean                    | 30.38          | 76.39              |
| Standard Deviation      | 0.80           | 4.26               |

**Table 6: Number of impacts and increases in velocity to fracture**

| Composite Bone Specimen | # Of Impacts To Fracture | # Of Increases In Velocity |
|-------------------------|--------------------------|----------------------------|
| 1                       | 3                        | 2                          |
| 2                       | 4                        | 3                          |
| 3                       | 2                        | 1                          |
| 4                       | 1                        | 0                          |
| 5                       | 2                        | 1                          |
| 6                       | 4                        | 2                          |
| 7                       | 3                        | 0                          |
| 8                       | 3                        | 1                          |

It was postulated that the impacts that did not hit the bone specimen squarely on the medial surface was due to the Porta-Puck being on wheels and that some motion during the pulling of the lever to fire the puck was influencing the trajectory of the puck. At the start of the second session of testing, which included bone specimens # 1-3, 5, and 6, the Porta-Puck was immobilized by placing sections of 2” x 4” lumber underneath (Figure 17). Placing the lumber under the Porta-Puck raised the exit port up by 4 cm. The impact frame was not adjusted and therefore the puck was impacting the bone specimens at a slightly higher position along the shaft of the specimen. This adjusted setup was used to impact bone specimens 1 and 2 only. Both of these specimens fractured at the inferior end at the level of the Denstone material (Figure 18). The lumber was removed from underneath the Porta-Puck for the remainder of testing after bones 1 and 2 were fractured.



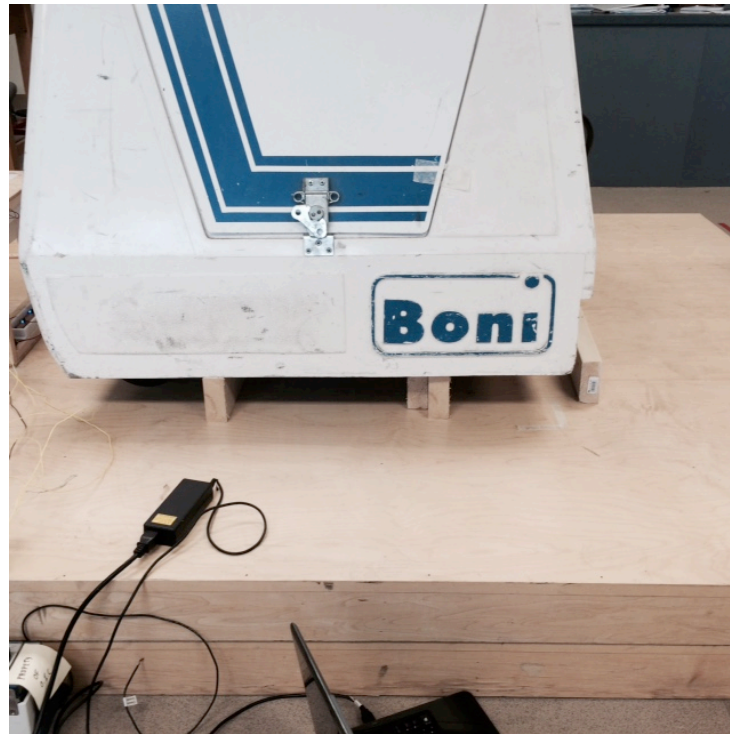


Figure 17: Immobilization of the Porta-Puck shooting machine with lumber

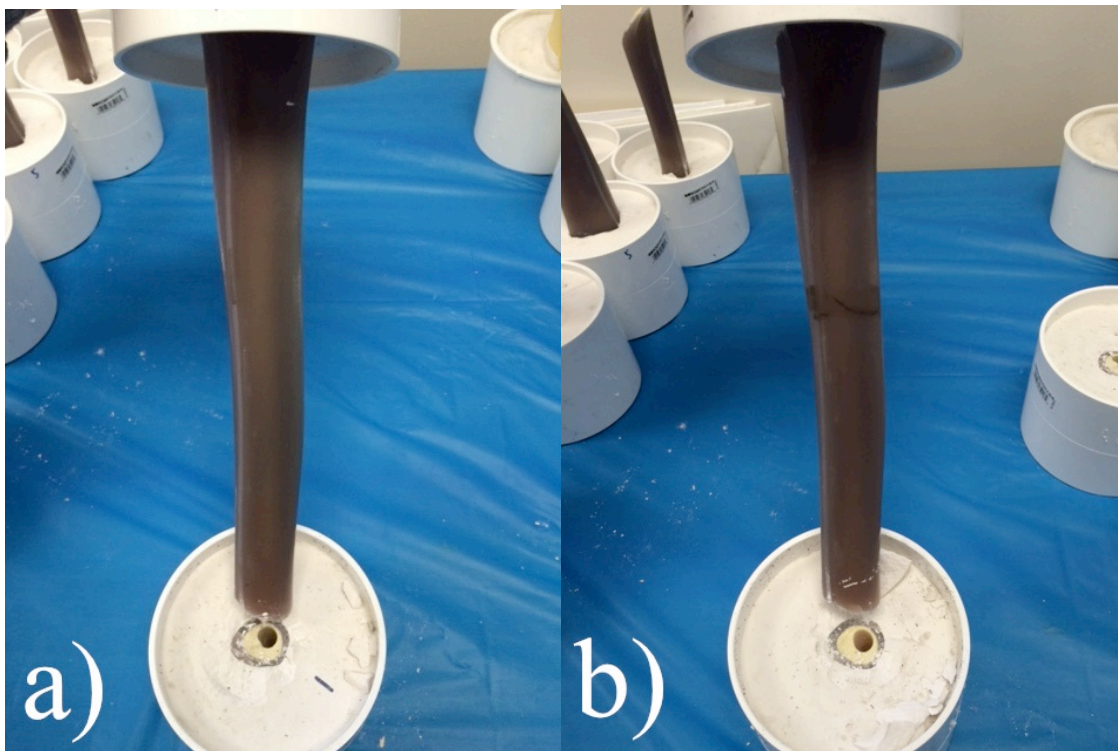


Figure 18: Fracture of the specimens a) Bone 1 and b) Bone 2 after immobilization of Porta-Puck shooting machine

Measurements of the bone specimens at the fracture site were taken using a digital caliper. The measurements include the width across the medial surface (Width), the thickness from the medial surface to the lateral surface (Thickness). Similar measurements of the inner foam core were taken across the center of the 9 mm canal. The locations of the measurements are indicated in figure 19 and figure 20. The measurements are presented in table 7.

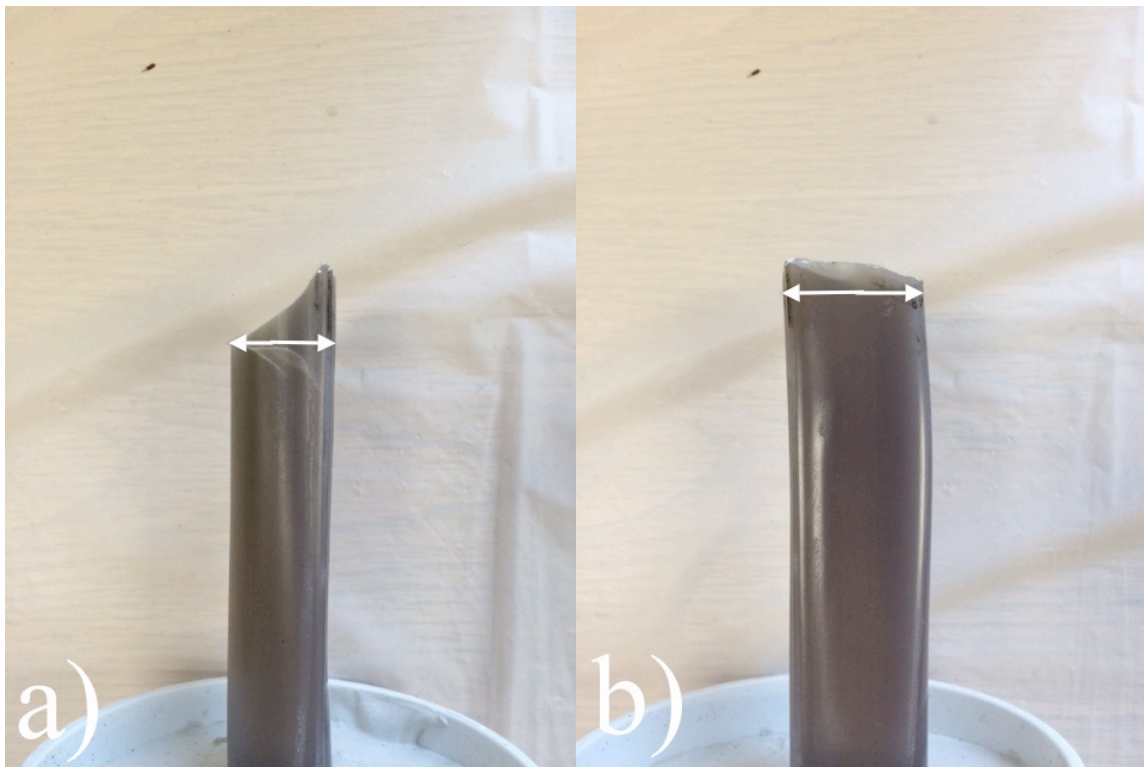


Figure 19: The measure of the a) outer thickness and b) outer width of the composite bone specimen

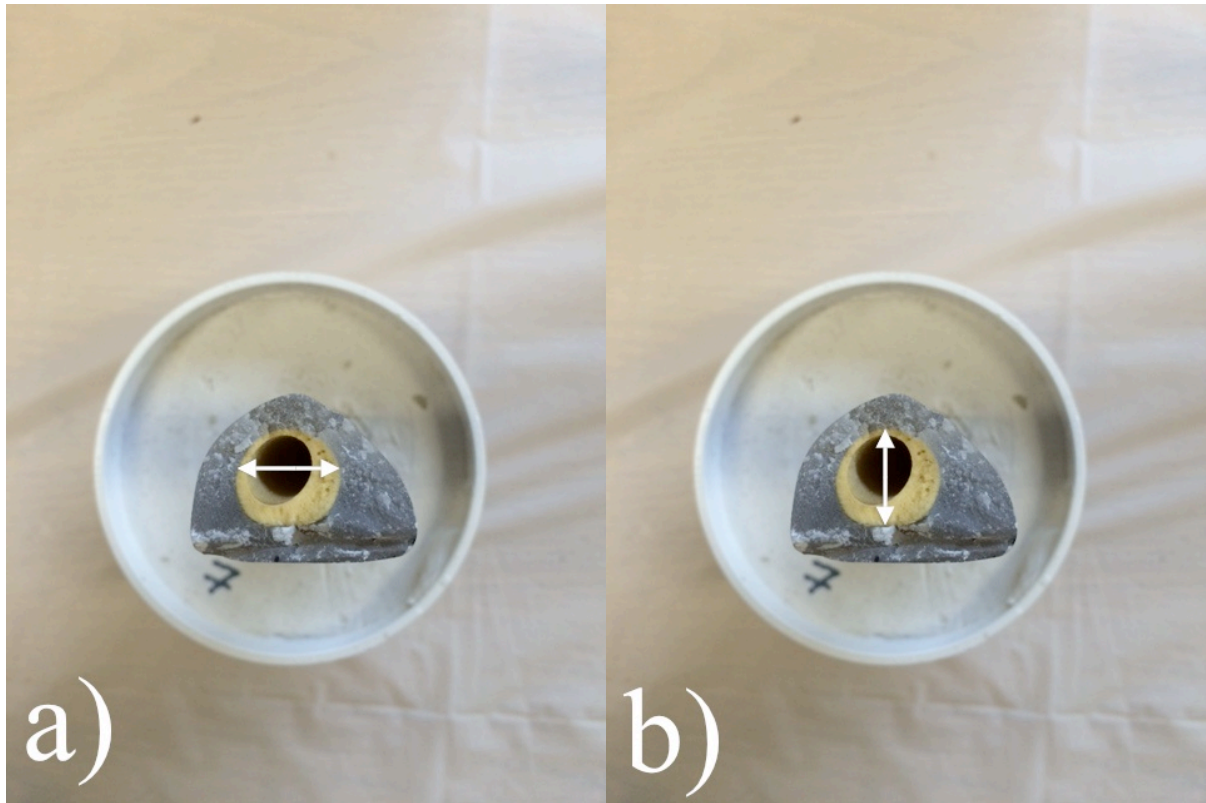


Figure 20: The measure of the a) inner width and b) inner thickness of the foam core

**Table 7: The measurements of the composite bone specimens at the fracture site**

| Bone Specimen      | Outer Thickness (mm) | Outer Width (mm) | Inner Thickness (mm) | Inner Width (mm) |
|--------------------|----------------------|------------------|----------------------|------------------|
| 1                  | 26.2                 | 29.6             | 16.8                 | 18.7             |
| 2                  | 26.8                 | 29.4             | 17.5                 | 18.8             |
| 3                  | 24.6                 | 33.2             | 15.0                 | 15.6             |
| 4                  | 24.5                 | 33.3             | 14.3                 | 16.6             |
| 5                  | 25.1                 | 33.5             | 14.6                 | 15.8             |
| 6                  | 24.6                 | 33.2             | 13.6                 | 16.2             |
| 7                  | 25.0                 | 33.2             | 13.8                 | 15.9             |
| 8                  | 24.9                 | 33.1             | 15.1                 | 15.5             |
| Mean               | 25.2                 | 32.3             | 15.1                 | 16.6             |
| Standard Deviation | 0.8                  | 1.7              | 1.4                  | 1.3              |

## 4.4 High Speed Camera Imaging

As previously mentioned, the FASTCAM MC1 was recording at 3000 frames per second with a resolution of 512 x 352 pixels. The use of the FASTCAM at these settings allowed for the visualization of the fractures caused by hockey puck impact. The frame rate was such that the orientation of the puck just prior to impact could be determined. Screenshots of the puck prior to impact are shown in figure 21. Images of the bone specimens just after fracture are displayed in figure 22. In addition to puck orientation and moment of fracture, the FASTCAM images provide an approximation of impact duration, as well as, a better estimate of which impacts were a direct hit squarely on the medial surface based on the rebound path.

An additional estimate of puck velocity was also obtained from video analysis. Two different references were used to approximate velocity. In session one of impact testing, a meter stick was placed on the flange of the impact frame and in view of the camera. The meter stick was in contact with the bone specimen, which places it approximately below and along the path of the puck. The puck velocity was estimated by the distance along the meter stick the puck travelled in a given amount of frames. The diameter of the pipe of the flange component, which is directly below the path of the puck, was used as an on-screen reference to estimate puck velocity for the second session of testing. Knowing these distances and the frame rate, the velocity is estimated using the distance travelled by the puck relative to the onscreen references and the time to travel the distance. The data from the high-speed video analysis is displayed in table 8.

**Table 8: Impact metrics obtained from the FASTCAM MC1**

| Bone Specimen | Impact # | Impact Duration (s) | Velocity (m/s) Device | Velocity (m/s) Camera | Direct or Indirect Impact |
|---------------|----------|---------------------|-----------------------|-----------------------|---------------------------|
| 1             | 1        | 0.0010              | 22.80*                | 25.00                 | Direct                    |
|               | 2        | 0.0010              | 31.25                 | 28.83                 | Indirect                  |
|               | 3        | 0.0013              | 30.00                 | 29.33                 | Direct                    |
| 2             | 1        | 0.0010              | 26.60                 | 37.50                 | Direct                    |
|               | 2        | 0.0003              | 28.83                 | 29.33                 | Indirect                  |
|               | 3        | 0.0010              | 30.00                 | 28.67                 | Indirect                  |
|               | 4        | 0.0007              | 31.25                 | 30.00                 | Indirect                  |
| 3             | 1        | 0.0010              | 30.76*                | 37.50                 | Indirect                  |
|               | 2        | 0.0003              | 30.00                 | 30.00                 | Direct                    |
| 4             | 1        | 0.0013              | 30.49*                | N/A                   | Direct                    |
| 5             | 1        | N/A                 | 30.67*                | N/A                   | N/A                       |
|               | 2        | 0.0003              | 31.25                 | 30.37                 | Direct                    |
| 6             | 1        | 0.0007              | 28.83                 | 29.99                 | Indirect                  |
|               | 2        | 0.0010              | 30.00                 | 30.00                 | Indirect                  |
|               | 3        | 0.0010              | 31.25                 | 29.26                 | Indirect                  |
|               | 4        | 0.0003              | 28.83                 | 28.89                 | Direct                    |
| 7             | 1        | 0.0007              | 31.25                 | 29.99                 | Indirect                  |
|               | 2        | N/A                 | 31.25                 | N/A                   | N/A                       |
|               | 3        | 0.0010              | 31.25                 | 30.01                 | Direct                    |
| 8             | 1        | 0.0003              | 31.25                 | 30.01                 | Indirect                  |
|               | 2        | 0.0010              | 30.00                 | 29.99                 | Indirect                  |
|               | 3        | 0.0007              | 30.00                 | 25.00                 | Direct                    |

An asterisk indicates an estimated velocity based on other impacts at the same dial setting

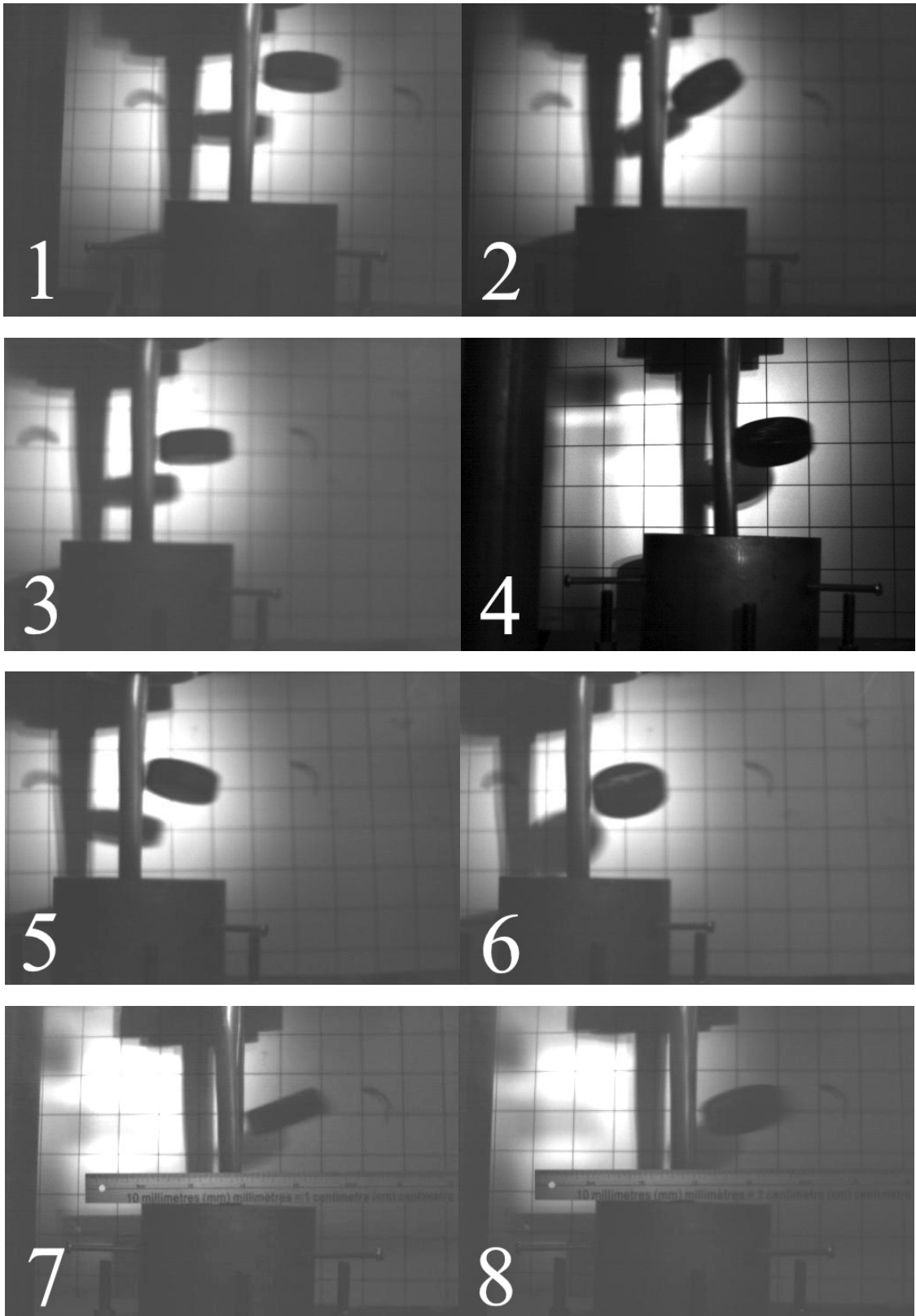


Figure 21: Puck orientation at impact of bone specimens 1 to 8



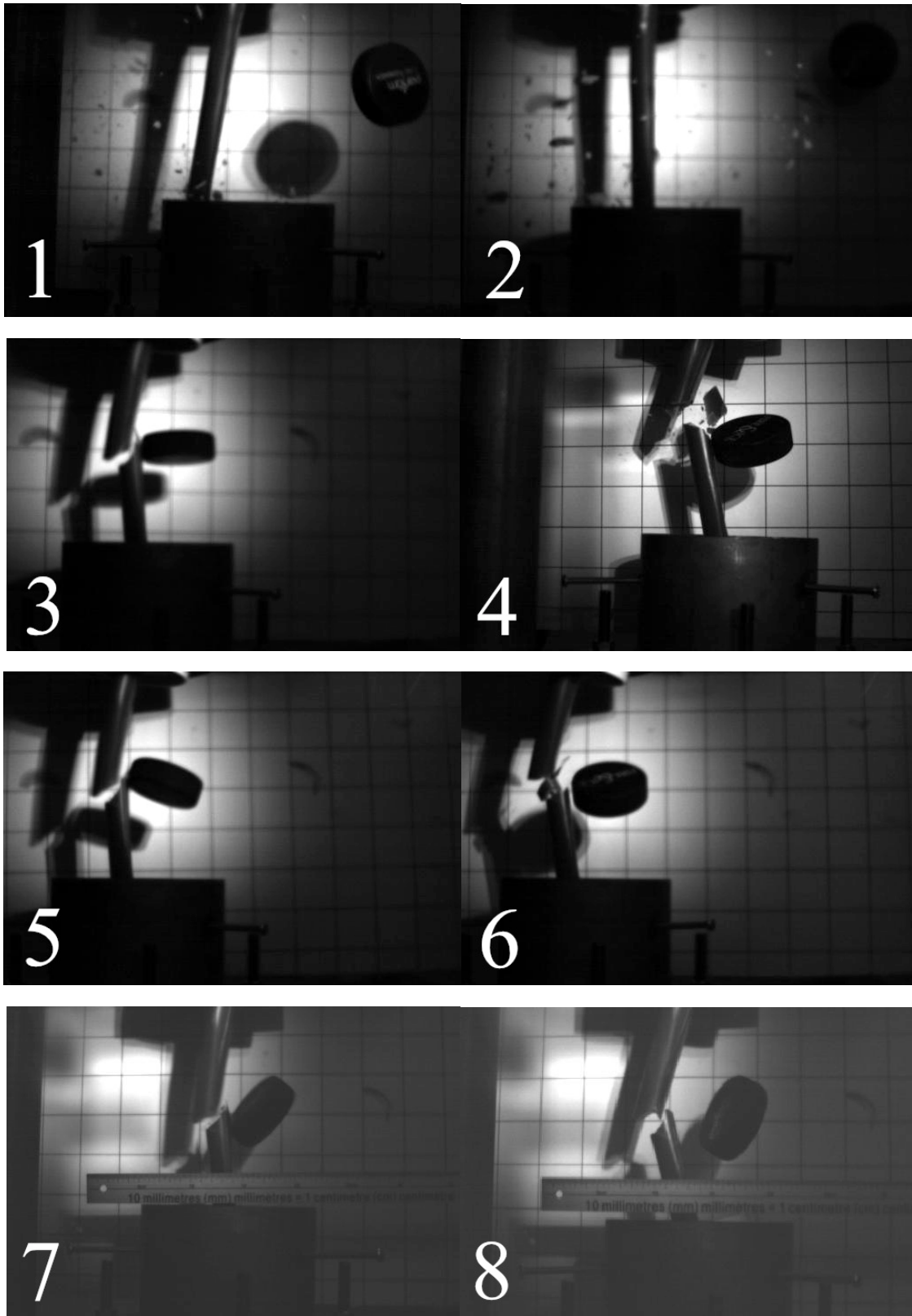


Figure 22: Fracture of bone specimens 1 to 8

# Chapter 5

## Discussion

In the evaluation of the testing setup, each of the components is considered. Firstly, the velocity measurement device appeared to have performed well in terms of operation. The circuit boards held up well and at no time in its use did it lose electrical power. There appeared to be no flaws in the optoelectronics, namely the infrared LEDs and phototransistors. In terms of the results produced with the data obtained with the cDAQ, the measurements looked very promising early on. In the initial testing of the device, the data for the velocity of an object in free-fall were very similar to a calculated value for a given drop height. This data can be seen in Table 2. The error was within 5 percent on average for both drop heights. The slight increase at the greater height could be due to air effects. These tests were performed indoors in a room with no significant airflow other than general building ventilation. However, as previously mentioned the calculated value does not take into account other effects. The increased drop height provides increased time in the air and potential air effects could have more of an influence.

When examining how the data translates to velocity, it is evident that for both heights the velocity is within 1 m/s of the calculated values (Table 3). This tolerance is required for the impact testing of goaltender helmets [21]. Meeting this requirement provided the confidence to proceed with the use of the device for testing.

Using the Porta-Puck to launch pucks through the velocity measurement device revealed the abilities of the shooting machine. It appeared as though the velocity of the puck did not travel at the speed as indicated on the dial of the Porta-Puck at lower settings, which is why it was



important to measure it separately. As seen in Table 4 and Figure 14, the measured velocity did not appear to be close to that of the dial setting until the dial was set in the 20 – 25 m/s range. The Porta-Puck used in this experiment was an older model. It is unknown whether the motors have been maintained throughout its lifetime, as the current ability of the motors could have been a limiting factor. It appeared as though the maximum velocity that this Porta-Puck could attain was around 31.25 m/s. Even when the dial was set at velocities greater than 35.0 m/s the measured velocity was no greater 32.89 m/s. It is possible that the puck may not have been sliding perfectly flat on the bottom surface of the exit port as it travelled through it. Just prior to impact the orientation of the puck was not always perfectly flat, which suggests that motion in the exit port could be a possibility (Figure 21). However, there does not seem to be a considerable difference in the velocity of the impacts where the puck orientation was at an angle compared to those where the puck was travelling flat. It may be more beneficial to make use of a puck accelerator that has the capabilities to consistently propel the puck in a flat orientation.

The puck shooting session with a radar gun was another indication of the performance of the velocity measurement device. In this session the sampling rate of the cDAQ was increased to 5kHz. It can be seen that the measurements are closer at some dial settings than at others (Figure 14). The greatest difference seen between the two measurements was 3.82 m/s at a dial setting of 26.82 m/s (60.00 mph). The differences in the measurements between the device and the radar gun could be attributed to their operating mechanism. As previously described, the custom built device determines velocity by recording the time at which there is a change in voltage as an object blocks the infrared beams of light directed at the phototransistors. The radar gun operates on the Doppler effect and senses signal frequencies between the gun and a moving object. The accuracy of the radar gun is influenced by the position of the operator of the gun [38]. If the

operator of the gun is not directly inline with the path of the moving object then an artifact known as the Cosine effect can influence the results [38]. It appeared as though the operator of the radar gun was aligned with the puck fairly well during this session. Another influence on the results could be the distance over which the measurements are taken. The velocity measurement device was placed 8 cm away from the exit port and was detecting the motion of the puck over the first 33 cm of travel. It is not known exactly over which distance that the radar gun may have been detecting the motion of the puck. It is possible that neither the device nor the radar gun is perfectly accurate. However, given the potential sources of the discrepancies and the magnitude of the differences in measurements, it is considered by the author that the results obtained with custom-built measurement device are sufficient to use for this thesis.

Issues arose in the first session of impact testing. The SignalExpress software malfunctioned during recordings. There were no changes in voltage in the output of all but one test. It was postulated that the laptop computer that was used to interface the SignalExpress software and the cDAQ did not have enough computing or processing power to handle the sampling rate at which it was set at. For the second session of testing, the sampling rate was decreased from 5kHz to 3kHz. Decreasing the sampling rate appeared to have corrected the issue. The robustness of a desktop computer could be beneficial for future testing. Added to these types of complications is the number of channels used in recording. The receiver circuit was built such that measurements were taken at each phototransistor. A new receiver circuit design that can record a voltage change from any one of the phototransistors while using only one channel could be beneficial.

Preliminary testing with a foam bone revealed an unanticipated result. It was overlooked that the foam bone could have fractured in the inferior region (Figure 16). The bone specimens were not placed into the frame in an anatomically correct position. They were placed such that the

medial surface would be as perpendicular to the horizontal as possible. This could affect the ability of an object with this geometry to withstand loading compared to the anatomically correct positioning. As mentioned in another chapter, the compressive load was removed by placing clamps onto the guide posts. The clamps held the loading plate such that the superior end of the specimen was being held in place in the top flange only by the bolts that feed through the wall of the flange. The foam bone is considerably weaker than the composite bone and a fracture at the thinnest section of the foam bone understandable to occur. To add more control to the experiment and keep the variables to a minimum, the clamps were left on the guide posts for the remainder of the tests. An additional test with a foam bone and a composite bone resulted in fractures in bending at mid-shaft.

The preliminary tests determined the spacing and placement of the testing setup components. The distance from the exit port of the Porta-Puck to the medial surface of the test specimens was 75 cm. The velocity measurement device was placed 8 cm from the exit port of the Porta-Puck. This placed the measurement of the velocity within 67 cm, which is just beyond the requirements of a 60 cm spacing of the test subject and the exit of the puck accelerator in the testing of goaltender facial protection [21]. The FASTCAM was placed inline with the bone specimen and 70 cm away. These distances were held constant for the remainder of testing.

The forces at impact were a desired metric in the design phase of this project. Once impact testing had commenced it was observed that the puck did not rebound back through the velocity measurement device. Although it was not possible to estimate impact forces in the x-direction for this experiment, the use of a velocity measurement device capable of detecting motion in the forward and backward directions would have allowed for it. Video analysis of one fracture (Bone 4) showed that after impact the puck appeared to hover in the air and had no rebound motion. If

the rebound velocity in the x-direction in this case is approximated to be zero then the impact force can be approximated using the impact duration, also obtained from video analysis. Calculating this reveals an impact force of approximately 3879 N. However, this is only an approximation of the average of one component of the force.

There appear to be no published data to compare the results obtained in this thesis at this current time. However, there is one publication that had a similar outcome in an impact load study using composite tibia bone specimens [29]. The average kinetic energy of the impacting masses that resulted in fracture were  $61.9 \pm 0.4$  J for a 3.9 kg mass and  $73.8 \pm 9.8$  J for a 6.8 kg mass [29]. Hockey puck impact testing in this thesis revealed average kinetic energy of  $76.39 \pm 4.26$  J for impacts resulting in fracture for a 0.1654 kg mass. This result seems to be similar to that of the larger impact mass in the other study [29]. The sample size used in this thesis was small ( $n = 8$ ). Further testing could reveal how well that average holds up.

A true measure of the effectiveness of this testing setup would include a validation of the data with other studies. Another indication of the suitability and effectiveness of this testing setup is the potential for errors. While there appeared to be no major flaws, there are a few issues and improvements that could be made. One of the difficulties of this setup was the timing of the FASTCAM recording and shooting the puck with the Porta-Puck. The amount of video that can be recorded is determined by the frame rate. For the frame rate used in this experiment (3000 fps) the amount of video that can be recorded is just under two seconds. The FASTCAM has several recording trigger modes. This high-speed camera has a controller unit that is connected to a computer. When the system is on there is always some data captured by the camera that is buffering in the system. Triggering the recording selects the data to keep. The triggering mode used in this experiment records video for two seconds after the trigger is initiated. This was

called the “START” trigger. Other triggering options include the “END” trigger and the “CENTER” trigger. The “END” trigger keeps the video from two seconds before the trigger was initiated. The “CENTER” trigger keeps video from one second before and one second after the trigger was initiated.

The impact was missed in two recordings in this experiment. In another recording there was not enough of the approach of the puck captured on camera to estimate velocity from video analysis. It could be beneficial to try other camera modes in future testing. The “CENTER” mode may be applicable in testing such as this. The trigger could be initiated when the sound of the puck hitting the bone specimen is heard. With the “CENTER” trigger mode the impact would theoretically occur at the midpoint of the video. It may also be possible to use a system that uses an optical trigger to start the recording. An improved high-speed camera system could make use of the puck as an optical trigger to start recording video.

Despite the minor mistimed recordings, high-speed video was a valuable asset in this experiment and is considered by the author to be an essential component to this type of testing. As mentioned in another chapter, the high-speed video can provide insight on several variables. These variables include puck orientation, impact duration, bone specimen deflection, and impact location. The high-speed video was used to estimate puck velocity in this experiment. There are some limitations in using high-speed video for velocity estimation. A reference for distance on-screen should be in the same plane as the path of the puck. Deviations from the plane will lead to less accurate results as the actual distance travelled in a given amount of time could be less or more. A comparison of measured velocity and estimated velocity from video analysis shows some differences (Table 8). Some of the differences could be attributed to the on-screen reference. Another possibility is the low resolution of the camera. Despite the high frame rate

there still appeared to be slight blurring in some of the videos, which is more likely to be due to the low resolution. The blurring made it difficult in some instances to clearly see the edge of the puck. With these artifacts in mind, the velocities obtained from video analysis are considered to be only estimates and the recorded measurements from the measurement device are considered to be a more accurate approximation to the true puck velocity. Use of a camera that captures images in color and high definition could alleviate some of the issues seen in this experiment.

As mentioned in the previous chapter, impacting the bone specimen squarely on the face on the medial surface seemed to be difficult to control. The width of the medial surface at the location of the fractures ranged from 29.4 – 33.5 mm (Table 7). The medial surface of the composite tibia is not perfectly flat. There are some slight curvatures along the shaft on that surface. It had appeared from video analysis that 11 out of 22 impacts were not direct and had glanced off to one side of the bone specimen or the other, which was the main deciding factor as to whether or not the impact was direct. Two impacts were undetermined as to whether or not they had impacted directly or not due to missed recordings. Considering that the puck is a flat round object, the initial point of contact of the medial surface and the edge of the puck is a tangent. If the perpendicular to that tangent does not go through the center of the puck, the puck will more than likely glance off the bone specimen.

The impact duration may also be an indicator of a direct impact. In an indirect impact, the puck is not likely to be in contact with the bone specimen for as long as in a direct impact. The results presented in table 8 show a variation of impact durations for direct and indirect impacts. Three out of five of the shortest impact durations (0.0003 seconds) were classified as direct impacts. The corresponding impact force could have provided more insight on the impulse and whether or not an impact could be classified as direct or indirect.

An effort to reduce the motion of the Porta-Puck, which was thought to influence the impact location, was performed. This effort involved placing lumber under the Porta-Puck so that the wheels under the machine were no longer touching the ground. The exit port was raised as a result of this. Bone specimens #1 and 2 were impacted with this adjusted setup. These bone specimens fractured at the inferior end. Video analysis of these impacts showed hardly any deflection in the specimens upon impact. Shear forces would be higher in the superior end where the puck was now impacting. It can be seen that the other bone specimens fractured in bending at mid-shaft (Figure 22). When the puck was impacting closer to mid-shaft the bone specimens did not fracture at the inferior end suggesting that shear forces in the inferior end were not sufficient to cause fracture even when the loading was closer to that location. It may be possible that the indirect impacts of bone specimens #1 and 2 were causing an increased torque due to being impacted in an area of the shaft that was wider. The rest of the bone specimens had similar fracture characteristics (Figure 23).



Figure 23: Inferior portions of the composite bone specimens after fracture

The supports of the bone specimens within the impact frame fixture may have not have behaved consistently. The bone specimen itself is fixed within the Denstone material inside of a PVC pipe coupling. The PVC pipe coupling, however, is held in place inside of the impact frame with 1/4 inch machine screws that feed through the wall of a larger stainless steel pipe. The machine screws were tightened by hand. After a few impacts during testing the machine screws were beginning to bend. This suggests that they were taking up some of the force of the impact. The screws were straightened and some were replaced when no longer useful. The ends of the machine screws were sharpened to a point with an angle grinder to provide a better grip onto the PVC pipe coupling. This sharpened point appeared to scratch and remove some of the PVC



material when the impacts occurred. Due to the bending of the machine screws there may have been impacts where the PVC pipe coupling was translating within the frame fixture. It is difficult to determine if this was the case or not. There were also cases of the PVC pipe couplings rotating after fracture of the bone specimens (Figure 24). It may be beneficial to have stronger machine screws as well as a stainless steel pipe in the impact frame that is just large enough to fit the PVC coupling inside. The impact frame performed flawlessly, except for the  $\frac{1}{4}$  inch machine screws. A major failure of any of the other elements of the impact frame due to puck impact is not expected should future tests be performed.



Figure 24: Orientation of the PVC pipe couplings after bone specimen fracture

# Chapter 6

## Conclusions

Projectile impact testing can be quite difficult to perform. Several complexities can arise such as monitoring projectile motion and velocity, effectively and accurately propelling projectile objects, and appropriately placing and supporting test subjects to be impacted. The testing setup for the impact of hockey pucks implemented in this thesis revealed the value of the components and equipment required. High-speed video is a highly recommended element for testing of this nature. Care must be taken when considering bone specimen placement, fixture, and support into the impact frame. Additional loading such as axial compression must be adequately accounted for. Anatomically correct support and fixture may not provide desired performance and behavior.

Determining an exact fracture tolerance to hockey puck impact may require an extensive amount of testing. A range of values, which when reached the potential for fracture is a greater possibility, may be more attainable as a short-term goal. Testing in this thesis revealed that for a composite tibia bone specimen, supported and oriented in a frame as outlined earlier, fracture due to hockey puck impact occurred at velocities of 28.83 – 31.25 m/s.

It may be possible to evaluate protective equipment using this type of testing. With this current test setup, the visual inspection of test specimens covered with protective materials and subjected to puck impact can allow for the development of a pass/fail grading of the protective materials. Instrumentation of a test specimen, including, but not limited to bones of the lower leg

or foot, can allow for a measureable and quantifiable variable, such as pressure or force, which better predicts injury potential to be determined.

# Chapter 7

## Recommendations For Future Work

There are several improvements to this testing setup that should be considered for future puck impact testing. The use of a puck accelerator that can propel puck at velocities as seen in game play and that can consistently launch the puck in a flat orientation is recommended. A puck accelerator that has a high accuracy would be beneficial. An upgrade in high-speed imaging is also recommended. Using a high-speed camera that can capture images in color and high definition would help make the puck more visible and allow for a closer investigation of the moment of impact. An upgrade in machine screws on the impact frame fixture to better withstand impact could provide more consistent support behavior. If possible and available, study radiographic images of fractures produced by hockey puck impact to more appropriately design the impact testing to best replicate fractures that transpire in game scenarios and provide repeatability in the laboratory.

Future testing could also include the use of hockey pucks at lower temperatures. The effects of altering the puck shot angle would be of interest in another study. It would also be of interest to compare the velocity to fracture different surfaces and aspects of the tibia. Testing differing orientations of the bone specimens could provide valuable data. The testing of different bones of the lower leg and foot would be desirable. If more composite bone models of these bones are developed in the future they can be tested as well.

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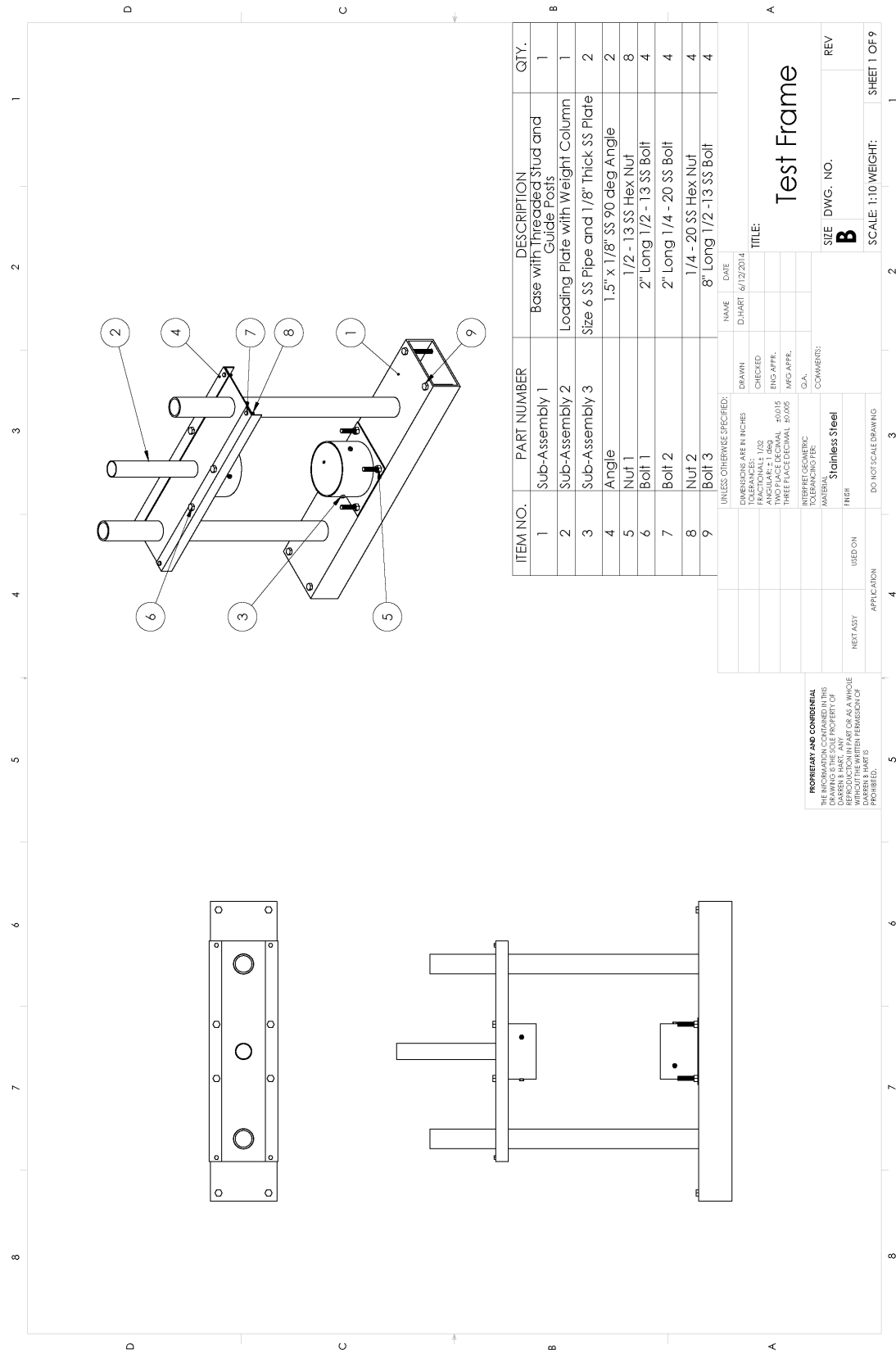
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## Appendix A

### Technical Drawings Of The Impact Frame





| ITEM NO. | PART NUMBER    | DESCRIPTION                             | QTY. |
|----------|----------------|-----------------------------------------|------|
| 1        | Sub-Assembly 1 | Base with Threaded Stud and Guide Posts | 1    |
| 2        | Sub-Assembly 2 | Loading Plate with Weight Column        | 1    |
| 3        | Sub-Assembly 3 | Size 6 SS Pipe and 1/8" Thick SS Plate  | 2    |
| 4        | Angle          | 1.5" x 1/8" SS 90 deg Angle             | 2    |
| 5        | Nut 1          | 1/2 - 13 SS Hex Nut                     | 8    |
| 6        | Bolt 1         | 2" Long 1/2 - 13 SS Bolt                | 4    |
| 7        | Bolt 2         | 2" Long 1/4 - 20 SS Bolt                | 4    |
| 8        | Nut 2          | 1/4 - 20 SS Hex Nut                     | 4    |
| 9        | Bolt 3         | 8" Long 1/2 - 13 SS Bolt                | 4    |

|                                  |  |        |           |
|----------------------------------|--|--------|-----------|
| UNLESS OTHERWISE SPECIFIED:      |  | NAME   | DATE      |
| DIMENSIONS ARE IN INCHES         |  | D.HART | 6/12/2014 |
| TOLERANCES:                      |  | DRAWN  | CHECKED   |
| FRACTIONAL: 1/32                 |  |        |           |
| DECIMAL: .005                    |  |        |           |
| TWO PLACE DECIMAL: ±0.015        |  |        |           |
| THREE PLACE DECIMAL: ±0.005      |  |        |           |
| INTERFEROMETRIC TOLERANCING PER: |  |        |           |
| MATERIAL:                        |  |        |           |
| FINISH:                          |  |        |           |
| DO NOT SCALE DRAWING             |  |        |           |

|            |  |      |          |     |
|------------|--|------|----------|-----|
| TITLE:     |  | SIZE | DWG. NO. | REV |
| Test Frame |  | B    |          |     |

|                     |  |              |  |
|---------------------|--|--------------|--|
| SCALE: 1:10 WEIGHT: |  | SHEET 1 OF 9 |  |
|---------------------|--|--------------|--|

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