SNOW SPORT HEAD INJURY: CHARACTERIZATION OF CLINICAL PRESENTATION AND DESIGN OF A RELEVANT HEAD IMPACT APPARATUS

by

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Abstract

With head injury being the leading cause of death from skiing and snowboarding in North America, a better understanding of the mechanisms at play and improved preventative measures are necessary. Safety certification standards exist for snow sport helmets in an effort to evaluate potential technologies as well as ensure helmets offer protection to the user. However, current protocols are seen to be oversimplifications of real world head impacts, particularly from skiing and snowboarding. The purpose of this work is to mechanistically characterize snow sport head injury and design a test apparatus capable of representing these real world head impact scenarios.

In an effort to characterize the fall mechanisms and injuries of snow sport head impact, a clinical investigation was performed. A 6 year retrospective clinical case review yielded a database of 760+ incidents for which basic demographic information, gross mechanism detail, nature and severity of injuries sustained and helmet use data was collected. In addition to epidemiological insight, the database highlighted the need for a revised standard testing protocol through observation of several general fall scenarios, a high prevalence of concussion (considered a low-energy injury) and the majority of impacts occurring to snow or ice surfaces.

This information, in conjunction with existing biomechanics literature, informed the design of a helmet testing apparatus capable of recreating snow sport head impact mechanisms. Through a formal design process involving stakeholder discovery, development of design requirements, concept generation and evaluation, and detailed design, a final apparatus was decided upon and fabricated. To investigate if the test apparatus was capable of satisfying the requirements set forth, namely impact velocity and repeatability, verification testing was performed. Recommendations are made for conditions that remained either partially met or unmet.

To address the need for an improved understanding of snow sport head injury mechanisms in the context of helmet testing, clinical data and existing literature was used. As a result, a test apparatus capable of more representative impact testing protocols was developed. Aspects of this work can be adopted by the head injury research and helmet standards communities in order to improve design and evaluation of preventative equipment.

Preface

This thesis was written entirely by the author, Cameron Stuart. Dr. Peter Cripton guided the development of the clinical study methodologies, acted as a consultant for the design portion of this work and revised this thesis. The clinical study methodology and data collection was also guided by Dr. Jeff Brubacher. Data collection for the clinical study was conducted by the author, Cameron Stuart, as well as Lawrence Yau and Ryan Yip. Clinical study data analysis and all aspects of the design, fabrication and testing of the test apparatus was performed by Cameron Stuart.

Study methodology outlined in Chapter 2 was reviewed and approved by the UBC Clinical Research Ethics Board under study # V14-03449. A version of the data presented in Chapter 2 has been submitted to the a peer reviewed journal for consideration for publication.

A portion of Chapter 4 has been submitted to an international conference for consideration to be published in the conference proceedings.

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List of Abbreviations

AIS	Abbreviated Injury Scale
COG	Center of Gravity
CSF	Cerebrospinal Fluid
DAQ	Data Acquisition System
HIC	Head Injury Criterion
HIII	Hybrid III (headform)
LGH	Lions Gate Hospital
MAIS	Maximum Abbreviated Injury Score
mTBI	Mild Traumatic Brain Injury
TBI	Traumatic Brain Injury
VGH	Vancouver General Hospital

Acknowledgements

As I am sure many students before me have experienced, graduate studies are an opportunity for self-exploration. Through this, support networks become extremely apparent and the realization of how far these stretch is very humbling.

First, I cannot thank my family enough for their continued encouragement. No matter how hectic life is, a family dinner to help forget the week's challenges always seems to remedy the mind. Even if explaining my thesis work puts you to sleep, I will always value the unique support you always offer.

Meg, you represent so many things in my life. I admire your intellect and appreciate that you are always willing to consult with me, even for the simplest of problems. You push me to make the most out of every situation and are always the one to encourage life balance when I get too intense. Thank you for helping me machine parts, cooking me dinner and listening when I need to tell you how much I hate soldering.

Peter, it has been an absolute pleasure working alongside you over the years. You have mentored me in so many respects and have always provided opportunity whenever you are able. I am lucky to have had you as my supervisor as I truly felt this project was one we accomplished together.

I am very lucky to be surrounded with brilliant individuals within the lab group as well as outside. As my clinical supervisor, Jeff Brubacher's expertise and modesty were invaluable; from shadowing in the ED on Halloween to paper edits while on vacation. The technical consult of Darrin Richards and Tom Whyte brought a well-rounded approach to this work as well as an enthusiasm that never waned.

The OIBG lab group is a fantastic collection of individuals who can offer both technical expertise as well as many laughs over lunch; I will miss our podcast style breaks. Kurt McInnes in particular was always available to consult and helped a great deal in the fabrication phase of this work.

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There are many other people who have helped me along the way and I offer my sincere thanks for your influence. This work would not have been possible without these support networks and I have been very fortunate to benefit from their expertise and friendship.

Dedication

~To Jan and Gav~

For standing by my every decision;

informed or not.

1.0 INTRODUCTION

1.1 Motivation

Sport-related head injuries have become a significant problem around the world with considerable short and long term effect to the individual and the healthcare system. With national databases seen to grossly underestimate the scale of traumatic brain injury (TBI) from sport, generally due to unreported injury or inclusion of only the most severe (categorized by loss of consciousness), epidemiologists are left to informed prediction.(1) In fact, injuries involving loss of consciousness are estimated to only account for 8% to 19% of sport-related head injury, meaning approximately 1.6 million to 3.8 million athletes suffer these injuries every year in the United States alone.(1–3) Depending on the sport, the severity of the head injury can vary, with concussion being most prevalent in sports such as American football, soccer and rugby and more severe injury risk in equestrian and pedal cycling.(4–18) Although dependent on the sport, head injury has been observed to account for up to 50% of all sport injuries.(19)

In North America, skiing and snowboarding are popular winter activities with 650 resorts recording over 75.9 million visits each year. (20) Head injury in these sports has proved slightly less prevalent than in other sports but still represents 9% to 47% of all reported injuries.(21–29) Like many other sports, snow sport helmets have been adopted to protect users against head injuries. However, literature available on helmet effectiveness for snow sports is mixed, with several studies finding little to no benefit.(30–33) Additionally, few studies exist that examine the mechanics of how snow sport participants are injured and how that may affect injury outcome (34–36)

The focus of this introduction is to familiarize the reader with the relevant anatomy and biomechanics of head injury as well as give a brief introduction to helmet testing. The following chapters further elaborate on the specific background for that section as well as detail the clinical, design and verification aspects to this work.

1.2 Biomechanics of Head Injury

Concussion, often referred to as mild traumatic brain injury (mTBI)[1], is derived from the Latin *concutere*, meaning to shake violently. Such injuries generally result from an impact occurring during a fall, a sport-related incident, or a motor vehicle accident, but can also be caused by a

[1] It is contested whether concussion is synonymous with mTBI but for the purposes of this report, it will be considered to be.

blast accident where the head interacts with a pressure wave. In the United States, 1.5 million people are reported to experience a traumatic brain injury each year, with approximately 75% of those classified as mild (37). In addition to the negative impact on the quality of life of individuals, TBI has been estimated to cost the US healthcare system $17 billion each year (37).

Although mTBI is a common research topic, consensus has yet to be reached on formal criteria for diagnosis and classification. The American Association of Neurological Surgeons defines a concussion to be “a clinical syndrome characterized by immediate and transient alteration in brain function, including alteration of mental status and level of consciousness, resulting from mechanical force or trauma”(38). However, several other international working groups and associations have defined mTBI differently, making epidemiological investigation difficult (39). Causing such discrepancies is the variability in clinical presentation, leading some definitions to incorporate language which suggests possible mechanisms. One such definition is “a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces” (40).

Similar to the definition of mTBI, consensus on a specific mechanism of concussion has yet to be achieved. However, researchers seem to agree that no single mechanism is responsible for all mTBI injuries. Coup/contre-coup, skull flexure and relative rotation of the brain inside the skull are three popular theories of the cause of such injury. Head injuries due to an explosive blast are also of significant concern to those in the military. In understanding how the brain is injured, innovators have developed ways of attenuating injurious forces and with such a high prevalence of mTBI, it remains a common focus of current research and development. The objective of this section is to describe the current understanding of these mechanisms, discuss the implications this has had on preventative measures being taken and to identify the direction of future work.

1.2.1 Relevant Anatomy

As the name suggests, TBI is an injury to the brain, but several specific structures can be further defined to gain a better understanding of the mechanisms of injury. The outermost layers of the human head include a layer of skin containing hair follicles and sebaceous glands (exocrine glands which secrete an oily substance), followed by a highly vascularized subcutaneous layer made up of fat and connective tissue. Next, thin layers of epicranial aponeurosis, areolar connective tissue and periosteum (or pericranium) provide separation from the previous layers of the scalp and provide nutrition to the underlying skull. An illustration of these layers can be seen in Figure 1. Although quite thin, these structures (in addition to hair) offer a small amount of cushioning in the event of an impact (41).

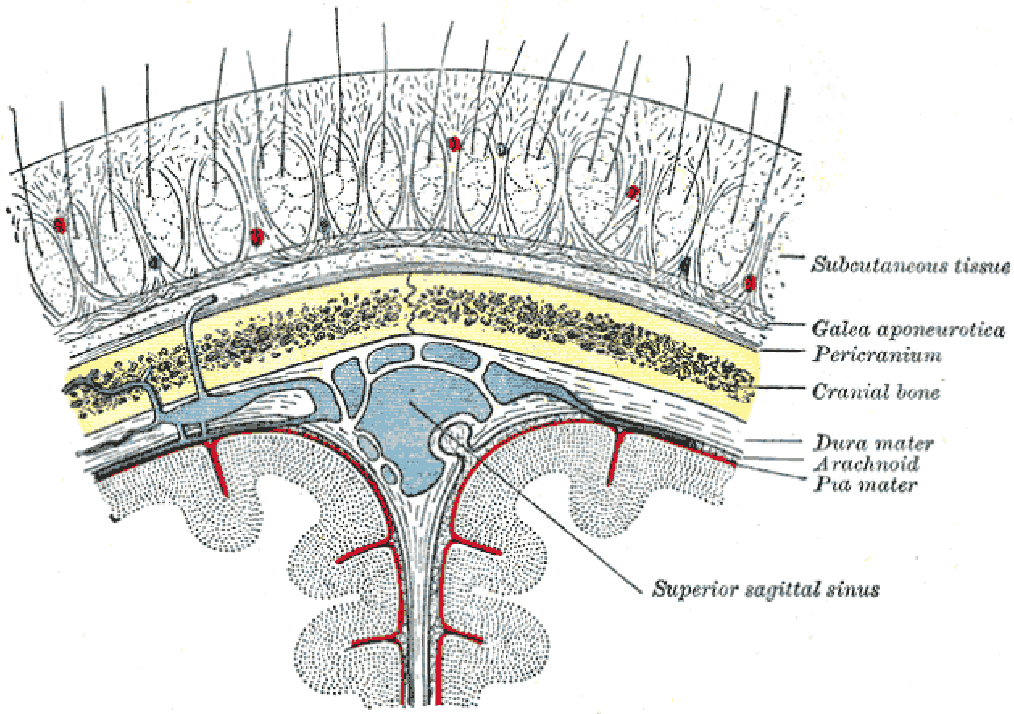


Figure 1: Cross Section of the outermost layers of the human head (source: Gray's Anatomy - 20th US ed.)

The human skull is made up of several bones which are generally subdivided into neurocranium and viscerocranium (or splanchnocranium) by their embryological origins. The neurocranium can be described in layman's terms as the collection of bony structures which encase the brain as well as the brainstem and include the frontal, parietal, occipital, temporal, sphenoid and ethmoid bones. The more superior of these structures are also known as the calvaria, or skullcap. This region is important as the bone structure is made up of two plate-like layers (known as the external and internal tables) and an internal spongy layer (known as diploe) which contains red bone marrow. Of particular note is the foramen magnum (Latin for 'great hole') which is a large opening in the occipital bone that allows passage of the spinal cord: an extension of the medulla oblongata (41). The 14 bones supporting the face are generally categorized as the viscerocranium. Interfaces of bone, called sutures, define all joints of skull bones with the exception of the mandible. Figure 2 illustrates a cross section of the human skull and highlights several of the main bones. These rigid structures provide a significant amount of protection to the brain as well as house and facilitate function of several structures of sensory systems such as the auditory, gustatory, olfactory and visual (41).

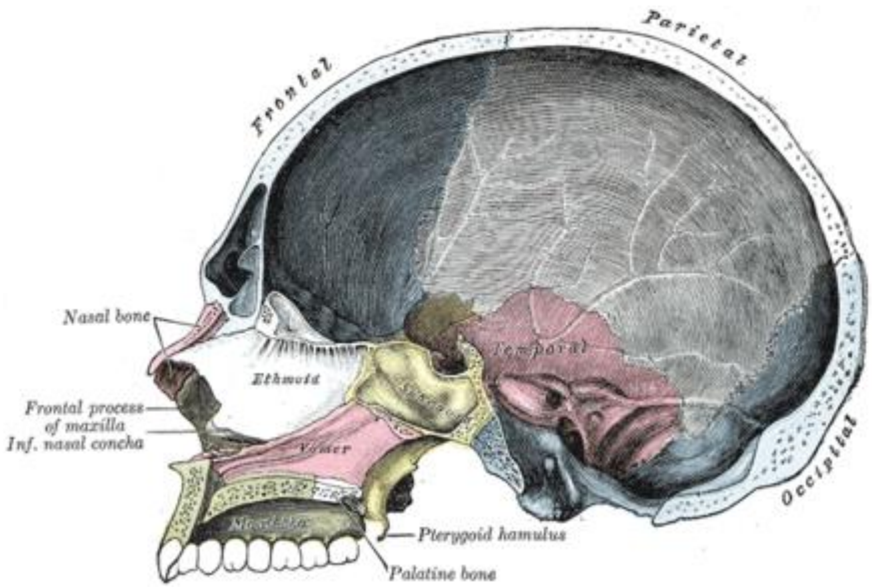


Figure 2: Sagittal section of the human skull (source: Gray's Anatomy - 20th US ed.)

Within the skull and surrounding the brain and spinal cord are three layers of tissue known as the meninges. Dura mater is the tough, outermost layer, which consists of a periosteal layer attached to the inner skull and a meningeal layer which interfaces with the arachnoid mater. Arachnoid mater is the delicate middle layer which is avascular and has small processes which extend inward to become continuous with a third layer: the pia mater. The pia mater is a delicate layer which tightly envelopes the surface of the brain tissue, following its fissures and contours. Of particular significance to head trauma are the extradural and subarachnoid spaces. The extradural space is a potential space and lies between the inner cranial bone and the periosteal membrane of the dura mater. In the event of head trauma, this space often fills with blood (41). The subarachnoid space is filled with cerebrospinal fluid (CSF) as well as blood vessels and lies between the arachnoid and pia layers (41). The CSF is of particular significance as it suspends the brain, preventing compression of cranial nerve roots and blood vessels, and acts as a damper for impact protection (42). Figure 1 illustrates these layers and their location.

The brain itself is made up of several regions including the cerebrum (right and left hemispheres), diencephalon (epithalamus, dorsal thalamus, and hypothalamus), cerebellum, midbrain, pons and medulla oblongata, which each serve a different function. The cerebrum is further divided into lobes known as frontal, parietal, temporal and occipital. Figure 3 illustrates the major anatomy of the brain as well as the regions of the cerebrum. The midbrain and cerebellum are important structures in understanding mTBI as these regions control alertness and responsiveness. As is common in concussion-type injuries, the injured person may experience loss of consciousness as well as suffer from post-traumatic amnesia, which suggests damage to these structures (39).

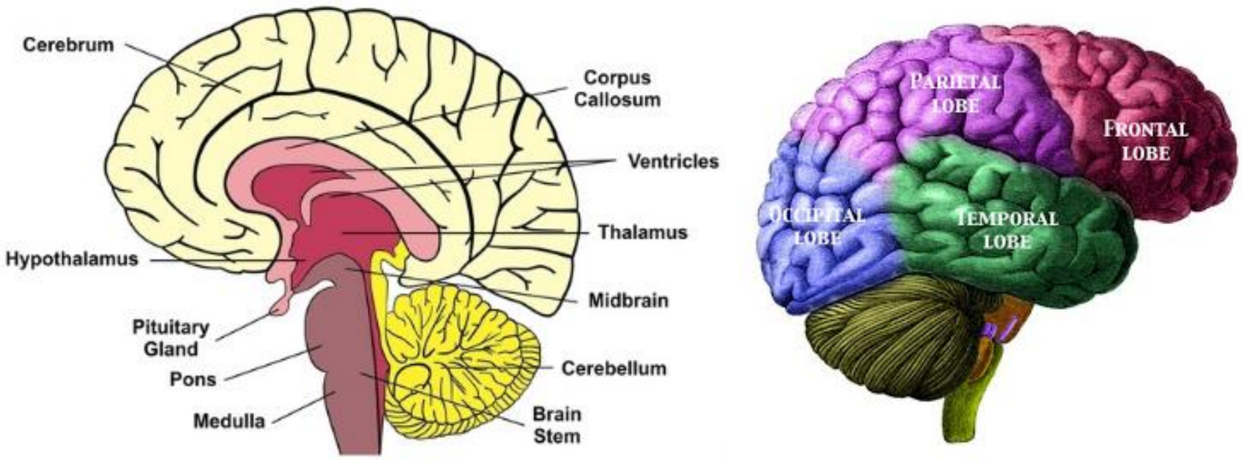


Figure 3: Cross section illustrating the anatomy of the brain (left) and regional map (right) (Source: Left - http://www.livescience.com/ and Right - http://adhd-treatment-options.blogspot.ca/)

Examining brain tissue on a cellular level reveals the building blocks of signal transmission: neurons. The human brain contains approximately 100 billion neurons with about 15% of those found in the cerebral cortex and about 70% found in the cerebellum (43). Similar to most cells, neurons contain a nucleus, a membrane, mitochondria, ribosomes and other typical structures; however, its distinguishing morphologic characteristic is its long shape. Some neuron specific structures include dendrites, an axon, myelin sheath, nodes of Ranvier and presynaptic terminals. The finger-like projections on either end of the structure (presynaptic terminals and dendrites) act as the interfaces between two neurons and facilitate transmission of the electro-chemical signal. The long axon connecting the cell body (soma) and synaptic terminals is encased in an insulating material called myelin sheath. The stimulus is transferred down the axon by way of an action potential (a propagating electrical impulse controlled by voltage-gated ion channels). As these structures allow for the transfer of information (both motor and sensory), damage can be catastrophic to basic function (43).

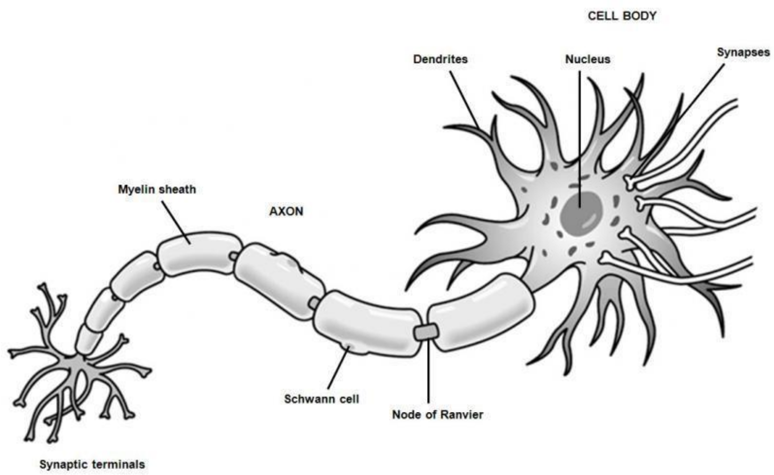


Figure 4: Diagram illustrating the basic structure of a neuron. (Source: www.brainhq.com)

1.2.2 Types of Injury

Although several potential injuries exist involving the associated anatomy of the head and face, certain mechanisms are more relevant to snow sports. For several of these injury types, biomechanical thresholds have been established to understand the severity of impacts as well as informing design of protective equipment.

1.2.2.1 General Types

Although each injury involves specific characteristics to consider in diagnosis, the nature of high energy trauma often involves multiple different injuries.

1.2.2.1.1 Skull Fracture

Skull fracture injuries are generally characterized by a moderate to high energy, focal, blunt force to the head. Due to the skull's spherical nature and rigidity, impact energy is often focused on a small area, increasing the risk of fracture. Given the high energy nature of snow sports in combination with the potential for head impact with hard surfaces, fracture of the skull is possible. These surfaces may include ice, tree's, sport equipment, other participants etc.

Through experimental testing (both cadaveric and anthropomorphic test devices (ATD's)) as well as finite element analysis, skull fracture thresholds have been investigated. One of the most widely accepted injury threshold investigations, known as the Wayne State tolerance curve, defines Injury Assessment Reference Values (IARVs) for various injury types.(44) With peak linear acceleration as the metric, the IARV for a 5% risk of suffering a skull fracture is 180 g's.(44)

1.2.2.1.2 Vascular and Intracranial Injuries

Although vascular intracranial injuries are sometimes associated with mTBI described in detail in section 1.2.2.2 below), they can also occur independently. These types of injuries are generally quite serious as damage to the brain's blood supply or sinuses may result in life threating consequences. Vascular and intracranial injuries can include laceration, thrombosis and traumatic aneurysm of arteries, veins and sinuses. Laceration is generally caused by high energy blunt trauma or interaction with other structures.

Trauma to the head can also result in intracranial hemorrhage and is generally categorized to be a cerebral hemorrhage (within the brain) or extra-cerebral (outside of the brain but within the skull). Extra-cerebral hemorrhage is further broken down into epidural (between the dura mater and the skull), subdural (between the dura and the arachnoid mater) and subarachnoid (between the arachnoid and pia mater). These injuries are generally characterized by tearing, laceration or aneurysm of the surrounding vasculature.

1.2.2.1.3 Facial Injury

Injuries to the face and its structures are quite common, particularly in activities involving forward travel which leave the individual susceptible to face/head first impact. Facial fracture often occurs to the nose, orbits, mandible, maxilla and teeth. One particular type of skeletal injury, categorized as a LeFort fracture, is defined through three levels of severity. LeFort I involves horizontal maxillary fracture, LeFort II involves pyramidal fracture and LeFort III is characterized by craniofacial dysjunction.(45) Nerve and vessel injuries can also occur and are generally caused by blunt force or interaction with sharp objects. Eye injuries are generally associated with abrasion/laceration to the outermost structures (ie. cornea, iris) or from blunt trauma causing conjunctival hemorrhage or periorbital hematoma. Dislodged or fractured teeth are also often a result of blunt trauma.

1.2.2.1.4 Superficial and Other Minor Injuries

Superficial injuries are those that occur on or to the outermost surface of the head and can include lacerations, abrasions and contusions. Lacerations are characterised by tearing or cutting of the skin while abrasions are typically involve wearing away or scraping of the skin. These injury types can be caused by interaction with sports equipment (ie. edge), the environment (ie. trees) or a frictional surface (ie. snow/ice). A contusion involves the rupture of capillaries in the skin or underlying tissue, resulting in discoloration, and is usually caused by a mild, blunt force (ie. low energy fall). Soft tissue strains and sprains are another example of a minor injury and are characterised by various grades of tearing of the fibres that make up the tissue. Although less common in the head and face, these types of injury can be caused by abrupt and unexpected movements that elongate these tissues beyond their tensile limits.

As these injuries, in the context of the head and face, are generally of low severity and the mechanism can vary, specific injury thresholds have not been developed.

1.2.2.2 Mild Traumatic Brain Injury

To understand the mechanics of mild traumatic brain injury (mTBI), one must first understand that the overarching mechanism of the injury is a force imparted on the brain which transfers kinetic energy almost instantaneously (46). Such a force can take two possible forms: contact and inertial. While both of these can occur when the head is struck by (or strikes) a surface, inertial forces can only occur independently when the head experiences impulsive motions without being struck (47). Focal and diffuse brain injuries are the result of these forces with the severity and nature depending on the magnitude and specific brain dynamics. In general, several factors influence the injury outcome such as size, shape and geometry of the skull, density and mass of neural tissue, thickness of the scalp and skull, and impulse direction and magnitude (46). The following sections identify the current understanding of the mechanisms of mTBI. It should be noted that although this section focuses on the mechanical responses, brain injury cannot be characterised without also considering cognitive and pathological responses.

1.2.2.2.1 Shearing of the Brain

One mechanism that has become increasingly popular in concussion research involves a rotational impulse experienced by the brain, resulting in tissue damage due to shearing. As the brain is suspended in cerebrospinal fluid, it has the ability to move relative to the skull. In a potentially injurious event (ie. impact), the force vector may be transmitted through an axis that is eccentric to the center of gravity of the brain. If this occurs, the impulse causes rotation of the brain within the skull as well as impact with the internal surface of the skull (see coup/contre-coup below). Given the physical properties of the human brain, its tissue deforms more readily in response to shear forces (47).

Diffuse axonal injury (DAI), which is a widespread, multifocal stretching and shearing of the brain's axons, has been identified as a result of this relative motion and can present clinically with varying severities (48). DAI injuries are common in motor vehicle accidents where the occupant experiences a sudden change in the head's inertial forces, even in the absence of impact (49,50). In addition to the cerebral white mater, the brain stem (considered to include the medulla oblongata, pons and midbrain) can also be injured by rotational acceleration. As the foramen magnum provides passage to the spinal cord, which is an extension of the medulla oblongata, through the occipital bone of the skull, a significant shear force is applied to the structures of the brainstem when rotation is experienced (39,51). On the cellular level, the axons are susceptible to damage due to the nature of their long, fragile structure. When loaded in shear and tension, the axons can be twisted and torn, eventually leading to cell death (46). Figure 5 illustrates these responses on both macro and micro scales.

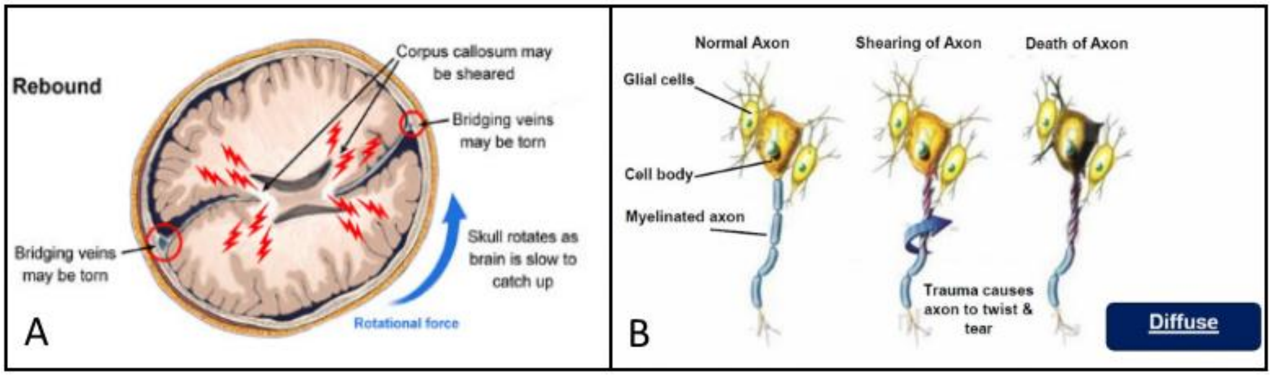


Figure 5: Injury cause by rotational acceleration of the brain. A) Mechanism and resulting deformation. B) Neuronal damage caused by the shearing force induced by rotation (Source: A - http://www.medicalexhibits.com/ B - http://studydroid.com/)

As discussed in the anatomy section above, loss of consciousness has been predicted to be a result of injury to the midbrain and cerebellum. Furthermore, it has been observed that rotational acceleration of the brain correlates to loss of consciousness when compared to purely linear acceleration (52).

1.2.2.2.2 Coup/Contre-Coup

One of the long-standing and still relevant explanations of the mechanics of mTBI is the concept of the brain impacting the inner surface of the skull in coup and contre-coup interaction. As a result of an imposed linear or rotational impulse, the brain has a tendency to move within the skull. If the impulse is of sufficient magnitude, the brain can impact the inner skull; this is denoted as the primary, or 'coup', injury.(52,53) The elastic nature of brain tissue in combination with the pressure gradient of cerebrospinal fluid induced by the initial impact can cause a rebound, resulting in a secondary impact with the inner skull directly opposite to the initial impact: the contre-coup injury. Figure 6 illustrates this response. Cerebral contusions, when the pia is stripped or torn from the surface of the brain, are a result of these interactions. They present clinically as lesions or hematomas and can have further implications such as increased intracranial pressure (54). Subdural hematomas are the most common result of this injury type and can be a consequence of damage to cortical veins and arteries, large-contusion bleeding, and tearing of bridging veins between the brain's tissue and Dural sinuses.(55)

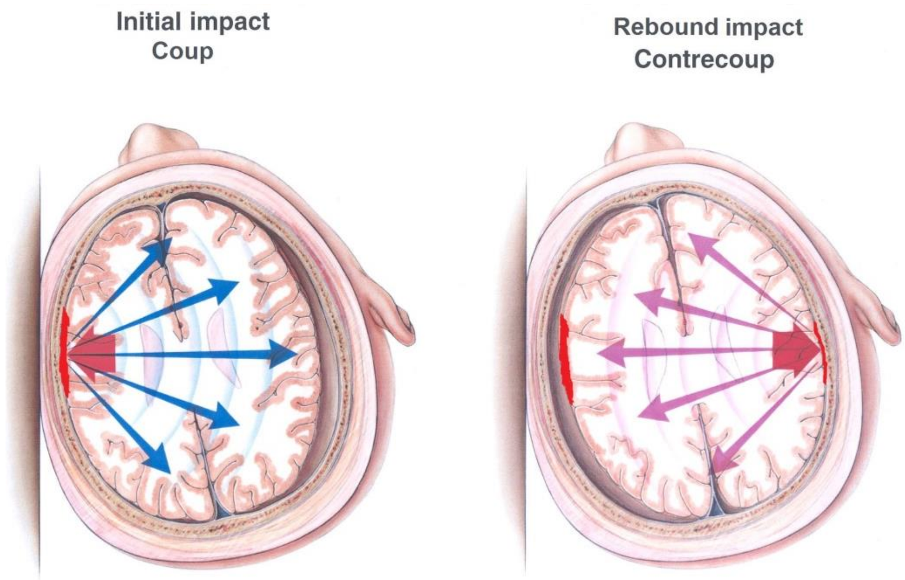


Figure 6: Illustration of a coup/contre-coup type brain injury cause by primary and secondary (rebound) brain impacts. The red indicates areas of cerebral contusion. The arrows represent how the force of the focal impact is dispersed through the whole brain (Source: www.allaboutconcussion.info/concussion)

Previous research on the coup/contre-coup mechanism has focused on characterisation and determination of specific incidents which may lead to both or only coup injuries occurring. It has been observed that coup/contre-coup injuries generally transpire when a moving head contacts an unyielding surface and occurs predominantly in temporal and frontal regions (56). In the case when a blunt force is applied to a resting yet movable head, a coup injury at the point of impact (rarely paired with a contre-coup) is the result (56). It is rare that coup or contre-coup injuries occur solely from rapid deceleration of the moving head through forces in the neck or due to interaction with an airbag (56). It has also been observed that contre-coup cerebral contusions are generally more clinically severe than coup contusions (57).

1.2.2.2.3 Skull Fracture and Flexure

Trauma to the skull is the result of impact with a surface or object, and as such, usually results in contact injuries. When the impact energy is high enough, bone of the skull can flex or fracture, causing focal injury to the brain at the point of deformation. This focal injury often presents clinically as intracranial lesions or hemorrhaging, typically in the epidural space, which may cascade to an increase in intracranial pressure (47,54). Epidural bleeding is generally associated with trauma to the skull and underlying meningeal vessels but may present occasionally in the absence of fracture (55). In some cases, bone stresses can propagate through the skull (ie. the smooth, elastic cranial vault) and present as fracture at a location different than the point of impact such as the irregularly, rigid base of the skull (47,58). Although these types of injury are generally associated with more severe brain injury, mTBI can also occur. Radiological investigation has observed the probability of intracranial lesion, an indication of mTBI, to increase five times with presentation of skull fracture (59). Cerebral lacerations can also result from skull fracture, presenting as ruptured blood vessels and bleeding into the brain and subarachnoid space (54). These injuries are often the result of a fall from considerable height (56).

As skull fracture is relatively easy to recreate in a laboratory setting, biomechanics research has been able to investigate thresholds for such an injury. In one investigation, cadaveric skulls were dropped to develop an understanding of the probability of skull fracture in the adult population (44). Known as the Wayne State Tolerance Curve, this study employed commonly used biomechanical metrics such as the Head Injury Criterion (HIC) and resultant peak acceleration to create curves for the probability of skull fracture (44). As an example, these curves identify a resultant peak acceleration of 180 Gravities[2], or a HIC of 700, to correspond to a 5% risk of skull fracture (44). The HIC quantifies head impact severity by incorporating time of acceleration exposure and acceleration magnitude (60). These injury metrics are important for innovators as they help to define design requirements for injury prevention equipment such as helmets.

1.2.3 Injury Thresholds

One area of particular interest to biomechanical engineers is characterisation of injury thresholds. By defining injury response as it correlates to metrics such as peak linear and rotational acceleration, improved mTBI prevention technology can be developed and standardised. The Head Injury Criterion (HIC) is an example of a specially derived injury metric which has been adopted as a way to quantify head impact severity by incorporating peak linear acceleration and duration of impulse.(61) One step further than this are Injury Assessment Reference Values (IARV's) which utilize testing of cadaveric material and ATD's to correlate measurable quantities (ie. acceleration) to injury risk. In the context of helmet testing, a peak resultant acceleration of 180 g corresponds to a 5% chance of skull fracture while a HIC of 700 correlates to a 5% risk of an AIS ≥4 brain injury.(62) It is important to realize that these values

[2] One 'gravity' is defined as the gravitational acceleration constant (9.81 m/s^2). As such, multiple gravities (or "g's") are just a multiple of the gravitational acceleration constant.

are not meant to define the exact threshold that these injuries occur but rather report a magnitude at which these injuries have been observed.

Early research investigating rotational acceleration has predicted 1800rad/s2 to be the threshold at which concussion occurs, but this has been criticized for being too vague and inaccurate.(53) Another approach being investigated uses strain as the predictive metric for mTBI and has been validated through finite element models.(63,64) Such a method has been proposed to be used in the future to drive design of equipment to prevent mTBI. In a publication from Stanford University, an injury biomechanics lab is measuring brain dynamics through an instrumented mouth guard and correlating the results to clinically-diagnosed concussion.(65) The goal of this study is to aid clinicians in identifying mTBI as early as possible through characterised injury metrics as well as to quantify the mechanics of injury to inform safety equipment design.

Tissue-level injury thresholds are another aspect for which biomechanics literature is able to offer insight. Bain et. al. (2000) determined a strain of 0.14 to be a conservative threshold for morphological changes in the white mater using a guinea pig model.(66) Unfortunately, such thresholds are limited as live experimental animal models are difficult to scale to humans and cadaveric brain tissue is not mechanically representative of live tissue.

1.2.4 Snow Sport Specific Fall Mechanics

Given that both skiing and snowboarding are activities performed on snow slopes, many of the same environmental conditions and obstacles are encountered, leading to similar characteristics of fall mechanics. However, the two activities are distinctly different in the equipment used and therefore planes of balance necessary. As such, fall mechanics have a number of inherent similarities and differences.

In a prospective study by Bailly et. al. (2016), a survey was given to injured snow sport participants with a series of illustrations representing possible fall scenarios.(67) The scenarios were generated from analysis of one hundred crash videos found in online searches, from which 18 distinct fall circumstances were pictorialized. The ten most selected mechanisms are illustrated in Figure 7.(67)

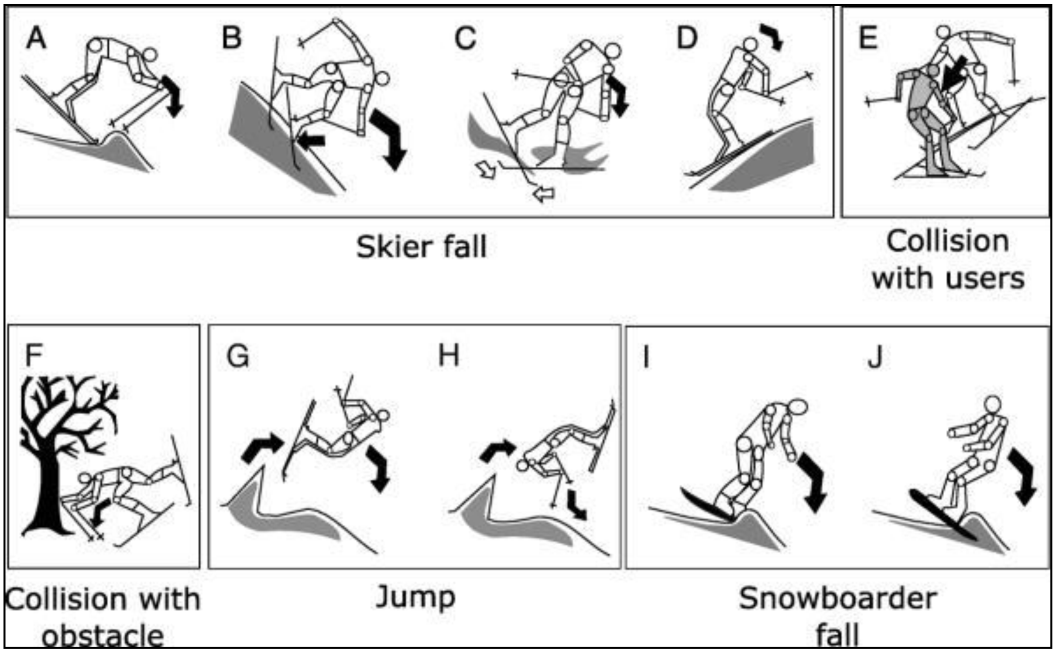


Figure 7: The 10 most selected scenarios: falling head first (n = 44) (A); falling sideways (edge catching) (n = 29) (B); crossing skis (n = 18) (C); falling backward (imbalance) (n = 22) (D); user collides with another immobile or less rapid user (n = 41) (E); self-fall, followed by a collision with obstacle (n = 35) (F); jump forward (n = 33) (G); jump backward (n = 23) (H); snowboarder falling head first (n = 15) (I); and snowboarder falling backward (n = 16) (J). Image taken from Bailly et. al., 2016

Although it is possible to have variation within these individual scenarios, they serve as a general representation and allow for a basic categorization to allow for further interpretation. For many of these, the incident is characterized by an abrupt disturbance causing the participant to approach the ground at an oblique angle with their general momentum being linear. For mechanisms that are characteristically distinguished, biomechanical studies have been performed to better understand the kinematics. One scenario in particular is known as the back-edge trip and is a snowboard specific mechanism which involves the snowboard's back edge acting as a pivot causing the individual to rotate backwards towards the ground. Using clinical data, multibody computer models and ATD reconstructions, researchers have been able to characterize this phenomenon and understand that the kinematics of the head at impact differ significantly from the linear impact in current helmet standards.(68–70) It is this detailed understanding that enables improved, more realistic testing protocols and injury prevention technology.

1.3 Helmets and Standards

Helmets are one mode of head injury prevention that has proven to be effective in mitigating severe head injury.(71) However, it is important to distinguish between severe head injury and mTBI. Most modern day helmets are designed and tested to attenuate energy from linear acceleration and offer little protection from rotational inertia. Thus, shearing and tearing forces caused by rotational inertia may not be attenuated. Furthermore, the certification standards that exist to ensure quality and effectiveness are designed for severe head injuries such as skull fracture and do not incorporate testing to investigate the helmet's ability to prevent against less severe injuries such as mTBI. Several research groups around the world, including the Neuronic Engineering group at the KTH Royal Institute of Technology (Stockholm, Sweden) and The Engineering Science, Computer Science and Imaging Laboratory (ICube) at the University of Strasbourg (Strasbourg, France), are investigating this aspect of helmet certification with the aim to incorporate rotational acceleration in the test protocol. By applying current head injury research to re-evaluate current helmet certification criteria, helmet designers will be encouraged to develop new technology which is more effective in preventing both linear and rotational injury. This approach is already taking effect with a few new technologies emerging, such as MIPS™ (www.mipshelmet.com) and 6D (www.6dhelmets.com), which attempt to reduce the effects of rotational acceleration on the brain.

1.3.1 Standardized Testing and Safety Certification

In an effort to reduce the risk of harm for consumers and establish consensus amongst industry stakeholders, standards organizations have developed and published testing protocols. For sport helmets, the most recognized organizations include the American Society for Testing and Materials (ASTM), the Consumer Product Safety Commission (CPSC), the Canadian Standards Association (CSA), the Snell Foundation (Snell) and the European Committee for Standardization (CEN). The protocols developed involve tests and requirements for several different aspects related to the helmet's safety such as stability, field of sight, shock absorption, toughness, retention and the ability to protect against penetration. In addition to these tests, a number of other requirements are defined and may include compatibility of construction materials (ie. use of cleaners, biocompatibility, finishes etc.), documentation (ie. materials used) and design necessities (ie. projections, retention strap design etc.).

To tests the helmet's ability to mitigate injury from blunt trauma by absorbing energy, certification protocols prescribe an impact test and define a kinematic threshold that the helmeted impact must stay below. For many standards to date, this involves a linear drop apparatus (illustrated in Figure 8) where an anthropomorphic test device (ATD) headform impacts an anvil with a linear accelerometer mounted at the centre of gravity (COG) of the headform. The headform is dropped from a defined height and the acceleration is measured over time. For an array of test scenarios, the peak linear acceleration (in the direction of gravity) is noted and the helmet is considered to have passed if this value is less than the threshold required in the standard. In general this threshold is between 250g and 300g, depending on the organization.(72–75) Although there are small discrepancies between additional prescribed tests, the linear impact protocol is consistent across most standards. Regardless of the sport, these test protocols are oversimplifications of real world fall scenarios.

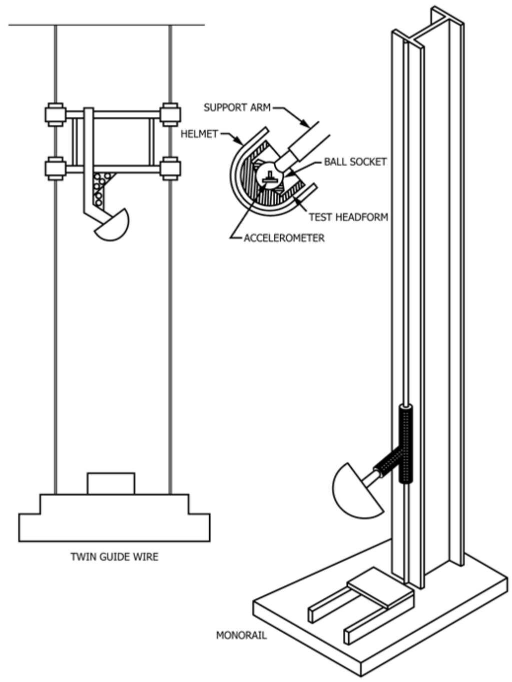


Figure 8: Guide wire and drop monorail schematics exemplifying test apparatuses used for linear impact testing in standardized testing protocols. This image is taken from the ASTM F08 standard.(76)

1.4 Objectives and Scope

The overarching objective of this work is to advance the current understanding of snow sport head injury to improve prevention of real world injuries. To achieve this, two phases have been defined. The main objective of the first phase of this work is to characterize the nature and severity of head injuries suffered while skiing or snowboarding. Secondarily, helmet use and the implications on injury outcome will be investigated. By relating injury outcome data through retrospective medical record review with sport specific kinetic and kinematic characteristics from existing literature, the relevant biomechanics of head trauma in snow sport accidents can be deduced. This information is directly relevant to both helmet certification protocols as well as development of technology to mitigate head injury. Benefit can be realised through prevention of head injury on both individual and societal levels.

The objective of the second phase of this work is to design a snow-sport-specific test apparatus capable of representing injurious real world head impacts. From the data collected in phase one of the project in conjunction with existing biomechanics literature, an improved and detailed understanding of the mechanics of head impact during skiing and snowboarding will be established. This understanding will then inform design requirements and evaluation criteria. A series of impact tests will be performed in order to verify the apparatus meets the requirements set forth.

2.0 CLINICAL PRESENTATION AND CHARACTERIZATION OF SNOW SPORT HEAD INJURY[3]

2.1 Introduction

With approximately 650 ski resorts in North America seeing over 75.9 million visits per year, skiing and snowboarding are identified as the second most practiced winter sports in Canada.(20,77,78) Due to several factors, including high speeds and variable conditions, snow sports also have a high incidence of injuries. Head injuries in particular account for approximately 50% of all snow sports injuries and are the leading cause of fatality for participants.(29,79) Although helmets have been found to protect users against severe head injury such as skull fracture, little is known about skiing- and snowboarding-specific injury mechanisms and their implications on head injury severity.(34–36)

With the established efficacy of helmets in protecting against severe head injury, manufacturers are faced with the challenge of tailoring technology for anticipated impact scenarios.(71) Activity specific helmet standards are one method to set performance requirements for manufacturers. Several organizations world-wide have published certification standards to define performance requirements for helmets used in snow sports.(72–75) Although slight protocol and threshold differences exist between organizations, most standards involve evaluation of the helmet's ability to attenuate energy transmission, prevent penetration and stay on the user's head.

For all current standards, the energy attenuation test involves a perpendicular impact to a helmeted anthropomorphic headform while measuring linear acceleration at the center of gravity. Linear drops are performed from 1.0-2.0 meters (approx. 4.5-6.3 m/s impact velocity) in each of these standards with maximum peak head acceleration threshold of 250-300 gravities (g's; where 1g is equal to gravitational acceleration).(72–75) Although helmets used for snow sports are certified using such standards, most of the impact attenuation testing protocols are similar to those used in testing bicycle, motorcycle, football, hockey and other sport helmets and by virtue of impact surface (metal, not snow), may not be biomechanically representative of typical snow sport impacts.(80)

[3] This chapter has been submitted to a peer reviewed journal for consideration to be published pending peer review.

In a study by Scher et. al., typical velocities of intermediate snowboarders were found to be 30.9 km/h (8.6 m/s), on average.(81) In a separate study, skiers wearing helmets were found to be travelling 45.8 km/h (12.7 m/s), on average.(82) In the event of a crash at these velocities, oblique impact is likely because the tangential velocity is large in contrast to the normal velocity and is generally not dissipated unless the person interacts with another object. This can cause significant rotational acceleration which has been identified as a potential cause of concussion. Understanding the role of rotational acceleration in causing head injuries is important in order to develop future injury mitigation technologies.(19,83–85)

To date, most literature aiming to characterize snow sport head injury has done so with an epidemiological focus and only a few studies have aimed to understand the mechanism of injury. In a recent prospective study by Bailly et al. (2016), crash analysis was combined with a medical survey in an effort to identify at-risk demographics and describe the mechanism of snow sport head injury.(67) Although this research is commendable, it was limited by the lack of a detailed medical diagnosis and broad classification of injury severity as well as failure to capture severe head injuries. Therefore, it has limited ability to identify specific scenarios which require attention.

Other studies investigating snow sport head injury have broadly identified mechanisms using descriptors such as direction of fall, impact surface, general injury type and treatment category.(70,79,86,87) Such studies bring valuable understanding but often lack resolution of reporting, are not relevant to present day snow sports or lack detailed correlation of mechanism to injury severity.

By relating injury outcome data through retrospective medical record review with sport specific kinetic and kinematic characteristics from existing literature, relevant biomechanics of head trauma in snow sport accidents can perhaps be deduced. This information is directly relevant to helmet certification protocols as well as development of novel helmet and other technologies to mitigate head injury.

The purpose of this study is to describe the severity and mechanisms of real world head injuries that occurred while participating in recreational alpine skiing and snowboarding and that resulted in a visit to the Emergency Department or transfer to the Coroner. As a secondary focus, helmet use and their implications on injury outcome will be investigated.

2.2 Methods

A retrospective, multi center chart review of snow sport head injuries over 6 years (January 1, 2009 to December 31, 2014) was performed. The study methods were reviewed and approved by the University of British Columbia Clinical Research Ethics Board. Vancouver General Hospital (Vancouver, British Columbia; VGH), Lions Gate Hospital (North Vancouver, British Columbia; LGH) served as the main study centres as they are in close proximity to the local snow sport recreation sites and service most severe trauma for the Greater Vancouver Area and the so-called Sea-to-Sky Corridor between Vancouver and the Whistler Blackcomb ski resort. Records were identified from the Regional Emergency Department Database and hospital patient care information systems. After eligible patients were identified, medical charts were requested from the appropriate medical records department. The BC Coroner's Office records were also accessed.

2.2.1 Inclusion Criteria

All incidents related to skiing and snowboarding, which resulted in head or face trauma, and were treated at either study center were included. Charts were pulled for cases that presented to the Emergency Department (ED) between January 1, 2009 and December 31, 2014. In addition, incidents presenting to either emergency department which involved head impact but did not result in head injury were included. Skiing and snowboarding fatalities concluding head injury as the cause of death were also included.

2.2.2 Exclusion Criteria

Those who sustained head injuries but were not associated with active participation in skiing or snowboarding activities were excluded from this analysis. An example of an injurious incident that is not considered active participation would be falling in the ski resort parking lot.

2.2.3 Vancouver General Hospital

Given that only basic patient and clinical presentation data was available electronically at VGH through the ED database, relevant cases were flagged using keyword identifiers. The ED database included general patient descriptors including name, birthdate, and medical reference number (MRN) as well as clinical information including chief complaint, triage code. Cases were initially flagged for the keywords *ski**[4], *snow**, *Whistler**, *Grouse**, *Cypress**, *Seymour**,

[4] The asterisk (*) is recognized by the database software as an indicator of the previous characters being the prefix of a word and will recognize any words including that prefix regardless of the additional characters (ie. searching *ski** will identify *skiing*)

*Manning**, *Sun Peaks**, and *Big White** in any of the ED database fields. A secondary search was conducted which further flagged the cases including the keywords s*calp*, facial*, face*, head*, concussion*, TBI*, mTBI*, mild trauma*, brain*, eye*, neck*, nose*, nasal*, jaw*, collar bone*, collarbone*, mandible*, multisystem trauma*, and *MS blunt**. Cases flagged in both of the keyword searches were considered to be 'high yield' cases. For the cases that were only flagged in the primary search (ie. Sport and/or location descriptors), further investigation was done using the VGH Patient Care Information System (PCIS); an electronic database which includes information regarding admissions, discharges, transfers, orders (lab & x-ray) and results as well as clinical documentation such as assessments, flow sheets, medication administration, plans of care, and clinical notes. A 'medium yield' subset of these cases was created for cases which, upon PCIS investigation, had indication of a CT Head ordered or mention of head trauma in consult reports. The remaining charts were considered 'low yield'. Paper charts were requested and reviewed for all high and medium yield cases identified. Low yield cases were then further filtered in the ED database to identify cases that resulted in the patient being admitted. This list was then further scrutinized using PCIS where all documentation was reviewed for any indication of head trauma and the identified cases were included in the chart review. Figure 9 illustrates the number of cases included and excluded through each stage of record identification.

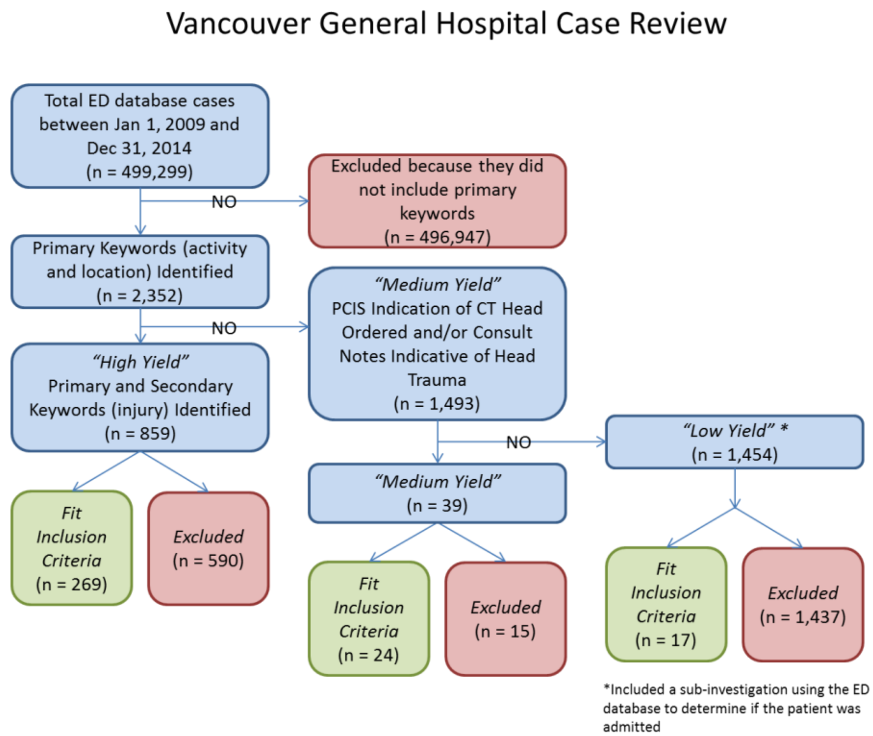


Figure 9: Flowchart describing inclusion and exclusion for cases identified at Vancouver General Hospital, Vancouver, British Columbia

2.2.4 Lions Gate Hospital

As the emergency department at LGH utilizes electronic medical records in some aspects of reporting, identifying relevant cases and extracting data was much more streamlined. All ski and snowboard related cases were first identified using the 'Accident Code' and 'Accident Description' fields in the electronic search. The 'Chief Complaint Description' and 'Discharge Diagnosis Description' fields were then independently queried to filter for trauma involving the head or facial regions. From the combined list, duplicate cases were removed. All physical records of the included cases were then interrogated to extract data. Figure 10 illustrates the process of record identification and the number of cases included.

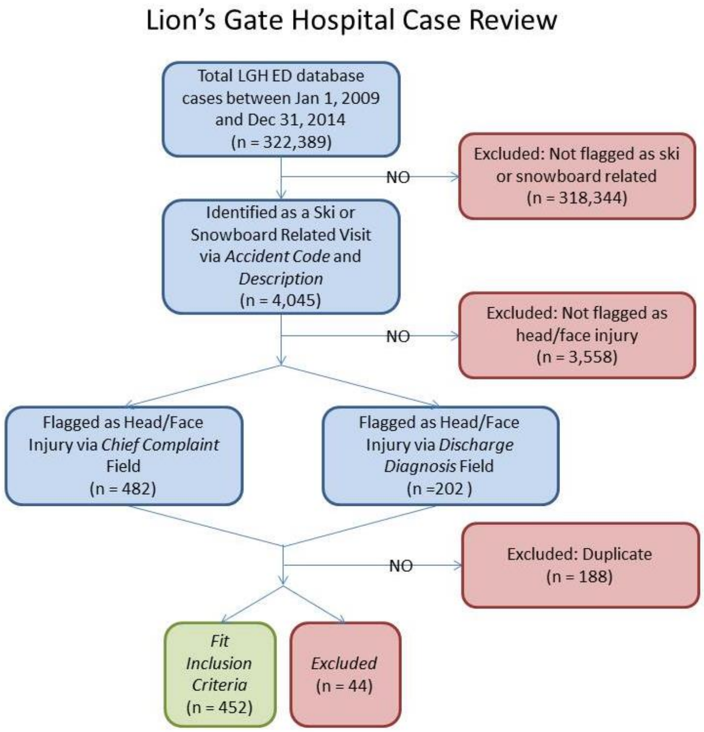


Figure 10: Flowchart describing inclusion and exclusion for cases identified at Lion's Gate Hospital, North Vancouver, British Columbia

2.2.5 Office of the British Columbia Coroner

Incident summaries related to skiing or snowboarding over the study period were provided by the BC Coroner's Office. Each case was investigated and only those with head trauma as the cause of death were included.

2.2.6 Chart Review

From the three records sources, a database was constructed using a standard data entry form with focus on information pertaining to the mechanism of fall, injury severity and helmet use. Information collected included demographic data (ie. gender, age in years, height and weight if recorded), any incident specific data (ie. nature, level of control prior to the incident, location, ability level, helmet use) as well as relevant information pertaining to the head injury such as diagnosis, additional injury, relevant history, medical imaging reports and notes from physicians, nurses or consultants. All reviewers were trained for consistency and regular meetings were held to reach consensus for issues that arose.

2.2.7 Data Analysis

Once the data was collected, injuries were scored using the Abbreviated Injury Scale (AIS). The AIS is an anatomically-based, consensus-derived global injury severity scoring system developed and administered by the Association for the Advancement of Automotive Medicine.(88) General descriptive and odds ratio (adjusted for age and gender) statistics were generated to characterize the database and to understand the relationships between head injury severity, helmet use, demographic and injury mechanism.

To address our primary objective, we compared the odds of moderate and severe head injury (AIS > 2 or 3, respectively) in helmeted versus un-helmeted skiers. Additionally, prevalence of each injury type, frequency of particular injury mechanisms and prevalence of specific head injury characteristics statistics were generated. Generalized linear regression models were generated using 'R' statistical software (R Core Team, Vienna, Austria).(89)

2.3 Results

The database includes 766 cases of snow sport head injury identified over 6 winter seasons. Table 1 presents general descriptors of the database. This included twelve fatalities which met the inclusion criteria.

Table 1: Basic descriptive statistics for the snow sport head injury database (MAIS = Maximum AIS)

Category	Statistic Descriptor	Total	Percent of Total Cases
Overall	Cases Included	766	100.0%
Gender	Male	522	68.1%
	Female	242	31.6%
Discipline	No. of Skiing	302	39.4%
	No. of Snowboarding	464	60.6%
Location	Whistler	207	27.0%
	Local Mountains (Cypress, Grouse, Seymour)	363	47.4%
	Other Locations	196	25.6%
Injury	MAIS2+ Head/Face	198	25.8%
	MAIS3+ Head/Face	43	5.6%
Helmet	Helmet Use	422	55.1%
	Helmet Not Used	226	29.5%
	Not Recorded	118	15.4%

As all of the injuries sustained were scored using the AIS, these values were used to differentiate injury types (Figure 11). Concussion was the most commonly diagnosed injury, representing 62.7% of all injuries. The majority of concussive injuries noted were scored as either minor (AIS=1) or moderate (AIS=2) with presence of loss of consciousness being the differentiator.(88) Headache, scalp injury (8.4%) and brain stem/cerebellum/cerebrum injury (5.2%) were the next most common head injuries while skin/subcutaneous/muscular facial injuries represented 16.4% of diagnosed injuries (categorization consistent with the AIS).

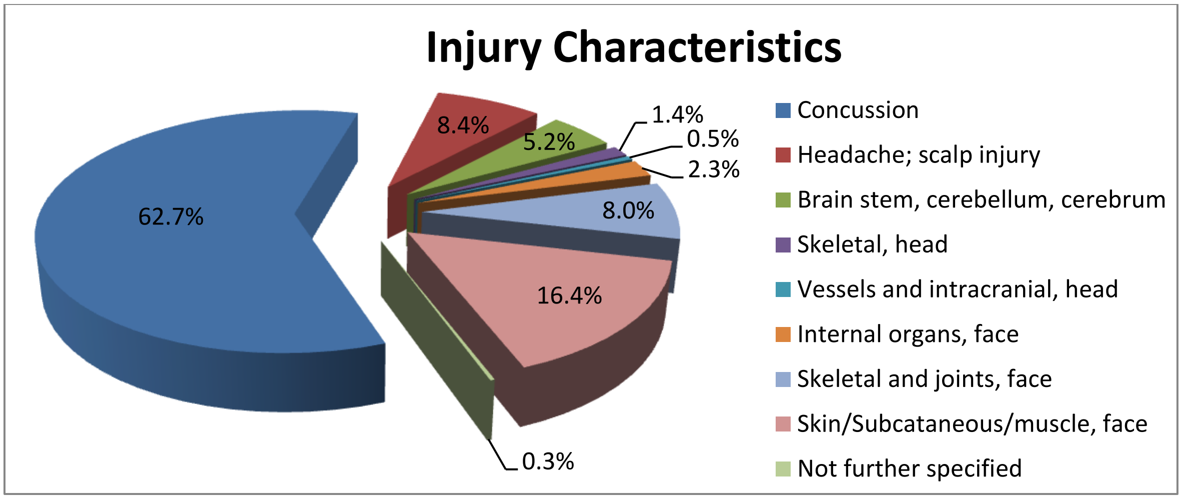


Figure 11: Characterization of all injuries suffered based on the AIS categories. Note: In some cases, multiple injury types were reported and coded with each individual injury being represented in this figure.

To further characterize head impact, impact location prevalence is presented in Figure 12. Impact location was not recorded for 57.4% of all cases. In the remaining cases, the most common site of impact was to the occipital region (49.6%), while face/frontal, side and top represented 35.5%, 12.0% and 2.8% of the reported impact locations, respectively.

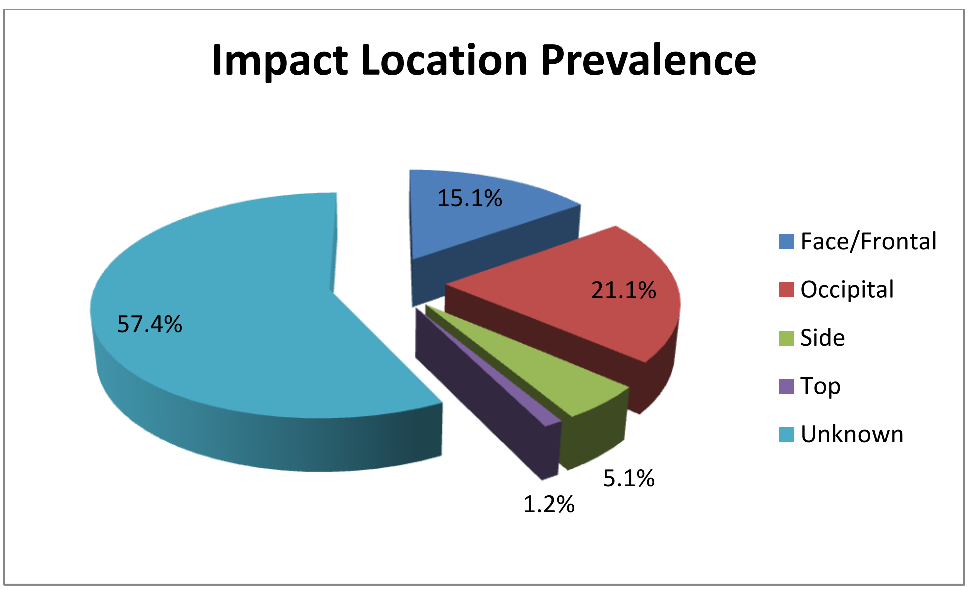


Figure 12: Prevalence of reported head impact location for all documented cases.

Gross injury mechanisms observed in the medical records were found to fit within six general categories including edge catch, fall from height, jump impact, impact with object, impact with person and simple fall. In 97.5% of cases, this general categorization was achieved. Additional descriptors were used to further categorize these mechanisms and include variables such as impact surface, self-reported speed, height of fall, difficulty of run and fall direction. Figure 13 outlines the prevalence of each of these mechanisms.

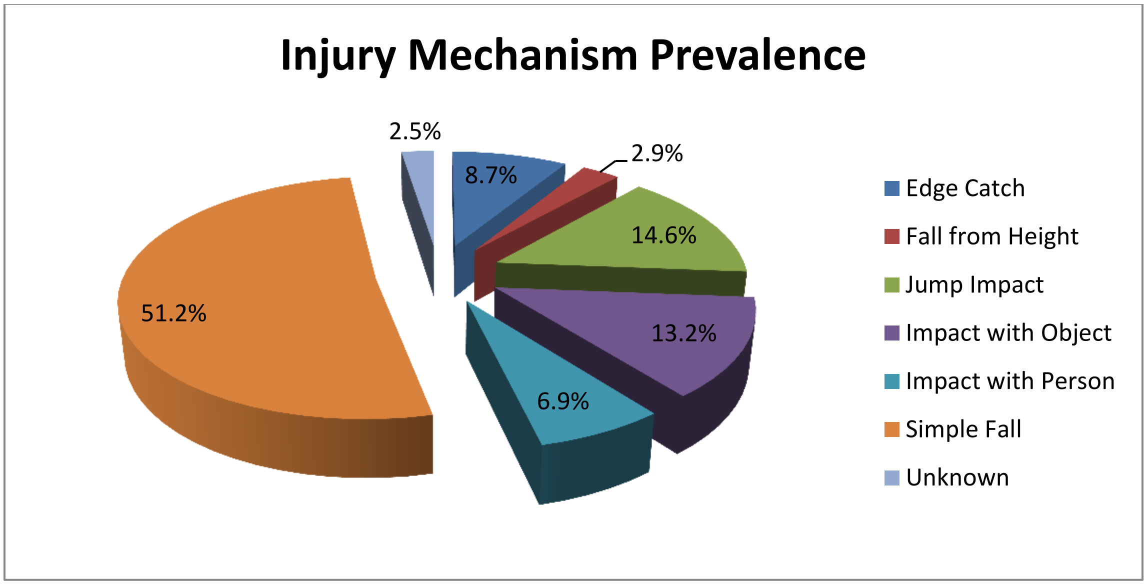


Figure 13: Prevalence of reported head injury mechanism for all documented cases.

Age and gender adjusted odds ratios were calculated with the aim of understanding the interplay between injury mechanisms, severity and helmet use. The likelihood of sustaining an MAIS 2 or higher head injury with different injury mechanisms was studied. Compared to edge catch, the following mechanisms were more likely to result in MAIS 2 or higher head injury: impact with object (OR 2.44; P=0.05; 95% CI 1.14-5.56), jump impact (OR 3.18; P=0.01; 95% CI 1.48-7.26) and fall from height (OR 4.69; P=0.05; 95% CI 1.44-16.23).

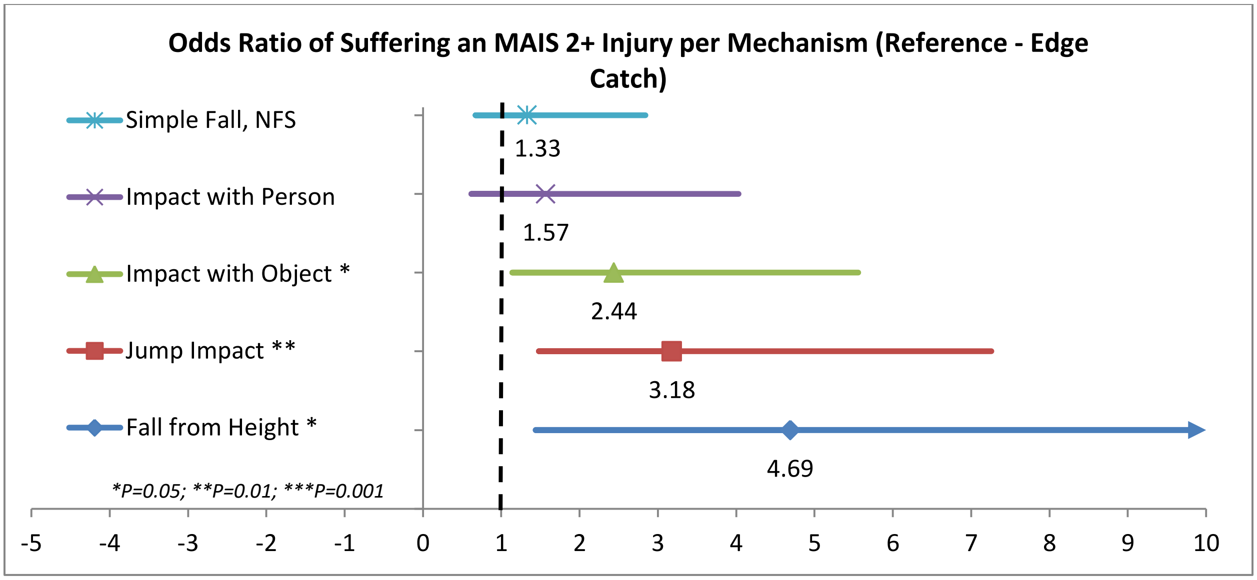


Figure 14: Forest plot illustrating age and gender adjusted odds ratio analysis for the odds of suffering an MAIS 2+ head injury per gross mechanism descriptor

It was also observed that, compared to occipital impact, the likelihood of concussion was lower with frontal/face impact (OR 0.17; P=0.01; 95% CI 0.10-0.28) and side (OR 0.44; P=0.01; 95% CI 0.21-0.99) impact. No significant influence was observed for the top impact location.

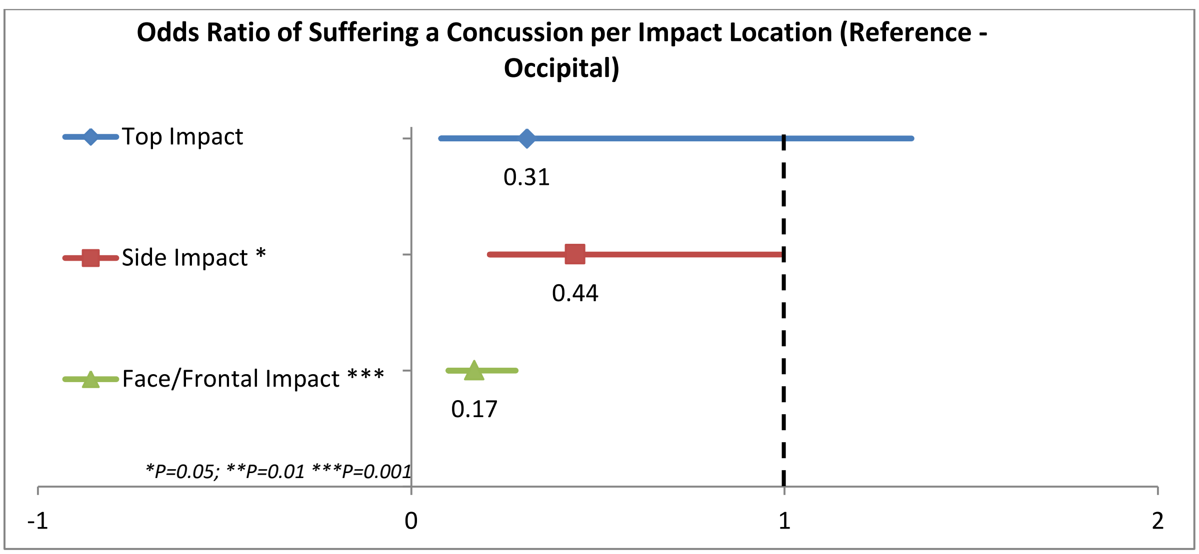


Figure 15: Forest plot illustrating age and gender adjusted odds ratio analysis for the odds of suffering a concussion per head impact location

Similar analysis was conducted to understand the relationship between head impact location and injury severity using MAIS 2+ head injury as a threshold. No statistically significant odds ratios were observed however, side and face/frontal impact locations showed a trend of an increased risk of MAIS 2+ head injury compared to occipital impact.

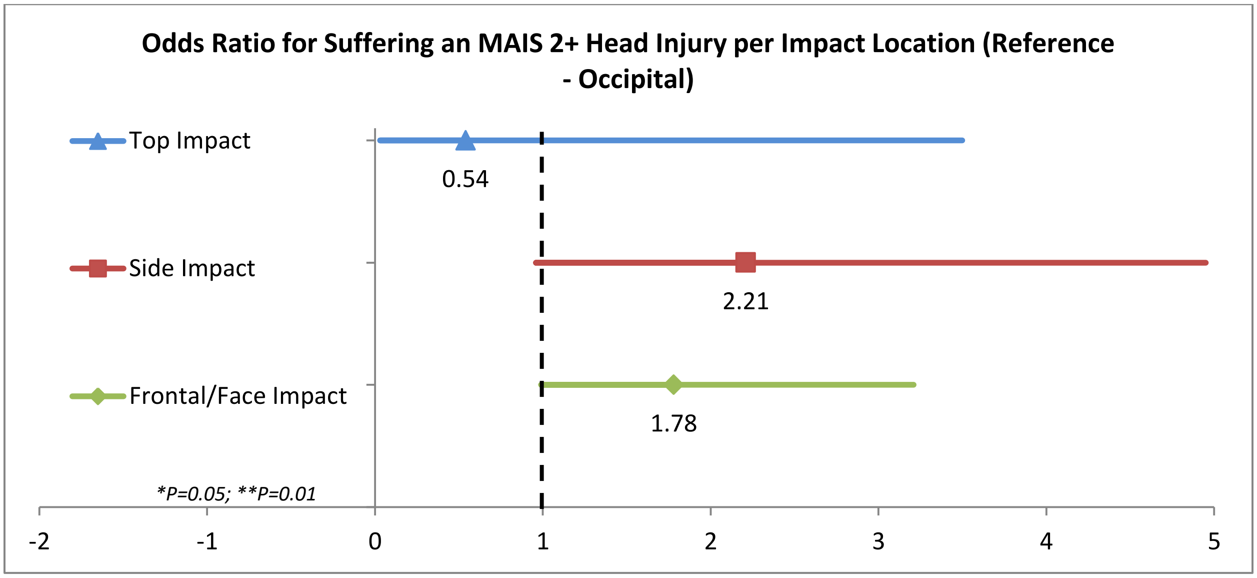


Figure 16: Forest plot illustrating age and gender adjusted odds ratio analysis for the odds of suffering an MAIS 2+ head injury per head impact location

In investigating the influence of helmet use, it was observed that helmet users who presented to the ED are 0.47 (P=0.05; 95% CI 0.23-0.95) times as likely to suffer an MAIS 3+ head injury (which excludes concussion) compared to those who are not wearing a helmet. When the injury threshold is reduced to MAIS 2+ (which includes concussion), helmet use correlates to an increase risk by 1.10 (not significant; 95% CI 0.75-1.62; age and gender adjusted) times. This finding suggests that helmets are more effective at reducing more severe head injuries but offer insignificant benefit in preventing mild traumatic brain injuries. In this sample of snow sport participants reporting to the ED, wearing a helmet trends towards an increased risk of concussion by 1.28 times (not significant; 95% CI 0.91-1.80), compared to not wearing a helmet. In this analysis the sample of skiers and snowboarders we studied was biased as they only visited the ED because they had a concussion or concussion-like symptoms. The results could be confounded by the fact that any people who were wearing a helmet and who hit their head but did not have concussion symptoms did not report to the ED.

2.4 Discussion

In an effort to characterize snow sport head injury, real world clinical data was used with the goal of determining trends that may be addressed by improved preventative measures. As with many sports, injury mechanisms cannot be characterized by a single scenario and are often complex. We found that injury type and mechanism have significant variation even when generalized (Figure 11 and Figure 13). However, this investigation identified important trends.

One important aspect of an impact test is the surface that the headform collides with. Current test standards use various geometries of steel anvils and modular elastomer programmer (MEP) pads. These surfaces allow for a repeatable surface on which the impact can take place but are markedly different than snow or ice found on a ski hill. Since ‘simple falls’ and ‘jump impacts’ represent 65.8% of the cases, and these mechanisms very likely result in head to snow/ice contact, there is support for helmet testing using an impact surface more similar to snow. This is supported by Bailly et. al. (2016), Dressler et. al. (2012) and Scher et. al. (2006) who conclude that helmet efficacy should be evaluated through impact with a snow surface.(67,81,90) The variable nature of snow based on environmental factors and the difficulty of maintaining representative conditions in a laboratory suggest that an in-field test apparatus could be utilized.

To understand the relationship between injury mechanism and injury severity, odds ratios were calculated. The likelihood of an MAIS 2+ head injury as a result of fall from height and jump impact was observed to increase 4.69 and 3.18 times, respectively, when compared to the edge catch mechanism (Figure 14). Given the high energy nature of these mechanisms and their association with higher severity injuries, it is apparent that a high velocity test is necessary. Some may argue that such a test is already represented in many test standards. However, with an observed average travelling velocity of 8.6 m/s – 12.7 m/s, versus 5.4 m/s – 6.3 m/s in standardized test protocols, skiers and snowboarders are likely exposed to much higher head impact velocities than used in testing standards, particularly when falling from height or jumping.(72–75,81,82)

Previous studies found kinematic thresholds for concussion between 53g and 169g for linear impacts, and 5022 rad/s^2 – 7600 rad/s^2 for rotational acceleration.(91–98) Certification standards evaluate a helmet’s ability to attenuate linear acceleration, with the threshold for passing being between 250g and 300g for a 1.5m-2.0m drop. Clearly current tests are more representative of high energy injuries (ie. skull fracture) suffered from linear mechanisms. Mertz et. al. found that a 50% risk of adult skull fracture correlates with a peak linear acceleration of 262g.(62) The notion that current helmets are designed for high severity, linear mechanisms is further supported by the finding that there is no significant difference in the risk of concussion for helmeted compared to unhelmeted snow sport participants. A recent meta-analysis concluded that no statistically significant relationship exists between helmet use and a risk of concussion.(99) Since 62.7% of injuries suffered in our study were concussions, justification can be made for the addition of a lower velocity impact test, to supplement a higher velocity impact test, which is more representative of the types of real world head impacts that result in a concussion.

Although information on impact velocities and angles was limited in this retrospective record review, current literature and video analysis provides insight into these head impact characteristics. An impact angle of 30 degrees was the most common scenario for motorcycling and equestrian head impacts which have similar tangential velocities to skiing and snowboarding.(100,101) Recommendation of an oblique helmet test in safety certification protocols is common in recent literature since pure radial (oriented towards the centre of gravity of the head) impact is rare in real world head impact.(19,102) A recent study used a full-body anthropomorphic test device to simulate a snowboarder experiencing a 'back-edge trip', a mechanism that is likely to result in significant normal velocity. The head impact angle in this experiment was still found to be 50 degrees to the slope.(69,81). Such oblique impacts result in eccentric loading and induce rotation of the head, a mechanism that has been observed to result in diffuse axonal injury.(103) The high frequency of oblique impact can be further confirmed by observing video footage available on the internet (www.YouTube.com and other sites).

By investigating impact location prevalence and association with injury severity, a deeper understanding of mechanism is achieved. Nearly half of all reported head impacts in our study were to the occipital region, and the likelihood of suffering a concussion from an occipital impact was 5.88 times higher than for a face/frontal impact. Thus, attention must be paid to optimizing protective measures to this area. In contrast, the odds ratio of suffering an MAIS2+ head injury (which excludes less severe concussions) from an occipital impact (reference face/frontal impact) was found to be 0.56 (95%CI:0.31-1.01;P=0.1). This may suggest occipital head impact being a more frequent occurrence at lower energy.

For cases where it was reported, helmets were used 65.2% of the time for participants in this study. Helmet efficacy for severe head injury was confirmed: the risk of an MAIS 3+ injury for helmet users was cut in half (OR = 0.47). However, no significant benefit was observed for helmet users in preventing MAIS 2+ head injuries, which includes AIS 2 concussions. With helmets currently being designed for an acceleration threshold of 250g – 300g, perhaps it is not surprising that helmets provide no significant benefit against injuries that occur at lower thresholds (concussions reportedly occur with head acceleration around 53g - 167g).(93–95,97,98) This is consistent with other observational studies which found that helmets offer little protection against concussion.(99) Such findings validate the necessity of current helmet testing protocols incorporating a high threshold pass/fail criteria but also emphasize the need for a lower energy test that is more representative of less severe but more common injury.

2.5 Strengths and Limitations

The biggest limitation of this work is its retrospective nature which limited our ability to definitively determine high resolution injury mechanisms. Nevertheless, we believe that the general mechanisms reported were accurate and that unreported mechanisms were consistent with this distribution. Additionally, this study only captures those with injuries that required medical attention and does not capture snow sport participants who hit their head but did not sustain a significant injury. The case summaries provided by the BC Coroner’s office included limited mechanism of injury detail. As such, these cases were only included if head trauma could be confirmed as cause of death.

Unlike many retrospective studies, this is the first to characterize real world snow sport head injury and investigate the influence of gross mechanism and helmet use on the nature and severity of injuries sustained. We captured a large number of cases with a wide range of injury severities and consulted radiographic images and written records. Through construction of a multi-centre database including over 750 cases of head trauma over 6 winter seasons, an accurate characterization of snow sport head injury is made.

2.6 Conclusions

This investigation to characterize clinical snow sport head injury confirms that such events are complex in nature and not represented by a single mechanism. A high prevalence of concussion supports the need to improve preventative measures to reduce risk of lower severity injuries. Further, investigation of helmet effectiveness showed reduced risk of more severe injury but no benefit in protecting against lower severity injuries such as concussion. By understanding the gross mechanism of injury, appropriate evaluation of such preventative measures and especially evaluation of concussion-specific prevention can likely be achieved. Such findings can be directly related to the improvement of safety equipment and re-evaluation of certification standards.

2.7 Implication of Clinical Database on Standardized Testing

From this clinical data, it is now possible to make informed recommendations as to possible modifications to existing standardized safety testing protocols. These suggestions will also act as requirements for the design of a relevant helmet testing apparatus in successive chapters of this document. It is worth noting that these recommendations are meant to complement existing test protocols.

The major findings and recommendations based on the clinical database include:

- High prevalence of simple falls and jump impacts supports impact testing using a surface more similar to snow.
- Increased risk of MAIS 2+ injury from high velocity mechanisms indicate a need for a higher velocity impact test.
- A high prevalence of concussion, an injury considered to have a relatively low biomechanical threshold, suggest the need for a lower velocity impact test and research focused on novel helmet designs that are designed to lower the potential for concussion specifically (with a lower pass/fail threshold)

Existing biomechanical and epidemiological literature will be used to recommend additional apparatus requirements in the following section.

3.0 DESIGN OF A CLINICALLY REPRESENTATIVE SNOW SPORT TEST APPARATUS

3.1 Apparatus Design

Given the observations from the clinical dataset, as well as additional evidence in existing literature, it is apparent that real-world snow sport head injury is more complex than is currently represented through helmet testing protocols. The clinical work supported the consideration of impacting surfaces more similar to snow, incorporation of a high velocity impact more representative of travelling speeds that skiers and snowboarders may fall at as well as a lower velocity impact that is more likely to be representative of incidents resulting in concussive injury. Although these clinical findings can aid determination of apparatus requirements, existing literature and interviews with key stakeholders are necessary to understand the full scope of the requirements the test device must be designed around.

In an effort to make testing more relevant to the sports for which the certified helmets are designed for, alternative test protocols and apparatuses have been developed. Many of these methods aim to incorporate rotational acceleration through eccentric or oblique impacts as well as incorporating a surrogate neck. One general method to achieve this is to perform drop impacts, both constrained and free fall, onto an angled impact platen.(104–107) Protocols involving a headform dropping onto a moving surface have also been identified as more representative of specific impact scenarios such as bicycle and motorcycle accidents.(108–110) To represent impacts more similar to head-head or shoulder-head contact, linear impactors and pendulum impacts protocols have been developed.(92,111–117)

As helmet evaluation moves more towards test protocols that are more similar to real-world events for many sports, snow helmet certification protocols remain oversimplified. The first step toward improved testing methods is to understand the mechanics of head impact. In an observational study performed on a ski resort, skiers and snowboarders were determined to be travelling 45.8 (12.7 m/s) and 30.9 km/n (8.6 m/s) on average, respectively.(81,82) Through principles of projectile motion, we can infer that such travelling velocities may result in impact angles of 20 to 35 degrees and resultant velocities of 10 m/s to 14 m/s (see Appendix C: Detailed Design). For certain mechanisms, such as a back-edge trip, head velocity at impact was found to be approximately 125% of the tangential velocity at the time of fall initiation.(69)

The following chapter outlines the design process followed to identify the need, define requirements, generate and evaluate concepts, design and construct an in-field helmet test apparatus that is representative of head injury scenarios. The design proceeded in accordance with principles documented in chapter 2.0 including the findings supporting testing on a surface more similar to snow as well as additional high and low velocity tests to represent more realistic impact scenarios for which severe injury and concussion can occur. The objective of this work is to propose a final design of a test apparatus capable of headform impact representative of real world snow sport head impact scenarios.

The final design selected and fabricated involves a large compression spring to accelerate a carriage that is capable of releasing the headform at a specified distance prior to impact. The spring is loaded using a hand winch and wire rope. A 3D model rendering of the final design is shown below in Figure 17.

Figure 17: A 3D rendering of the final impact apparatus design.

3.1.1 Stakeholders

In an effort to identify and consider all relevant needs, all stakeholders and their interests were investigated. Table 2 summarizes the identified stakeholders and their relevance to the project scope.

Table 2: Summary of relevant stakeholders as well as their relation to the project and main considerations

Stakeholder	Relation	Main Considerations
Helmet users	Direct impact given they are using the technology that has been deemed appropriate for protecting against severe head injury; this can be further divided into recreational and competitive users.	Safety
Regulatory bodies (ASTM, EN, CPSC, CSA, Snell etc.) (73–76,118)	Adoption or endorsement of test protocols	Safety, conformity, ease of implementation, impact to industry, injury threshold validity, difficulty to pass test
Helmet companies	Designing and marketing helmet technology to consumers	Safety, ease of implementation, cost of test, difficulty to pass test, impact to industry
Researchers	Use of protocol to investigate new technology or conduct parallel research with standardized methods. Investigation of injury thresholds	Safety, relevance of test, ease of implementation, injury threshold validity, cost of test
3rd Party test facilities	Performing test protocol and certifying helmet design for companies.	Ease of implementation, repeatability, cost of test
Government	Currently no legislation that helmets sold in Canada need to be certified; potential support for mode of increasing safety of helmet without influencing industry and adoption	Safety, impact to industry, influence on consumer uptake
Hospitals/Clinics/Medical Patrol	Treating head injuries from snow sport activities	Safety, influence on consumer uptake
Families of helmet users	Concern with helmet use and potential buyer	Safety
Ski Resorts	Snow sport participants pay to use the resorts. The ski resorts have safety staff and protocols of their own as well as being concerned with liability. Their facilities may also be used for testing.	Safety, location of test, user experience, liability

3.1.2 Needs Identification

Champions in the major stakeholder groups were contacted and interviewed to gain insight into the main needs of the stakeholder groups. Dr. Irv Scher, a biomedical consultant and Chairman of *the ASTM F27 Committee on Snow Skiing*, served as a stakeholder champion from the perspective of the regulatory bodies. Dr. Peter Halldin, CTO of MIPS and Assistant Professor at KTH Royal Institute of Technology, was consulted to offer an industry and researcher perspective. Further discussion with Mr. Darrin Richards and Dr. Peter Cripton gave additional insight into other perspectives that were not accounted for in the formal interviews. Notes from these discussions can be found in Appendix A: Stakeholder Communications. To further capture the perspective of the regulatory organizations, the ASTM - F08 Sports Equipment and Facilities was attended In November of 2014. Notes taken from this conference can also be found in Appendix A: Stakeholder Communications. This primary research proved extremely valuable in developing a comprehensive set of needs to base the apparatus design from.

Secondary research entailed understanding current standardized and research based test protocols. Safety standards from organizations including the Canadian Standards Association (CSA), ASTM International, the Snell Foundation, the Consumer Product Safety Commission (CPSC) and the European Committee for Standardization (CEN) were studied to understand the commonalities and differences. In addition, impact testing apparatuses used for research were studied to gain a perspective on possible future directions of safety performance testing. General categories for such apparatuses included devices which perform drops with a neck surrogate, drops onto a moving surface, angled surface impacts, linear impactors, impact pendulums and projectile tests.

Throughout this research, it was important to translate findings into clear and concise ‘needs statements’ for which to begin to construct the basic requirements of the test device. A comprehensive list of the discovered needs can be found in Table 3 along with the most relevant stakeholders.

Table 3: Summary of the identified needs and the relevant stakeholders to that need

Need	Most Relevant Stakeholder(s)
Device must fit inside an automobile	Regulatory bodies, researchers, 3rd party test facilities
Device must be representative of traumatic head injury (or injuries) suffered while participating in snow sports	Helmet users, families of helmet users, regulatory bodies

Need	Most Relevant Stakeholder(s)
Device must be able to endure summer and winter conditions at high altitudes	Regulatory bodies, researchers, 3rd party test facilities
Tests must be repeatable (impact velocity, orientation, acceleration); a consideration of this will be the snow characteristics changing after impact	Regulatory bodies, 3rd party test facilities, researchers
Device must not damage other test equipment (ie. Headform, Data Acquisition hardware (DAQ) , accelerometers)	3rd party test facilities, researchers
Device must be easy and quick to assemble and disassemble	3rd party test facilities, researchers
Device must be transportable under the power of two people	3rd party test facilities, researchers
Device must allow for mounting of a camera	3rd party test facilities, researchers
Camera mount must be adjustable to visualize point of impact	3rd party test facilities, researchers
Impact surface conditions must be quantifiable (ie. hardness, granularity, moisture content, crystal structure etc.)	3rd party test facilities, researchers, regulatory bodies
Impact velocity must be quantifiable	3rd party test facilities, researchers, regulatory bodies
User must be able to initiate test manually	3rd party test facilities, researchers
Testing must not permanently damage set up location (within reason; ie. Drilling rock)	Ski resorts
Device must have the ability to be constructed on various slope angles	3rd party test facilities, researchers
Headform must be restrained from escaping the immediate vicinity of the test device	3rd party test facilities, researchers
Test can be performed by 1 person	3rd party test facilities, researchers
Tests can be repeated within 3 minutes	3rd party test facilities, researchers, regulatory bodies

Need	Most Relevant Stakeholder(s)
Device must not cause harm to anyone	3rd party test facilities, researchers, ski resort
Device must allow for adjustment of impact angle	3rd party test facilities, researchers, regulatory bodies

3.1.2.1 Clinical Study Outcomes

As defined in chapter 2.0, several findings from the retrospective clinical study can be used as needs to incorporate in the apparatus design. To summarize, those needs include:

- Need for impact testing using a surface more similar to snow.
- Need for a higher velocity impact test more similar to travelling speeds of snow sport participants.
- Need for a lower velocity impact more similar to the biomechanical threshold for concussion

3.1.3 Specifications

3.1.3.1 Requirements

To turn each needs statement into a measurable requirement, it is necessary to consider the apparatus design from an engineering perspective. These requirements are used to evaluate concepts based on the defined metrics and their importance to the final performance of the apparatus. Each need's statement was broken down individually into one or several specific requirements of the apparatus and then a metric was determined based on current practise in standardized testing, existing research, industry expectation or intuition. An example of a requirement, its defined metric and justification includes:

- Time between same-series tests must be short
- Justification: Many certification standards require a defined maximum amount of time between tests to investigate the helmets toughness. This may also be necessary to ensure impact surface does not change significantly between tests
- Metric Threshold: 180 seconds (3 minutes)
- Reference: CSA Z263.1-14 Recreational alpine skiing and snowboarding helmets - Toughness Test (119)

The most deterministic requirements set forth include:

- The apparatus must allow for variable impact velocity
- The apparatus must allow for variable impact angle
- The apparatus must be portable (broken down into several more specific requirements)
- The headform should be able to collect linear and rotational kinematics
- The apparatus must allow for variable head impact locations

Further elaboration of these requirements, their metrics and justification can be found in Appendix B: Design Phase Documentation, Table 14.

3.1.3.2 Evaluation Criteria

To allow for objective evaluation of each concept, evaluation criteria were developed based on the needs identified by the stakeholder discovery. These criteria were then used in conjunction with Pugh Charts and Weighted Decision Matrices (see sections 3.1.6.2 and 3.1.6.3.3). Overall, nine criteria were decided upon which are summarized in Table 4.

Table 4: Summary of evaluation criteria and a short description of its relevance

Evaluation Criteria	Descriptor
Cost	Overall cost of all necessary components for testing
Precision	The ability of the test apparatus to perform a single, exact test with the parameters defined (incl. impact angle, velocity, head orientation)
Weight	Overall mass of all included components
Ease of Use	The ease of each test with regard to resetting, initiating, performing, collecting data, verifying conditions etc.
Durability	The ability of all test components to resist breaking or deteriorating as well as changing in variable conditions (ie. Temperature, wind, precipitation etc.). Consideration as to the how critical failure is should be taken into account
Set-Up Time	The total time it takes to set up and take down the apparatus (does not include time between tests)
Size	The total volume of all of the necessary test equipment
Repeatability	The ability of the test apparatus to perform repeat impacts with the same parameters
Safety	The safety factors as they relate to the public surrounding the device and the operators of the device (could include changes to the environment (open pit from testing). May also involve influence on the environment in the long term.

3.1.4 Functional Decomposition

Now that design requirements have been set and evaluation criteria defined, an in-depth understanding of the basic fundamental function of the device can be outlined. From these top level functions, concept fragments can be generated independently and then combined to form integrated solutions. This method allows for the most creative solutions for each basic function without concern, at least initially, for compatibility. The top level functions identified are:

FR1: Hold headform relative to ground
FR2: Induce known acceleration to headform relative to ground
FR3: Control headform orientation at impact
FR4: Contain headform within test zone
FR5: Adjust impact orientation of headform
FR6: Release headform from test apparatus prior to impact
FR7: Quantify headform impact velocity
FR8: Maintain consistent impact surface between tests

3.1.5 Concept Generation

To explore several different ways to address the functions outlined in the functional decomposition (Section 3.1.4), two general methods of brainstorming were applied. These included an initial individual brainstorming and a subsequent structured group brainstorm.(120,121)

As an initial step in individual brainstorming, concepts for each function identified were generated without assistance or critical evaluation of any kind. Following this, a second step of revisiting each function and using research for conceptualization was used. Research included drawing inspiration from existing mechanisms that shared related functionality through investigating mechanism patents and using internet searches and mechanism encyclopedia's. (122) Basic internet searches for words describing key functions were also used to identify unfamiliar mechanisms. A comprehensive list of all of the ideas generated can be found in Appendix B: Design Phase Documentation.

To take advantage of the knowledge and experience of individuals in the Orthopaedic and Injury Biomechanics Lab Group, a group brainstorming session was held which involved 1 post-doctoral student, 2 PhD candidates, 1 research engineer and 1 professor. The structure of the session was formed around the eight top level functions and creative, unconventional ideas were encouraged. This session proved to be very valuable in generating a wide variety of solutions. A comprehensive list of all of the concepts generated can be found in Appendix B: Design Phase Documentation.

3.1.6 Concept Evaluation

For each of the top level functions, several concepts were generated, necessitating evaluation to eliminate some of the ideas that may not be feasible or do not meet the requirements. To formalize this process, tools such as winnowing, Pugh charts and weighted decision matrices were used.(121,123)

3.1.6.1 Winnowing

This process entails screening each concept on a top level for each of feasibility, requirements and technical readiness and eliminating the concepts with the least chance of success. To investigate feasibility, the idea is scrutinized to understand if it could offer the general performance necessary of the apparatus. At this stage, basic calculations or drawing were used to understand if the idea was physically possible (see Appendix B: Design Phase Documentation). Next, each requirement is revisited to understand if the concept can satisfy it. Lastly, the technical readiness is evaluated by understanding if the necessary technology for construction and operation of the concept is available. If a concept fails to pass any one of these stages, the concept is eliminated from further consideration. Table 15 in Appendix B: Design Phase Documentation shows each concept sorted by function and the result of each stage of winnowing.

3.1.6.2 Pugh Charts

Pugh charts were used as a tool to compare and rank the remaining concepts. In situations where the best option was not trivial, research and further calculation was performed. An example of a Pugh chart is seen below in Table 5 with all of the charts being found in Appendix B: Design Phase Documentation. In each Pugh chart, all concepts were evaluated against a ‘datum’ concept and determined to be better (‘+’), worse (‘-‘) or the same (‘S’).

Table 5: Pugh chart showing the first iteration of evaluation of the "Hold Headform Relative to Ground" function. The purple column represents the datum for this iteration.

Evaluation Criteria	Rail with Hard Stop	Tensioned tether with release pin (similar to drop	Suspension cables on a drop frame	Suspended Mesh bag	Table/shelf	Clamp mounted on post	Hold with hands	Magnet	Adhesive	Pole with bowl (ie. T-Ball stand)
Cost	S	+	S	+	+	+	+	-	+	+

Evaluation Criteria	Rail with Hard Stop	Tensioned tether with release pin (similar to drop	Suspension cables on a drop frame	Suspended Mesh bag	Table/shelf	Clamp mounted on post	Hold with hands	Magnet	Adhesive	Pole with bowl (ie. T-Ball stand)
Precision	S	S	S	S	S	-	-	S	-	-
Weight	S	+	S	S	S	S	+	+	+	+
Ease of Use	S	S	S	S	S	S	+	S	S	+
Durability	S	-	-	-	-	S	-	-	-	-
Set-Up Time	S	S	S	-	-	S	+	S	S	S
Size	S	+	S	S	-	S	+	+	+	S
Repeatability	S	-	-	-	S	-	-	S	-	-
Safety	S	S	S	S	S	S	-	-	-	-
Σ+	-	+3	+0	+1	+1	+1	+5	+2	+3	+3
ΣS	-	4	7	5	5	6	0	4	2	2
Σ-	-	-2	-2	-3	-3	-2	-4	-3	-4	-4
Net Score	-	0	-2	-2	-2	-1	+1	-3	-1	-1
Rank	-	2nd	4th	4th	4th	3rd	1st	5th	3rd	3rd

In general, concepts are combined into integrated solutions before evaluating them. Given the high number of concepts that came out of the winnowing process, this step was completed on the concept fragments. This allowed for a thorough investigation of each concept and how it compared to other concepts. One criticism of using concept fragments at this stage is that synergies between ideas are not taken into account and a combination of all of the highest ranked concepts may not necessarily be ideal. For this design, given the high number of concepts passing the winnowing stage, Pugh charts are being used to further cull the concepts generated. As such, concepts were eliminated if they were consistently in the bottom third of the rankings so as to not eliminate concepts that may be more synergistic that another slightly higher ranked idea.

3.1.6.3 Quantitative Evaluation of Integrated Concepts

The next step was to combine concept fragments into several integrated solutions which were then assessed using Weighted Decision Matrices (WDM). A WDM is a tool that can quantitatively assess an integrated solution using weightings for each evaluation criteria. This first requires an objective way of determining those weightings which was achieved using the Analytical Hierarchical Process (AHP).

3.1.6.3.1 Analytical Hierarchical Process

To determine the weight of each evaluation criteria relies on relative importance, the Analytical Hierarchical Process was utilized. A table showing the raw rank assigned for each comparison as well as the complete table of normalized values can be found in Appendix B: Design Phase Documentation. Table 6 shows the weightings as determined through the AHP.

Table 6: Summary of evaluation criteria weightings as determined using the AHP

Evaluation Criteria	Weight	**Weight (%)**
Cost	0.02	**2.24**
Precision	0.22	**21.62**
Weight	0.04	**3.91**
Ease of Use	0.08	**8.28**
Durability	0.07	**7.44**
Set-Up Time	0.09	**8.52**
Size	0.04	**3.63**
Repeatability	0.25	**24.98**
Safety	0.19	**19.40**

3.1.6.3.2 Integrated Concepts

Using the concept fragments that passed the Pugh Chart phase of evaluation, integrated concepts were created. At this stage, the top level function of “induce a known acceleration to the headform” was found to be the most deterministic function and as such, integrated concepts were generated based on the eight concepts that remained for this function. Full descriptions and sketches of the final eight integrated solutions can be found in Appendix B: Design Phase Documentation and can be summarized, based on the most deterministic concept fragment (mode of accelerating the headform), as:

- Inverted Pendulum (gravity)
- Flywheel with Clutch (powered)
- Loaded Spring (linear)

- Freefall Drop
- Pulley System (4:1)
- Inverted Pendulum (torsional spring)
- Winch
- Electromagnet

3.1.6.3.3 Weighted Decision Matrix

Similar to the Pugh Charts described earlier, WDM column headers were populated with each integrated concept with two sub columns for each displaying the assigned score and the weighted score. The first row header was filled with the evaluation criteria with the second column of row headers being filled with the associated weighting.

To ensure the input scores for the WDM were as objective as possible, each integrated concept was broken down into a list of anticipated components. This allowed for each component to be taken into account for evaluation criteria which necessitated a more detailed scoring (ie. cost, weight, durability etc.). For each criterion, a specific scoring system from 1 to 6 was defined. These criteria-specific scoring rubrics as well as the component breakdown summary can be found in Appendix B: Design Phase Documentation.

Based on the component-by-component scoring, overall criterion scores were generated and input into the weighted decision matrix. After all scores were multiplied by the weightings, the Loaded Linear Spring concept emerged as the best concept. Given the extensive evaluation process, the decision to proceed with detailed design for the linear spring was made. Table 7 illustrates the full WDM.

Table 7: Weighted Decision Matrix highlighting evaluation of each integrated concept

Evaluation Criteria	Descriptor	Overall Weight	Concepts															
			Inverted Pendulum (gravity)		Flywheel w Clutch (powered)		Loaded Spring (linear)		Freefall Drop		Pulley System (4:1)		Inverted Pendulum (spring)		Winch		Electro-magnet	
			Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight
Cost	Overall cost of all necessary components for testing	0.02	8	0.18	5	0.11	6	0.13	7	0.16	7	0.16	6	0.13	4	0.09	6	0.13

Eval. Crit.	Descriptor	Overall Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight
Precision	The ability of the test apparatus to perform a single, exact test with the parameters defined (incl. impact angle, velocity, head orientation)	0.22	5	1.08	7	1.51	8	1.73	3	0.65	7	1.51	7	1.51	5	1.08	3	0.65
Weight	Overall mass of all included components	0.04	4	0.16	1	0.04	6	0.23	8	0.31	2	0.08	6	0.23	3	0.12	0	0
Ease of Use	The ease of each test with regard to resetting, initiating, performing, collecting data, verifying conditions etc.	0.08	5	0.41	5	0.41	7	0.58	7	0.58	5	0.41	5	0.41	8	0.66	3	0.25
Durability	The ability of all test components to resist breakage and as well as changing in variable conditions (ie. Temperature, wind, precipitation etc.). Consideration as to the how critical failure is should be taken into account	0.07	6	0.45	6	0.45	7	0.52	6	0.45	7	0.52	7	0.52	6	0.45	6	0.45
Set-Up Time	The total time it takes to set up and take down the apparatus (does not include time between tests)	0.09	6	0.51	1	0.09	5	0.43	6	0.51	5	0.43	5	0.43	4	0.34	4	0.34

Eval. Crit.	Descriptor	Overall Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight
Size	The total volume of all of the necessary test equipment	0.04	7	0.25	1	0.04	5	0.18	7	0.25	5	0.18	7	0.25	3	0.11	3	0.11
Repeatability	The ability of the test apparatus to perform repeat impacts with the same parameters	0.25	3	0.75	7	1.75	8	2.00	3	0.75	5	1.25	7	1.75	7	1.75	5	1.25
Safety	The safety factors as they relate to the public surrounding the device and the operators of the device (could include changes to the environment (open pit from testing). May also involve influence on the environment in the long term.	0.19	3	0.58	5	0.97	7	1.36	5	0.97	5	0.97	5	0.97	5	0.97	2	0.39
Net Score		-	4.37		5.36		7.16		4.62		5.50		6.21		5.56		3.56	
Rank		-	**7th**		**5th**		**1st**		**6th**		**4th**		**2nd**		**3rd**		**8th**	

3.1.7 Design in Detail

The final design decided upon from the evaluation was based around a linear spring to accelerate the headform to a known acceleration. Other concepts to satisfy the additional top level functions include:

- A rail mounted ball arm to hold the headform relative to the ground and manipulate the orientation
- A large pad to control the headform within the test zone

- A displacement controlled release mechanism to allow the headform to detach from the apparatus prior to impacting the ground
- Integration of the acceleration signal to determine impact velocity
- Raking of the impact surface for consistency

The next step was to perform a detailed analysis of each aspect to optimize performance and synergies.

3.1.7.1 Spring Design

One of the first design parameters to consider was the spring itself as the specifications (namely force and geometry) directly influence other aspects of the apparatus. As a first step, research was conducted on spring parameters to grasp what is available in regards to spring constant, the ratio of maximum compressed length to uncompressed length and diameter. Given the desire to perform tests at a multitude of impact speeds, a spring with a small compressed/uncompressed length ratio is preferred to allow for precise adjustment of stored energy.

With a basic understanding of what was available, a parametric analysis of the head kinematics at various stages of the test was performed with the manipulated parameters including spring constant, distance compressed, rail length and apparatus angle. The geometric equation for the apparatus orientation was set up based on the schematic shown in Figure 18 and Equation 1. Figure 19 illustrates the energy states that were used in the analysis.

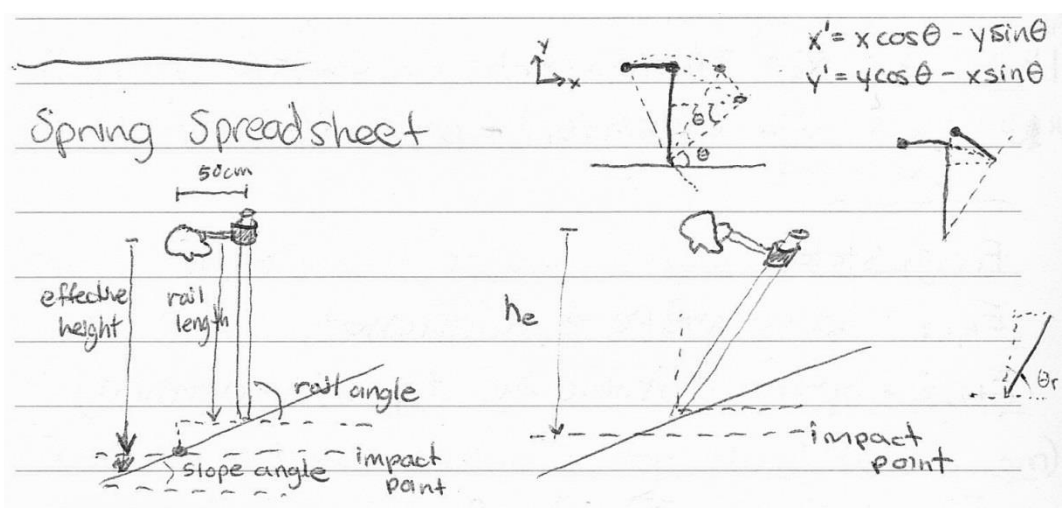
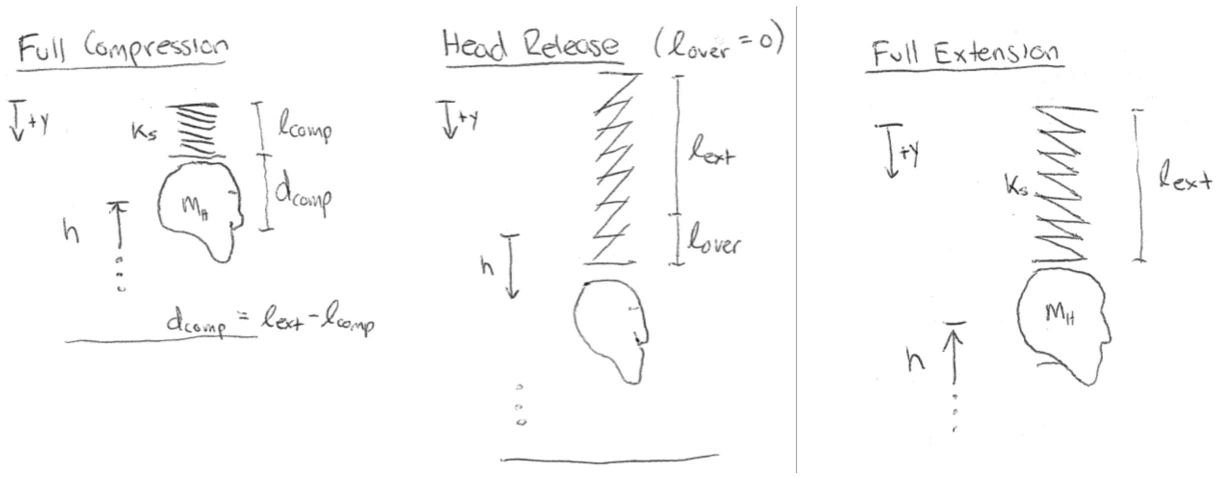


Figure 18: Schematic showing the apparatus orientation used to develop the geometric equations applied in the parametric analysis. Note: this diagram does not show the energy of system, only the geometric considerations of the system at different orientations

Equation 1: Geometric equations used to determine the potential energy in the parametric analysis

$$h_e = l_{rail} + 0.5m * \tan(slope\ anlge) + y_h' \qquad y_h' = l_{rail} * \sin(\theta_r) - 0.5 * \cos(\theta_r)$$



Phase 1 Phase 2 Phase 3

Figure 19: Energy states used to set up the parametric model to estimate head impact velocity

Conservation of energy was applied at three time points in the test to understand the energy states and head kinematics at each stage. It was assumed that all kinetic energy of the spring is transferred to the head. Frictional losses on the rail were assumed to be accounted for by applying a 5% reduction in the final head velocity calculated at each. The general equation applied at each phase is show in Equation 2 where KE represents the kinetic energy, PE represents the potential energy and E represents the total energy.

Equation 2: Conservation of energy applied to the linear spring apparatus

$$E_{Tot} = PE_{Head} + KE_{Head} + PE_{Spring} + KE_{Spring}$$

Potential energy of the spring was calculated by Equation 3.

Equation 3: Potential energy of a spring

$$PE_{Spring} = \frac{1}{2}kx^2$$

Further, the total energy of the head can be expressed through a combination of kinetic and potential energy. Equation 4 and Equation 5 show these relationships where ‘m’ is the mass, ‘g’ is the gravitational constant, ‘h’ is the height and ‘v’ is the velocity.

Equation 4: Potential energy of the headform. Note: The equation found in Figure 18: Schematic showing the apparatus orientation used to develop the geometric equations applied in the parametric analysis

$$PE_{Head} = m_{Head}gh_{springcomp} + m_{Head}gh_{unloaded}$$

Equation 5: Kinetic energy of the headform

$$KE_{Head} = \frac{1}{2} m_{Head} v_{head}^2$$

For the first phase, the total energy of the system was calculated at the moment the spring was at maximum compression. Since the system is being held static, its kinetic energy is zero. This state is represented by Equation 6.

Equation 6: Total energy of the system at maximum spring compression

$$E_{Tot} = PE_{Head,1} + PE_{Spring,1}$$

Once the total energy in the system was calculated, it became possible to solve for the velocity of the headform once the spring was unloaded. Phase 2 represented the moment at which the spring reached zero displacement and the headform is still in contact with the spring. Using the total energy from the previous phase, and the fact that the potential energy of the spring is zero, it was possible to solve for the head's velocity as shown in Equation 7.

Equation 7: Solving for the velocity of the headform when the spring is a displacement of zero

$$v_{head.2} = \sqrt{2(\frac{E_{Tot} - PE_{head,2}}{m})}$$

Phase 3 was defined as the moment the head impacts the ground and therefore all of its potential energy is converted to kinetic energy. Again, the velocity of the headform at this stage was calculated as shown in Equation 8.

Equation 8: Solving for the velocity of the headform at the instant it first contacts the ground

$$v_{head.3} = \sqrt{2(\frac{E_{Tot}}{m})}$$

The full parametric analysis can be found in Appendix C: Detailed Design. The main benefit from this analysis was being able to identify the necessary spring characteristics to achieve a head impact speed of 10 m/s. This led to choosing a spring with a constant of 50 kN/m, an uncompressed length of 0.35 m, an outer diameter of 0.1 m and a fully compressed length of 0.164 m. To allow for easier integration, closed, squared and ground ends were selected. This configuration was available and also satisfied the need for a long range of displacement to reach more precise forces, and therefore velocities.

A variety of slope angles, firing angles, maximum forces and apparatus heights were explored with the above spring configuration being able to achieve the maximum impact velocity within the range of its capability. As an example, with a perpendicular firing angle on a 15 degree slope from a height of 0.5 m above the ground, the spring would need to be deflected 0.1 m (resulting in a spring force of 5000 N) and would achieve an impact speed of 10.33 m/s (see Figure 20).

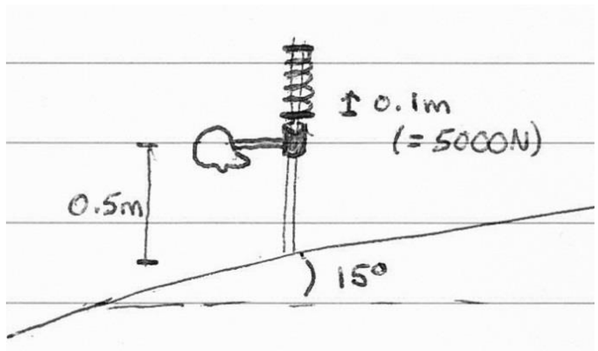


Figure 20: Sketch of the example scenario involving the headform being released from 0.5m above the ground with a 0.1m spring deflection.

In an effort to further validate the kinematics of this model, MSC Adams software was utilized. A simple model including a 3D scan of the hybrid III headform, a linear rail, a rigid ball arm with linear constraint to the rail and a rail mounted, linear spring was constructed. A solid-to-solid contact type was used at the spring/ball arm interface and friction was applied at the ball arm/rail joint ($\mu\_static = 0.6$; $\mu\_dyna = 0.3$). Although simplified, this analysis verified that achieving the 10 m/s impact speed was possible and gave insight into the influence of friction coefficient. Results of the Adams model were comparable to the parametric analysis conducted with the exception that the computer simulation was slightly more accurate in applying frictional losses and therefore estimated the necessary drop height to be slightly higher.

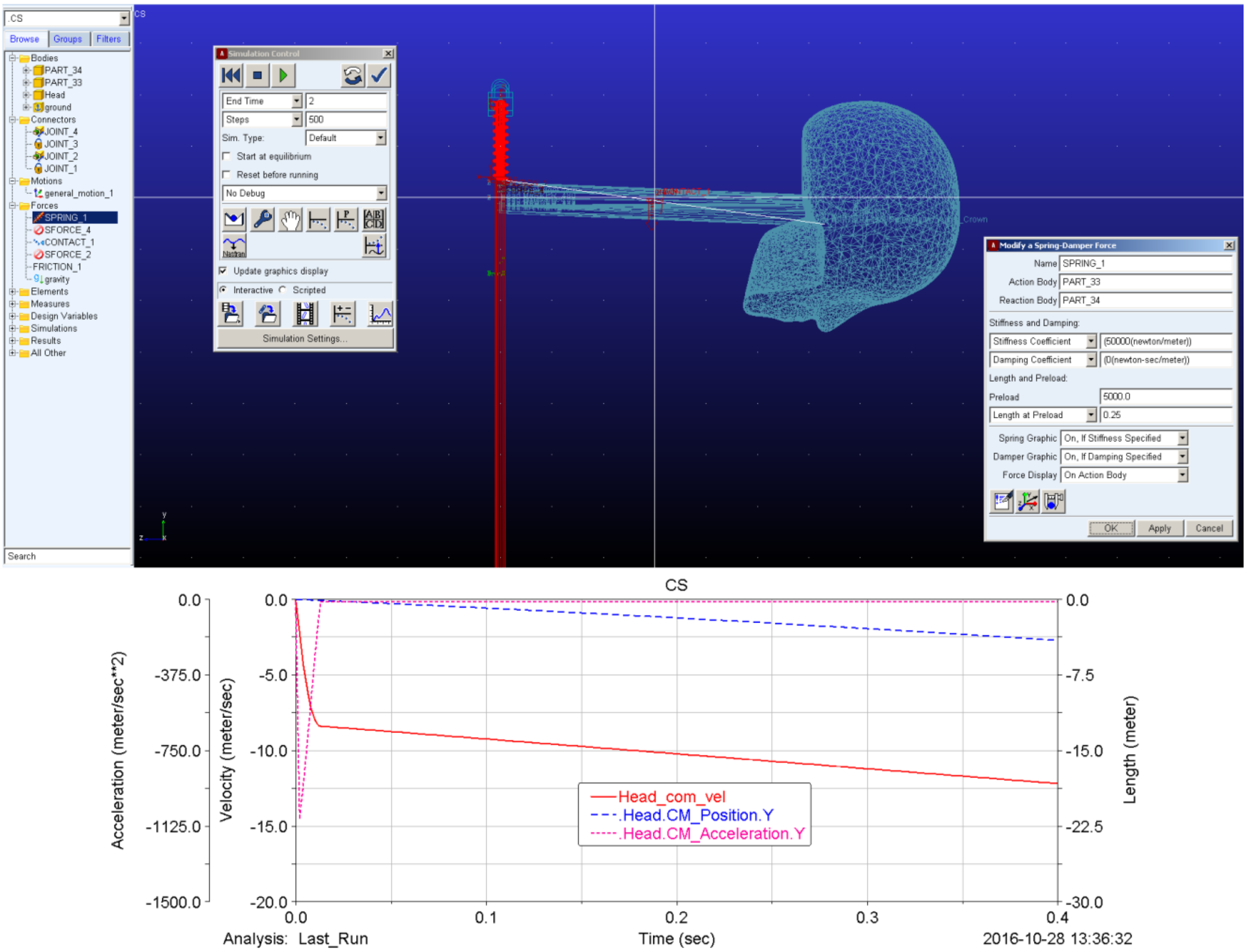


Figure 21: Screenshot of the MSC Adams analysis configuration and a time plot showing the head velocity, acceleration and displacement over time.

3.1.7.2 Control of the Spring

Following the selection of the spring, a means of controllably loading and releasing it must be designed. From the parametric analysis, it became evident that considerable spring forces will be necessary to achieve high velocity impacts. As such, safely depressing and unloading the spring is of paramount concern. Additional considerations include placement of the spring, loading the spring linearly (without eccentricity), supporting the mechanism which loads/unloads the spring and mounting the spring to the apparatus.

In approaching where to place the spring in relation to the apparatus, several concepts were generated. It was realised that a spring could be used to either push or to pull the headform to the desired velocity and therefore could be placed above or below the head. In addition, brainstorming was conducted for specific mechanisms to load and unload the spring in a controlled manner. From this concept generation it became apparent that in order to pull the head to the desired velocity (spring below the headform), additional components would be necessary to load the spring linearly and to couple the extended spring to the head. For these reasons, mounting of the spring below the head was dismissed. From the mechanisms generated, simple research into existing components as well as basic order of magnitude calculations were required.

3.1.7.2.1 Lever-Arm Concept

In investigating the feasibility of using a lever arm in combination with some method of holding the applied force static to achieve the desired spring compression, an understanding of the required geometry was necessary. Figure 22 shows sketches for the pulling and pushing force necessary to implement the magnet (A) or pull cord (B) concepts while Equation 9: Calculations to determine necessary force for the magnet lever concept (Figure 22, sketch A) and Equation 10 show the relevant calculations.

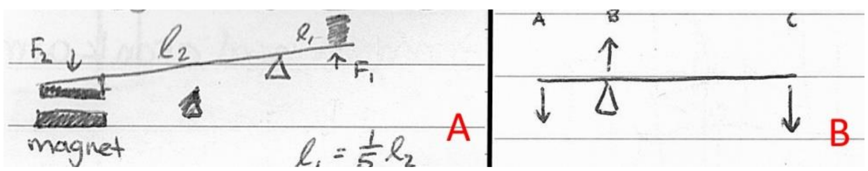


Figure 22: Design sketches for spring loading via lever arm concepts. A) represents the sketch pertaining to the magnet concept while B) is specific to the pull cord concept.

Equation 9: Calculations to determine necessary force for the magnet lever concept (Figure 22, sketch A)

$$M_1 = F_1 * l_1;\ M_2 = F_2 * l_2;\ l_1 = \frac{1}{5} l_2 \rightarrow\ M_1 = F_1 cos\theta * l_1;\ M_2 = F_2 cos\theta * l_2;\ M_1 = M_2\ \therefore\ F_1 = 5F_2$$

Equation 10: Stress calculation to determine stress in a rod used to apply force on a lever mechanism (Figure 22, sketch B)

$$F_C = \frac{1}{5} F_A;\ F_A = 5kN;\ Instantaneously\ F_A + F_B + F_C = 0;\ 5kN + 1kN = -F_B = -6kN$$

$$\sigma = \frac{F}{A} = \frac{5kN}{\pi * \left(\frac{0.0064m}{2}\right)^2} = 158MPa\ \ using\ a \frac{1}{4}^{"}\ threaded\ rod;\ \ \sigma = 39.5MPa\ using\ a \frac{1}{2}^{"}\ rod$$

Based on this analysis, it became apparent that the length of the lever arm would need to be relatively large in order to accommodate the displacement and high force necessary for the desired velocity. In investigating the threaded rod that the applied force would act through (seen to be the most likely element of the mechanism to fail), it was found that the tensile stress was well within the capabilities of readily available materials.

3.1.7.2.2 Gear Concept

Upon investigation into the use of gear ratios to achieve mechanical advantage, it was found that worm gears offer several benefits over spur gears. These include worm gears being non-back driveable as well as achieving a high gear ratio in a small volume.

Further investigation into current worm gear applications illuminated existing hand winch systems utilizing worm gears which were also capable of high loads. Another aspect of this concept would be to identify a rope that could withstand the peak force imparted by the string. This rope would allow for fast release of the load by including a trigger release mechanism in series between the crank and the tensioned cables loading the spring. Given wire rope is often used in high load lifting scenarios, this seemed an obvious choice if this method of spring loading was selected.

In consideration of implementing a worm driven power-screw, number of components, mounting of the power screw collar and release of the load were investigated. By removing the spur gears and driving the worm gear itself with a crank, the number of components could be reduced. The force could also be applied precisely and safely. One significant disadvantage to this system was found to be the mechanism of release under load. In addition, having the power screw through the central axis of the spring would limit the ability to incorporate a central rail that the head carriage travels on.

3.1.7.2.3 Selected Spring Control Concept

Based on the above discussion and calculation, a worm gear, hand winch with wire rope was selected based on its proven reliability in similar situation.

With wire rope being available in various diameters and working load capacities, selection of the hand winch was deemed to be more important to specify first. Upon researching several possibilities, a Dutton-Lainson WG2000 Worm Gear Winch was selected. With a 2000 lbf (8896.44 N) load rating, a safety factor of 1.78 is achieved (additional safety factor likely incorporated into the product load limit). This option was also inexpensive and readily available. Details of this particular product can be found in Appendix D: Product Specification.

With a single reel winch selected, a single strand of wire rope must be specified to take the 5000 N load of the spring. Through research of safe working limits, 1/4" Steel, 6x19 wire rope was selected. In the specification sheet that the capacity includes a safety factor of 5 (see Appendix D: Product Specification). It is anticipated that a trigger mechanism be incorporated between the spring load and the hand winch which also allows for multiple, parallel wire rope segments to act in loading the spring itself (see Figure 23). As used in current impact testing equipment used in the OIBG lab, a high load snap shackle will serve as the trigger mechanism (see Appendix D: Product Specification). It was originally anticipated that a conventional snap shackle would suffice but upon further investigation, these are not rated for release under load and therefore a trigger snap shackle was selected (see Appendix D: Product Specification).

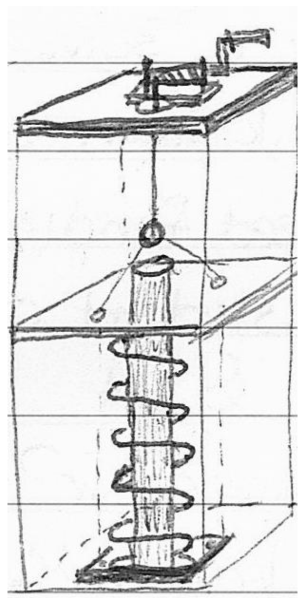


Figure 23: Schematic showing the hand winch and wire cable combination

The next aspect to the design is the structures supporting the spring. As shown in Figure 23, parallel wire rope segments will be incorporated to disperse the force of the spring. Given the concern of loading the spring eccentrically, having the wire rope segments attached to the free floating bottom spring platform via threaded fasteners will allow for micro adjustment once the spring is mounted. For symmetry and adjustability, 4 parallel wire rope segments were designed for. A rigid plate incorporated into the main structure of the apparatus will provide a fixed surface to load the spring against and facilitate clamping of a central rail. Finally, the wire rope can be swaged with compression sleeves and thimbles to provide reliable connection points.

In order to mount the fixed end of the spring and the winch, plates were designed. A parametric analysis investigating a simplified beam bending scenario and Solidworks simulations were performed to optimize the material properties and geometry (see Appendix C: Detailed Design). Simple geometries were utilized whenever possible. Additionally, Solidworks Simulation was used to investigate the top plate in particular as it would be subjected to the force of the loaded spring through the single wire rope and the winch. Analysis of ¼" and ½" plate designs are shown in Figure 24 This analysis aided optimization of the plate geometry, particularly in finding that the thickness of the top plate must be at least 0.5 inches to prevent significant deflection at the max spring load.

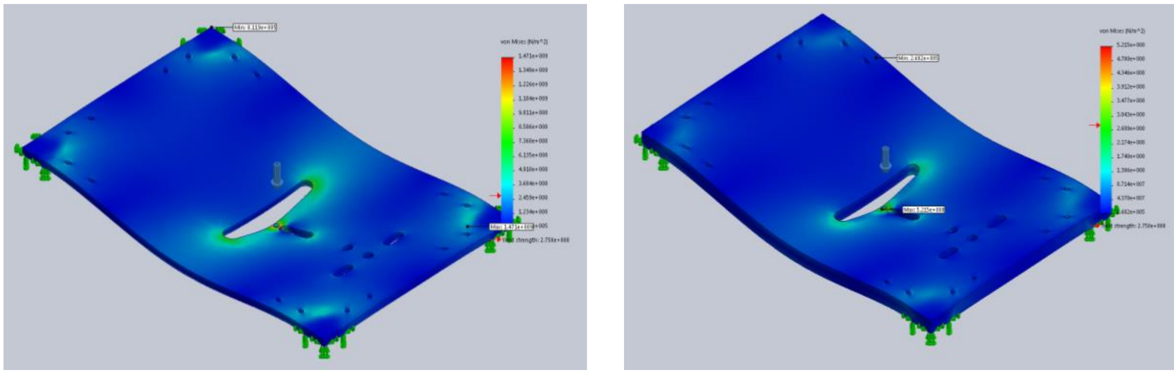


Figure 24: Solidworks Simulation results showing plate strain from a 5000 N point load applied at the center. The left image illustrates the analysis on a ¼" plate while the right image shows a ½" plate. Four 30 mm by 30 mm fixtures at each corner were included.

Given this plate design was identified as a possible point of failure given the high loads, a more detailed simulation was performed. With wire rope pulling downwards, an eccentric (from the center of the winch spool) distributed force along the front edge of the winch mount is experienced in the plate. Additionally, two upward and equal loads act on the plate through the two rear bolts. These changes were reflected in another simulation of the most extreme loading conditions (see Figure 25). The maximum displacement for this design was determined to be 0.90 mm.

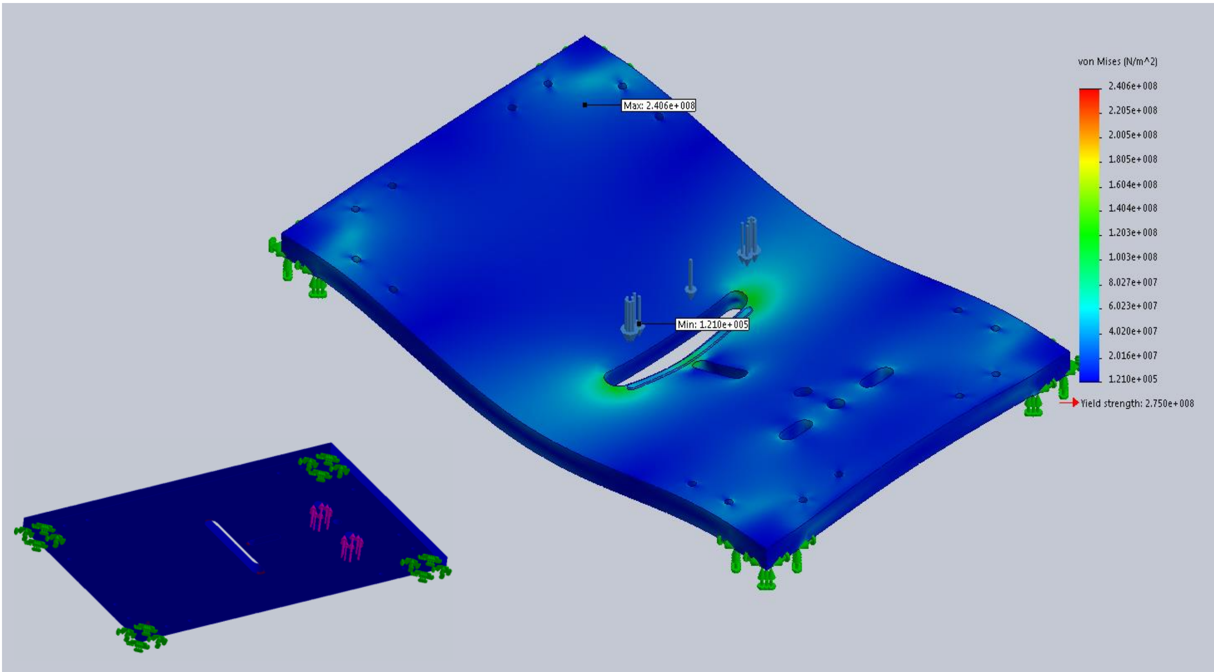


Figure 25: Comprehensive analysis of the top plate on which the winch is mounted. The color map illustrates the Von Mises stress on the plate (Max 240 GPa; 1.15 SF). The fixtures and two bolt loads on the bottom surface of the plate are shown in the bottom left image

The plate fixed to the bottom surface of the spring which acts as an interface between the wire rope and the spring was also determined to be a potential point of failure and therefore required analysis to specify the necessary material and geometry. Similar to the top plate analysis, Solidworks Simulation software was utilized to understand the implication of the specific loading scenario. A simple circular geometry with holes for the central rail and four eye bolt attachments was modeled and an elastic support connector matching the rate (50 kN/m) and spring base geometry was applied. Equal forces were applied to circular areas around the four eye bolts and the simulation was run with a fine mesh. Several iterations of the material and thickness informed the selection of ¼" 6061 aluminum which resulted in maximum stress of 172 GPa (minimum safety factor of 1.60). Figure 26 illustrates the results of the stress analysis,

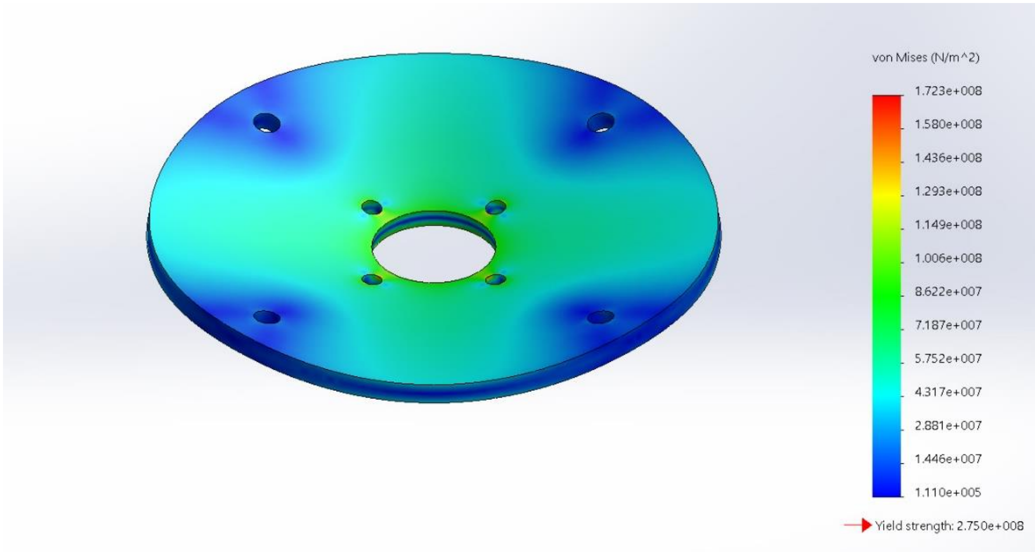


Figure 26: Solidworks simulation results showing a stress map for maximum loading (5 kN) of the spring base plate. The maximum stress was found to be 172 GPa.

Lastly, a support structure must be designed to support the spring load between the plate that the hand winch is mounted on and the plate the spring is loaded against. To determine the geometry needed in this compressive application, buckling calculations were performed based on the cross sectional areas of cylindrical rod, threaded rod and extruded aluminum (80/20). A spreadsheet showing the parametric analysis performed can be found in Appendix C: Detailed Design. Due to its ease of assembly, corrosion resistance and low weight, 80/20 extruded aluminum was used in this design. The analysis concluded that 30 series (30 mm x 30 mm) T-slotted profile will be more than sufficient (safety factor of 15.1 for a single 1 m length). For the purpose of securing the plates to the supports and to provide further structural integrity, inside corner brackets were added to each corner (see Appendix D: Product Specification). The outcome of this analysis resulted in the spring and top frame assembly illustrated in Figure 27.

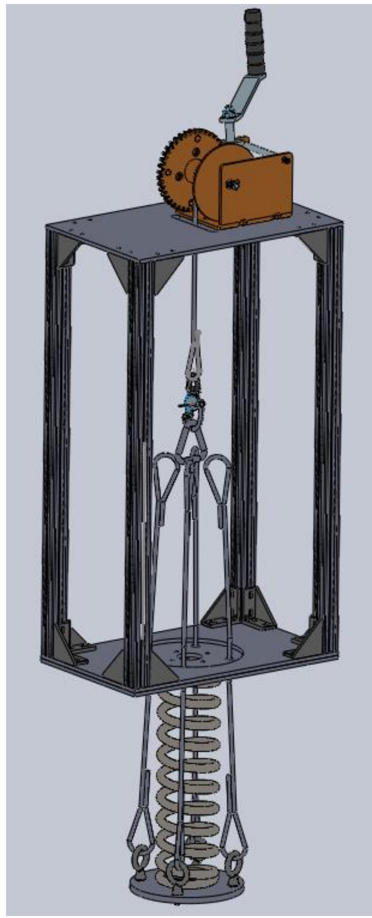


Figure 27: 3D model of the final design for the spring control mechanism

3.1.7.3 Support Structure

Following from the design of the frame to support the spring, design of a support structure for the base of the apparatus, below the spring, was necessary. Requirements of the bottom structure are to hold the spring frame and headform control mechanism off the ground, serve as a mount for the central rail and facilitate variable oblique impact. Although this structure does not bear significant loads caused by the spring, it is necessary to make the structure rigid and durable to support the head release carriage and rail. 80/20 was again selected for its ease of assembly, weight and corrosion resistance.

With the vertical supports selected, the focus was then placed on a means to mount the central shaft that will act as a bearing surface for the head control mechanism. With a natural mounting point for the top of the shaft being the bottom plate of the spring support structure, design of a bottom mount is necessary. This led to conceptualization of a bottom support structure as depicted in Figure 28.

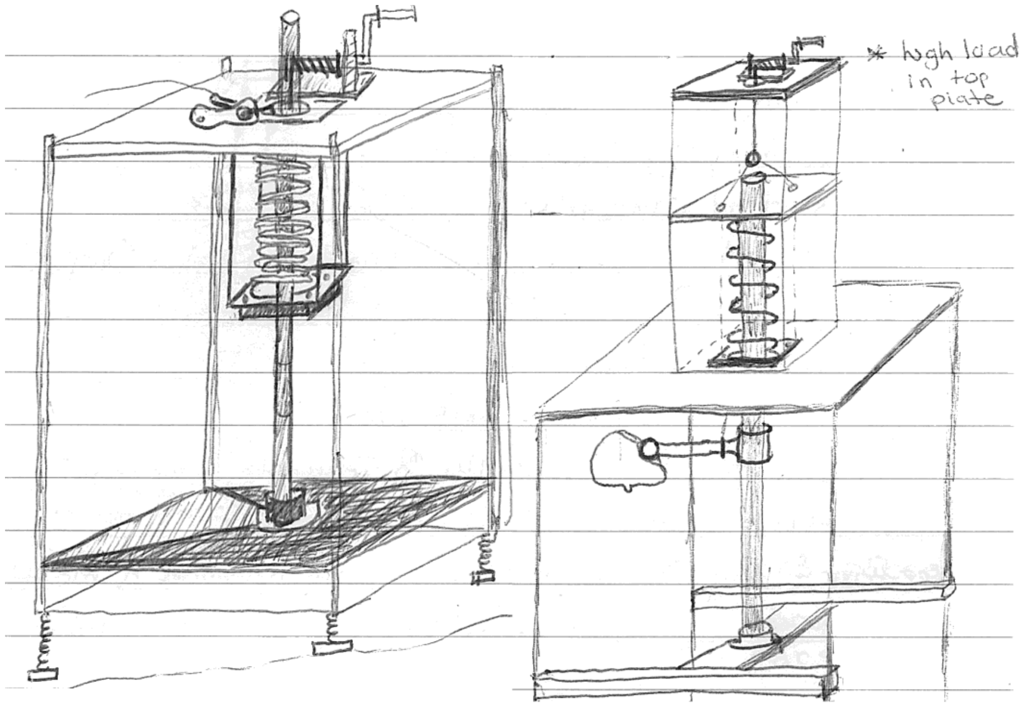


Figure 28: Schematic drawings illustrating concepts for the bottom frame design.

Given that the head control mechanism would impact the base structure with considerable momentum, it was decided that a more complete plate structure would be best suited (the image on the left of Figure 28 as opposed to the image on the right). With that said it is also important to leave and opening in the plate for the head to travel freely to the ground without interacting with any support structures.

To mount the central shaft to the bottom and spring plates, shaft collars were selected from McMaster Carr (specifications can be found in Appendix D: Product Specification). These collars can be fixed to the plates with some tolerance to allow for minor adjustments.

As the nature of the apparatus is to impart a linear impulse to the headform control mechanism through a loaded spring via a portable, lightweight structure, it is logical that oblique impact be facilitated by altering the angle of the entire apparatus relative to the ground. The simplest way to secure the apparatus in a tiled configuration would be the addition of lockable pivot arms on the rear of the structures support frame. Using 80/20 pivot components (specifications found in Appendix D: Product Specification) and additional extruded aluminum (30 mm x 30mm T-slotted), two swing arms were designed for this purpose. Again, aluminum components were selected based on their resistance to oxidation and relatively low mass. The full bottom support structure integrated with the spring and upper support frame is illustrated in Figure 29.

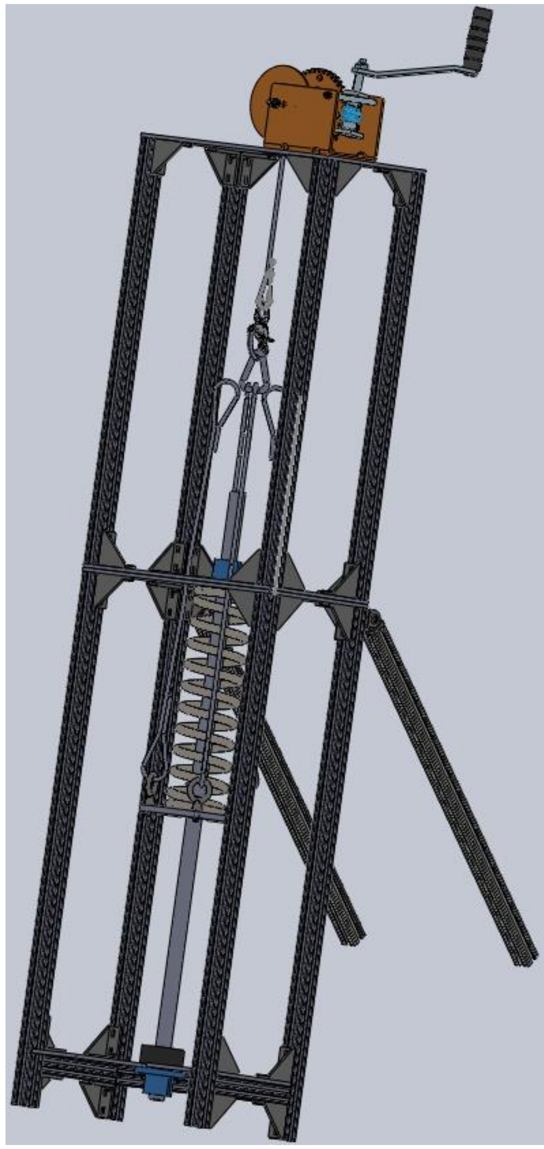


Figure 29: Integrated spring control mount and bottoms support structure including the pivot arms to facilitate angled impacts. The shaft collars are highlighted in blue.

3.1.7.4 Control of the Headform

The next challenge was to design the mechanism that allows for control of the headform in the loading and firing phase as well as release prior to impacting the ground.

3.1.7.4.1 Ball arm Design Considerations

From the evaluation phase, the concept that emerged was to use a ball arm and a linear bearing on a monorail. Use of a ball arm is common in helmet testing as it allows for easy adjustment and fixation of the head in the three rotational degrees of freedom about the COG of the head. In the Orthopaedic and Injury Biomechanics Lab, a ball arm is used in conjunction with a guide follower system on a linear monorail as a test apparatus that adheres to most standardized helmet testing protocols (see Figure 30). This design allows for the ball arm to be fixed under the chin of the ATD head with the center of the ball being near to the COG of the head. A single axis accelerometer (sensing axis being parallel to the drop axis) can then be mounted at the center of the ball to measure the severity of the impact.

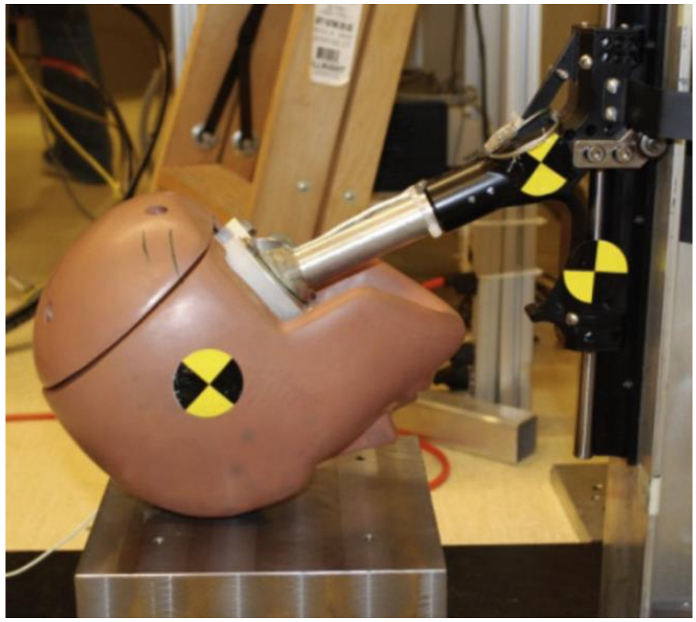


Figure 30: Monorail guide follower, ball arm and headform. Note: the ball arm is partially inside the headform.

One unanticipated challenge that was faced when looking to implement a ball arm with the Hybrid III headform was that the instrumentation needed to make the head free from external cables (ie. DAQ, accelerometers, power supply) would be mounted in the same place the ball sits for the linear monorail design. Additionally, if the ball arm penetrated the envelope of the headform, breakaway prior to impact would not be possible in all orientations. Given these concerns, the ball arm design was reconsidered.

A possible solution would be to mount the ball arm to the external surface of the Hybrid III headform. This would achieve manipulation in three rotational degrees of freedom and a breakaway mechanism could be designed into the shaft of the ball arm. However, any additional mass still attached to the headform after breakaway is unacceptable as it will change the mass moment of inertia of the head; something that would be of great concern to the research and standards community.

3.1.7.4.2 Alternative Design Considerations

As an alternative, the ball arm design was abandoned and other solutions were investigated. Two concepts that emerged from brainstorming including a scissor grab mechanism and a spring loaded clamp as seen in Figure 31 and Figure 32. A benefit to designing the head control mechanisms as standalone offers the benefit of the head being free from rigid attachment to the carriage. With that said, interaction with structures during deployment, fast release of the headform, precision in holding the head in the desired orientation and quick test reset must be considered moving forward.

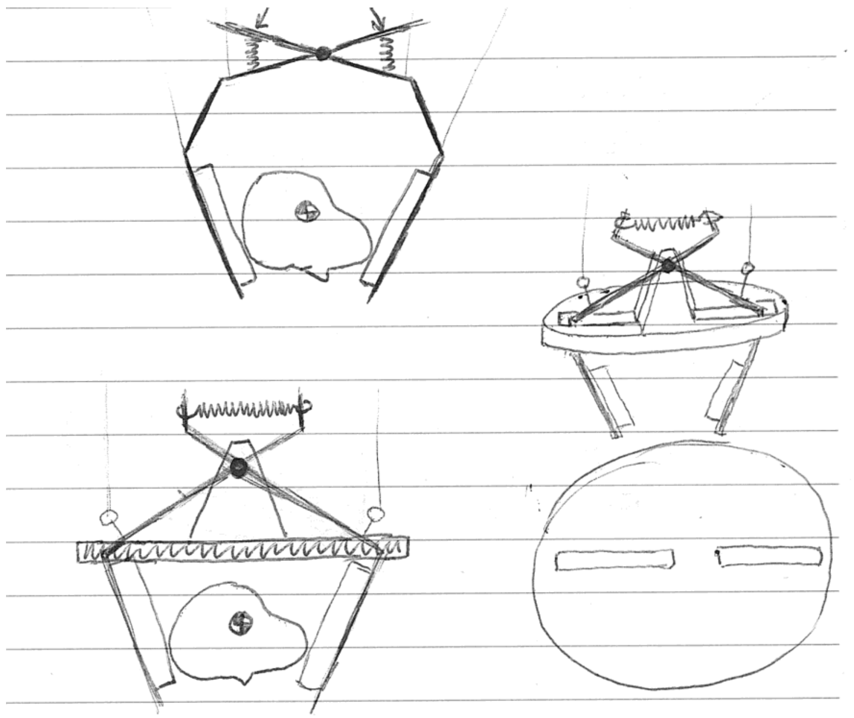


Figure 31: Scissor grab mechanism concept sketch to control and release the headform

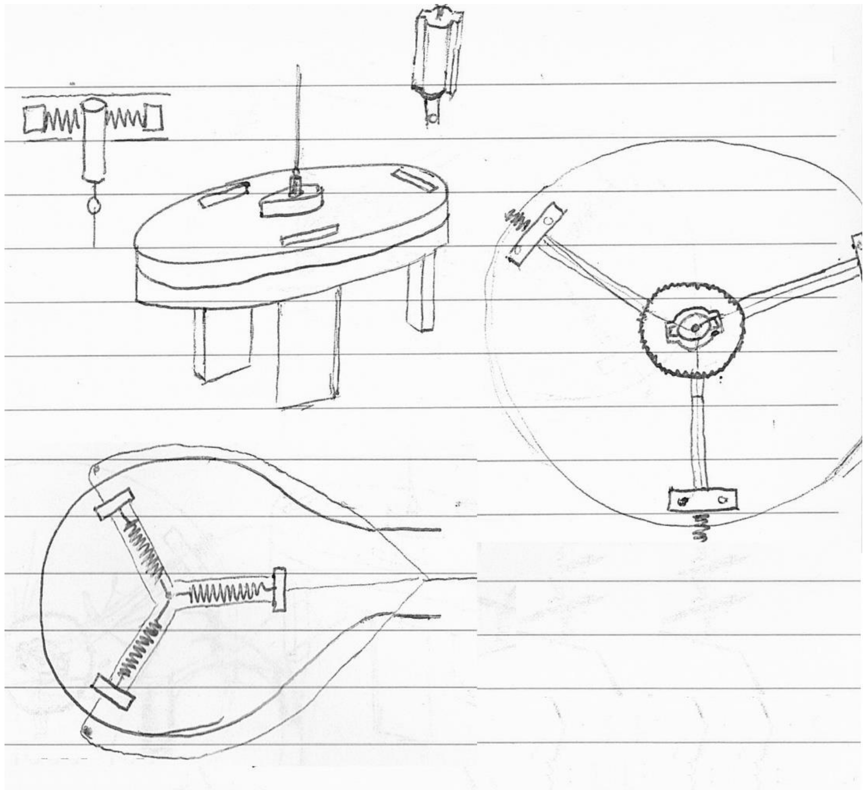


Figure 32: Spring Clamp Release mechanism to control and release the headform

Although both concepts offer means to quickly release the head at a desired displacement from when the spring reaches its neutral position and reset the test swiftly, there was concern that the scissor grab mechanism would not get out of the way of the headform quickly enough, causing rotation of the head. For this reason, the spring clamp mechanism was investigated further.

Elaborating on the design of the spring clamp mechanism, examination of potential clamping methods was necessary. In order to apply a constant inward radial force to the head, a means of constraining the slide bars is necessary. As shown in Figure 33, set interval (hard stop or constraint pin) or infinite interval concepts were generated. Given the adjustability of using a threaded rod and nut to loosen or tighten the clamp slide, this concept was selected.

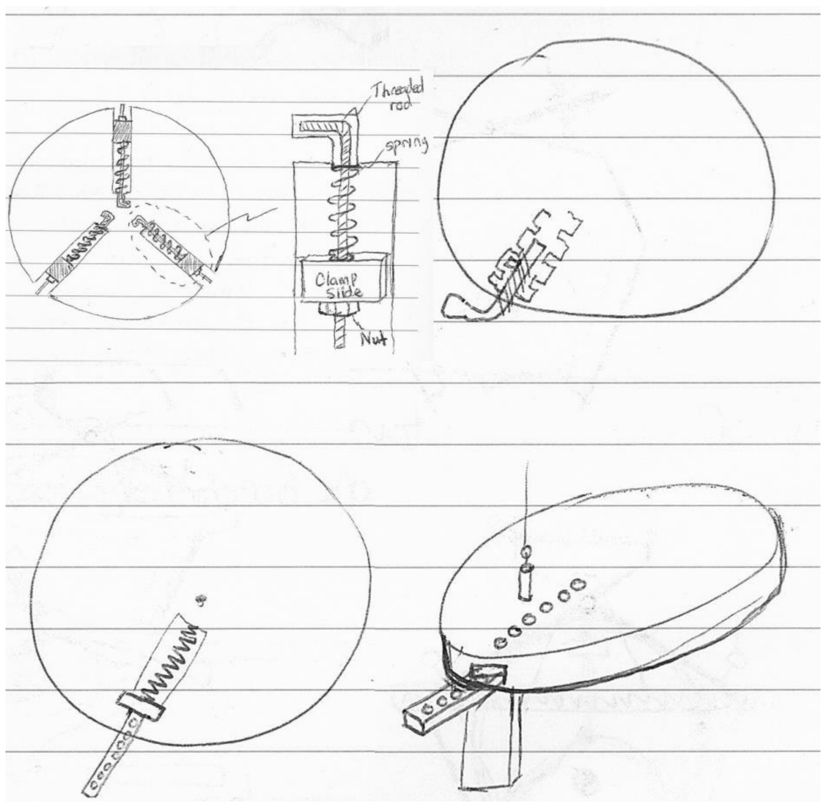


Figure 33: Head release mechanism concepts

3.1.7.4.3 Selected Head Control Mechanism Concept

With the spring clamp mechanism selected, detailed design was undertaken. The components of the design include the support plate, the clamp slides, the threaded rod and nut, and the spring.

Given that the clamp slide must be free to slide radially but be constrained in the axial direction, a multilayer approach to the support plate was taken. This would allow for easy fabrication of complex geometries using a waterjet and easy assembly using common fasteners. A 3-layer plate assembly was chosen using 0.25" thick 6061 aluminum. With a slightly larger slot width on the middle plate, a single degree of freedom is provided for the sliding clamps. The three layers were fixed together using six circumferential fasteners with wing-nuts for easy assembly. Ninety degree channels were cut into the top of the slots in the middle and top plates to allow for the spring to be compressed radially and then locked into place with threaded rod with a ninety degree bend (see Figure 34).

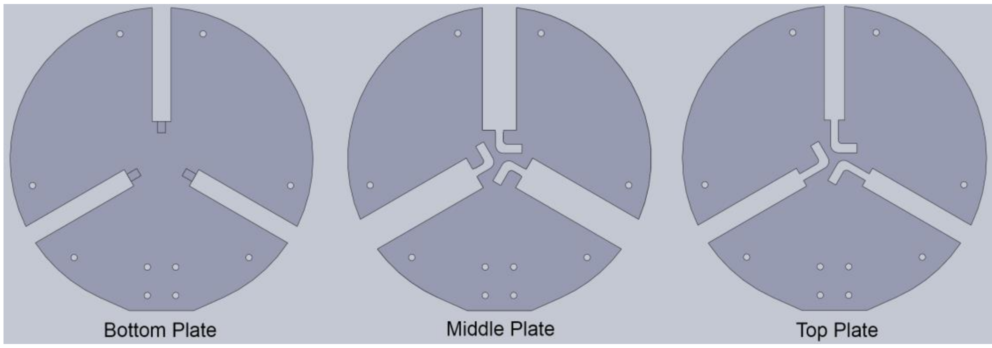


Figure 34: Profiles of the three plates that make up the main platform for the head release mechanism.

Based on the need to translate freely out of the way once triggered, the material selected for the slide clamps must be low friction as well as light and corrosion resistant. A material that satisfies all of these requirements as well as being commonly used in biomechanical apparatuses due to its low wear, machinability and radio-transparent nature is ultra-high molecular weight polyethylene (UHMWPE; http://www.polytechindustrial.com/products/plastic-stock-shapes/uhmw-polyethylene). For these reasons, UHMWPE was chosen as the material for the clamp slides (seen in Figure 35).

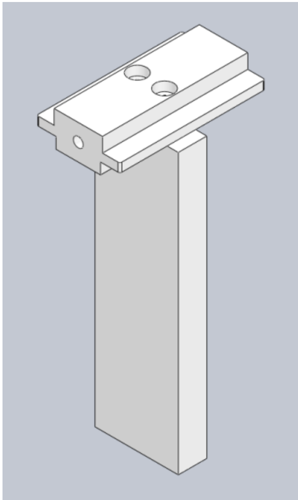


Figure 35: 3D rendering of the slide clamp design

In selecting the springs, the most important requirement was to push the slide clamps out of the way quickly to prevent interaction with the headform. As such, the spring must be stiff and allow for compression over a relatively large distance to allow for a full range of adjustment (ie. for a helmeted and unhelmeted head). Zinc coated (moderate corrosion resistance), steel springs with a rate of 26.5 lbs/in (4.64 kN/m) and the ability to compress 4.29 cm.

The threaded rod used to lock the spring in place was 10-24 steel and a flanged nut was used to constrain the slide clamp. The nut also served as a means to adjust the radial location of the slide clamp and therefore secure or loosen the head in place. A 3D rendering of the head control mechanism can be found in Figure 36.

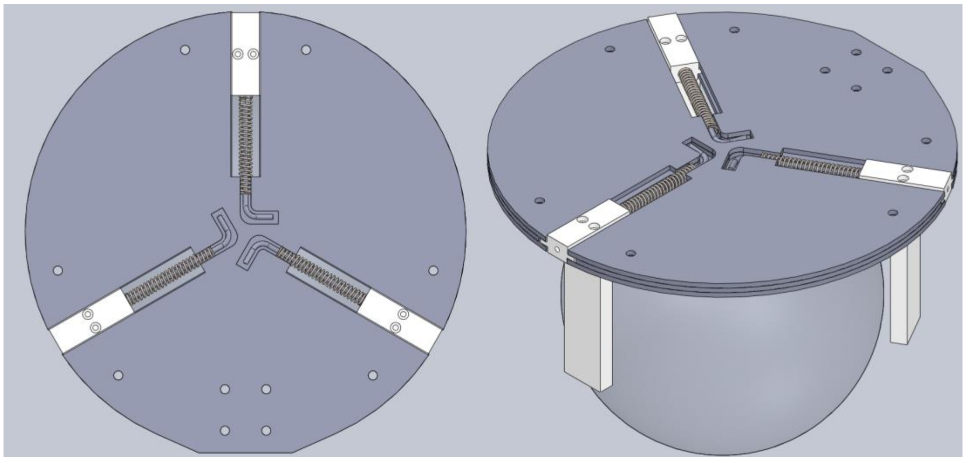


Figure 36: Final design of the head control mechanism. Note: the sphere recommends the approximate geometry of a helmeted headform

3.1.7.5 Guide Rail and Bearing Mount

The final aspect in the design of the snow sport head impact test apparatus is to define the method of constraining the head control mechanism to an axial motion. With a rail system emerging as the best solution for this, previous aspects of the design have been made to accommodate a centrally mounted rail. As such, a means for the head carriage to be attached and translate on the rail was necessary.

3.1.7.5.1 Linear Bearing Selection

The biggest consideration in designing for linear motion of the head control mechanism is the forces imparted due to the impulse when the loaded spring is released. As an initial step, Saint Venant's principle was considered so that alignment of the bearings with the shaft and necessary bearing spacing is incorporated optimize force transmission and therefore prevent jamming of the bearings. The principle suggests that the distance between bearing pairs be at least 3 times the diameter of the shaft.(124) Next, an understanding of the forces that the bearing system must take was investigated using a free body diagram and force/moment balance (shown in Figure 37). To investigate the worst case scenario, the trigger event was analyzed instantaneously with the inertial reaction force of the headform being equal to the spring force (assuming a horizontal rigid beam between the two).

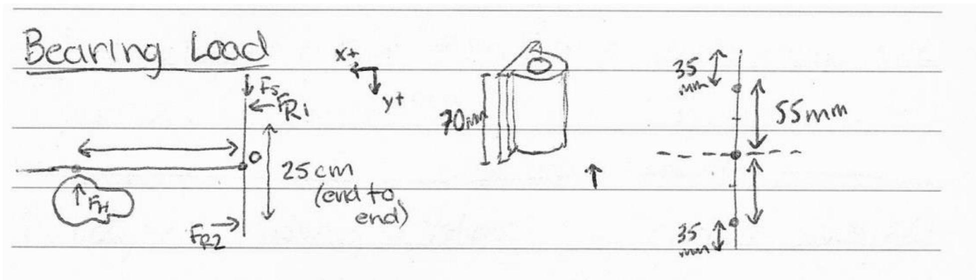


Figure 37: Free body diagram to determine the necessary geometry of the bearing mount. Although several iterations were performed in an attempt to optimize the moment arms, this particular calculation uses a horizontal distance of 0.3 m for the head with the bearings spaced 0.11 m apart.

This analysis was iterated in an attempt to optimize the distance between the bearings and the distance away from the central shaft that the head is placed. It was found that by decreasing the horizontal distance of the head placement (vertical reaction force) and increasing the vertical distance of the bearings, the horizontal reaction forces acting on the bearings is reduced. It became apparent that large bearings were necessary to satisfy the radial load rating required and as such, alternative means of balancing the moment were investigated. By incorporating a counter mass on the opposite side of the rail to the head control mechanism, the moment from the head's vertical inertial force could be balanced effectively (shown by the free body diagram in Figure 38 and Equation 11).

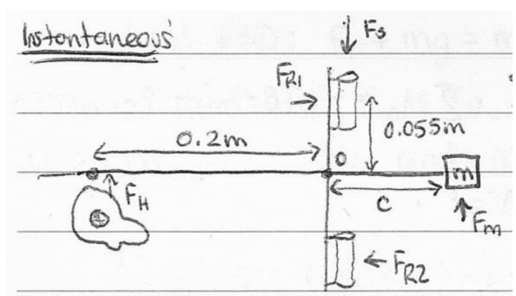


Figure 38: Free body diagram for the bearing mount incorporating a counter mass.

Equation 11: Force and moment balance for the bearing mount configuration

$$\sum F_x = F_{R1} - F_{R2} = 0 \qquad \sum F_y = F_H + F_m - F_s = 0$$

$$\sum M_o = (F_H * 0.2m) - (2 * F_R * 0.055m) - F_m * 0$$

Once the counter-mass concept was incorporated, more standard bearing designs could be considered. As such, a self-aligning, linear ball bearing with housing was selected which has a 648 lb (3042 N) dynamic limit (specifications shown in Appendix D: Product Specification). The final geometry of the bearing mount involves the bearings being placed 0.23 m apart vertically (measuring from the center of each bearing) with the center of the head control platform (point at which the head's reaction force is applied) being 0.2 m in the horizontal direction. This horizontal distance was mimicked for the counter-mass.

It was later realized that this analysis was extremely conservative given the force and moment balance (shown in Figure 37) considered the static scenario. In an effort to estimate more realistic forces, an analysis to understand the acceleration of the whole head release mechanism system was conducted. This acceleration was then used to calculate a more accurate inertial force that the headform imparts on the release mechanism plate (shown in Figure 39 and Equation 12). This analysis illustrated that the inertial force of the head during triggering is significantly less than the previous conservative estimate and a safety factor of 2.10 was determined for the radial load on the bearings.

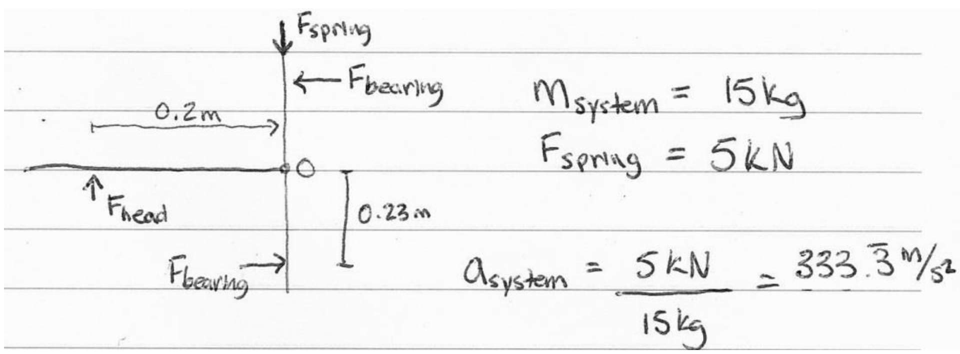


Figure 39: Revised free body diagram and calculation for estimating the force imparted on the release mechanism by the head.

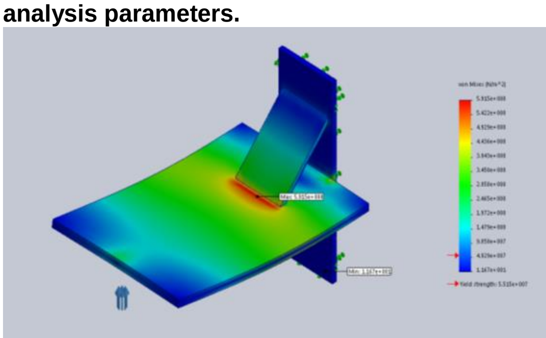
Equation 12: Calculations to determine the bearing load and safety factor using Newton's law.

$$F_{Head} = m_{head} * a_{system} = (5kg) * \left(333.3\frac{m}{s^2}\right) = 1666.7N$$

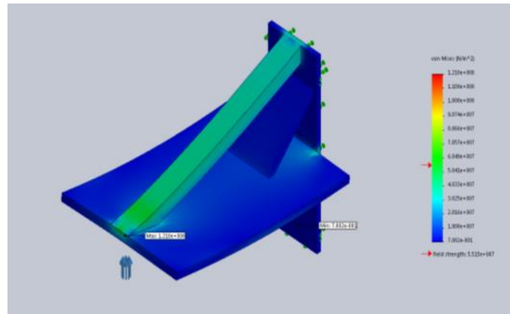
$$\sum M = (1.67kN) * (0.2m) - 2 * F_{bearing} * \left(\frac{0.23m}{2}\right) \rightarrow F_{bearing} = 1449.3N\ (2.10\ Safety\ Factor)$$

The final consideration for this aspect of the design includes investigation of the stress and strain in the head control mechanism to minimize stress and therefore deflection, which may cause unwanted acceleration and/or shifting of the head's orientation prior to impact. This was achieved using the Solidworks Simulation tool (Table 8). The simulation was set up to include a point load applied at the center of the head control plate and a fixture at the surface on which the bearings were mounted. As a first step, a simplified geometry was analysed using 6061 aluminum. With the findings of this analysis illustrating a significant deflection in the plate, the study was iterated to include the exact geometry and manipulate the mesh size as well as add features such as trusses and brackets to stiffen the structure. In the later iterations, more focal bearing fixtures (vs. the whole bearing mount plate) were included.

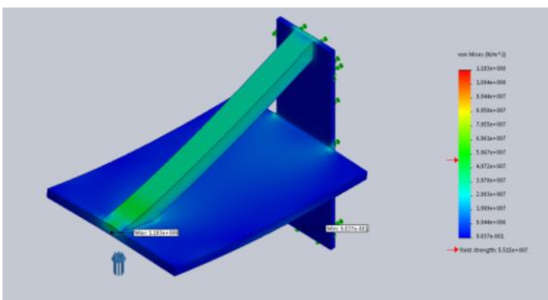
Table 8: Solidworks Simulation iterations showing stress investigation of several configurations and analysis parameters.



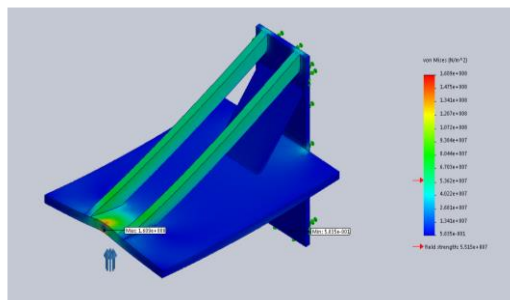
Simplified Geometry; Coarse Mesh; Surface Fixtures; Max. Disp. = 32.3 mm



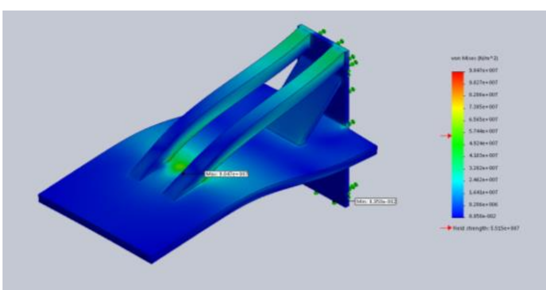
Simplified Geometry; Coarse Mesh; Surface Fixtures; Max. Disp. = 0.60 mm



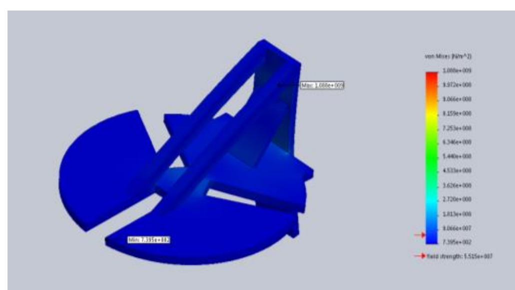
Simplified Geometry; Coarse Mesh; Surface Fixtures; Max. Disp. = 0.60 mm



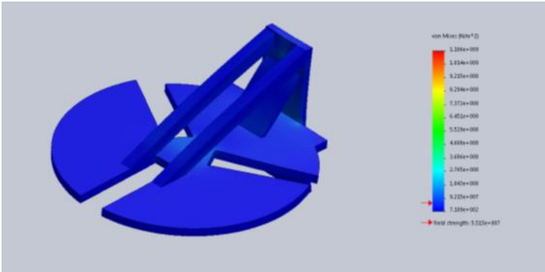
Simplified Geometry; Coarse Mesh; Surface Fixtures; Max. Disp. = 0.89 mm



Exact Geometry; Fine Mesh; Surface Fixtures; Max. Disp. = 0.34 mm



Exact Geometry; Fine Mesh; Focal Fixtures; Max. Disp. = 3.88 mm



Exact Geometry; Fine Mesh; Focal Fixtures;
Max. Disp. = 3.43 mm

As a result of this analysis, two trusses were added to the head control/bearing mount design to increase rigidity. Additionally, 80/20 brackets were added to both mount the head control mechanism to the bearing plate and increase rigidity. Specifications for these brackets can be found in Appendix D: Product Specification.

3.1.7.5.2 Selected Guide Rail and Bearing Mount Concepts

Additionally, two aluminum 80/20 brackets were added to mount the head control mechanism to the bearing plate and increase rigidity. Specifications for these brackets can be found in Appendix D: Product Specification. A custom steel plate acts as a rigid interface between the head control mechanism and linear bearings. Two self-aligning, linear ball bearings with closed housing (Schaffer; KGNZ-16PP) were selected based on their profile, availability and load limit. Fasteners with a smaller diameter than the holes pre-drilled in the bearing were used to allow for shaft alignment before securing. The central shaft was selected to be a 1” diameter, anodized aluminum linear shaft (see Appendix D: Product Specification) and as such the bearings selected accommodate a 1” diameter. The counter-mass includes a customized steel plate with two cylindrical A36 hot rolled steel masses mounted 0.2 m from the bearing plate. A 3D rendering of the final design is shown in Figure 40.

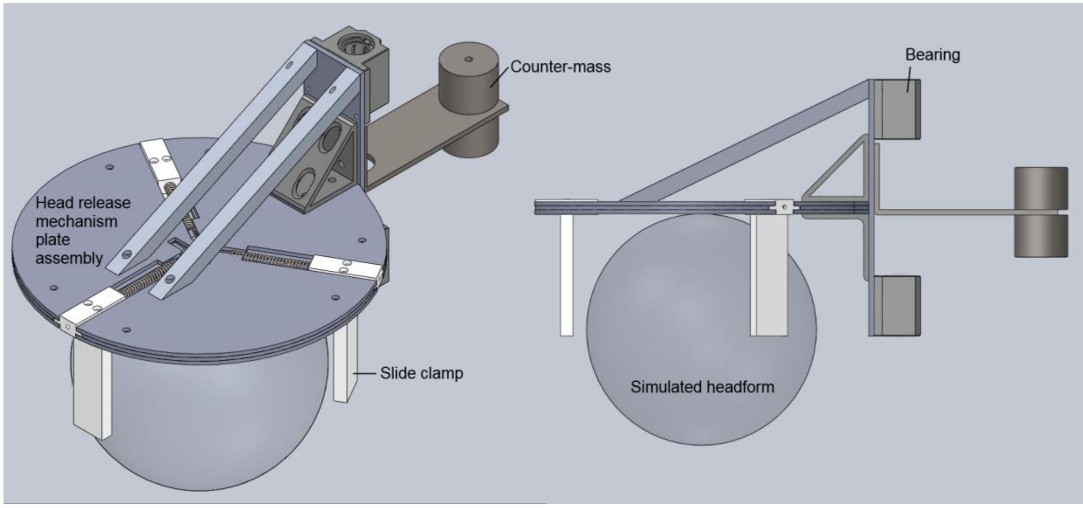


Figure 40: 3D rendering for the final design of the bearing mount (including the head control mechanism) and counter-mass

3.1.7.6 Additional Design Components

3.1.7.6.1 Headform Containment

As the cable-free headform is anticipated to be travelling 10 m/s at impact, an oblique impact may result in significant excursion from the test apparatus. For the safety of those performing the testing as well as nearby snow sport participants, the headform must be contained. As determined in the evaluation, a padded barrier around the perimeter of the impact area will be used for containment. Simple aluminum frames will be fixed to the back of the pads so they can be securely placed in the snow.

3.1.7.6.2 Velocity Measurement

Velocity measurement is an important aspect of helmet testing standards as multiple impacts are performed which all must be within a certain percentage (defined as +/- 5% for most certification standards) of the desired velocity. The concept that was selected involves integration of the linear resultant acceleration prior to impact. This method will involve development of a post processing algorithm to give an impact velocity shortly after the test is performed. High speed video of the impact will be used to validate this method.

3.1.7.6.3 Impact Surface Maintenance and Characterization

One challenge of on-snow testing is the variability in the impact surface. Although snow testing is important to recreate a real-world impact scenario, maintenance and characterization of the surface must be considered. The concept that was selected to do this involves a prescribed raking protocol of the impact surface. Following removal of excess loose snow from the top of the surface using a shovel, two passes of a standard aluminum, fine tooth rake will be performed without addition of force (ie. only the mass of the rake). Additionally, the snow surface will be characterized using a tool designed to measure snow hardness (www.SnowPak.net; Fraser Instruments Ltd., Vancouver, BC). A snow profile will be dug within a 1 m radius of the impact site and the tool will be used to generate a hardness profile for the first 0.3 m of the snowpack. This will allow for comparison of hardness to tests performed in other areas with different snow-packs. Figure 41 shows the SnowPak tool being using on a snow profile.

Figure 41: Demonstration of the SnowPak tool to measure the snow hardness as different snow layers. Image taken from www.snowpak.net.

3.1.7.7 Hybrid III Head Modifications

Although the headform is not directly associated with the design of the test apparatus, several modifications had to be made in order for it to function as a free motion headform (all instrumentation mounted inside the head). The steps involved sourcing the appropriate power supply and cables for the DAQ, modification and calibration of accelerometers, fabrication of an instrumentation mounting bracket, fabrication of a base plate and addition of multiple gaskets.

Given Diversified Technical Systems (DTS; Seal Beach, CA) were in the process of developing the appropriate hardware to convert existing Hybrid III ATD headform's into a free motion headform's, much communication was necessary to provide insight into this particular application. An engineering drawing was provided by DTS for the instrumentation mounting bracket. Given its complex design, fabrication of this part was contracted out. Figure 42 illustrates the mounting bracket design.

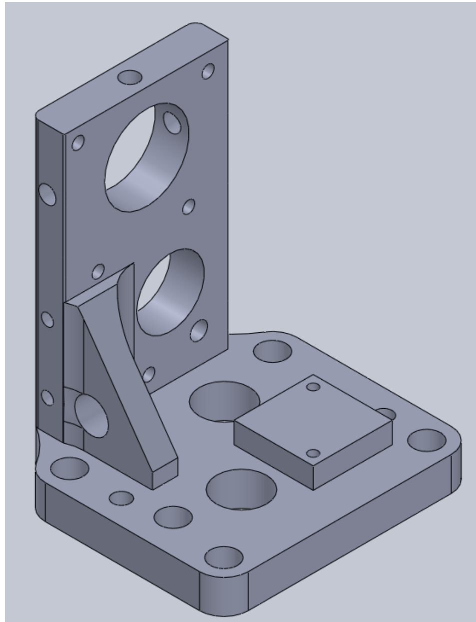


Figure 42: Instrumentation mounting bracket designed by Diversified Technical Systems (Seal Beach, CA)

Additional hardware specified and purchased from DTS necessary to arm and power the DAQ system included a USB Interface Kit, an Extended Battery Stack and several cables. Once implemented, this system allowed for arming of the DAQ, removal of all external cables, data to be collected during testing once a pre-defined acceleration threshold is exceeded, reconnection to a computer and download of the test data.

One further step to equip the headform with the appropriate accelerometers was to significantly shorten the cables so as to not influence the overall mass of the head (ie. 15-20 ft. of cable for each of the 3 sensors). In doing this, the sensitivity of the sensor changes due to the new cable resistance. To recalibrate the sensors once the cables were cut, repeated linear headform drops were conducted with a cut cable accelerometer mounted in the same axis as an accelerometer with a known sensitivity. Five drops were conducted from two different drop heights and the accelerations were compared. Average sensitivities and standard deviations were calculated for the repeated impacts. All standard deviations for the calculated sensitivities were found to be less than 0.001 mV/g. Data from the calibration testing can be found in Appendix C: Detailed Design.

As the Hybrid III headform is designed to either fix a ball arm mount or cervical neck to the region under the jaw, a custom plate was designed to both seal the hole in the headform and serve as a flat, secure surface to mount the instrumentation mounting bracket on. As such, a simple design was employed which included 4 holes to mount it to the headform and four holes for the instrumentation bracket to be mounted to the base plate (Figure 43). The two smaller holes are for dowel pins to locate the proper orientation of the instrumentation bracket.

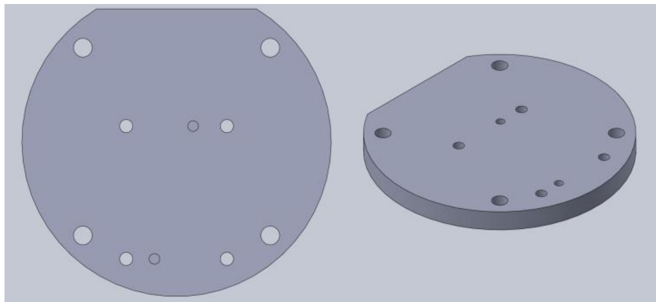


Figure 43: Head base plate design to seal the headform and to act as a mounting surface for the instrumentation bracket

To keep moisture from the electronics inside the head during on-slope testing, it was important to design and fabricate seals for the openings in the head. To do this, rubber matting was purchased and custom shapes were cut to fit the exact geometry of the openings (Figure 44). These gaskets are held in place by compressive forces imparted by the mating structures and fasteners.

Figure 44: Custom gaskets made to keep moisture from entering the headform during on-slope testing

As a result of this work, an isolated headform free from external cables was made possible. The overall configuration of the mounted DAQ and sensors can be seen in Figure 45.

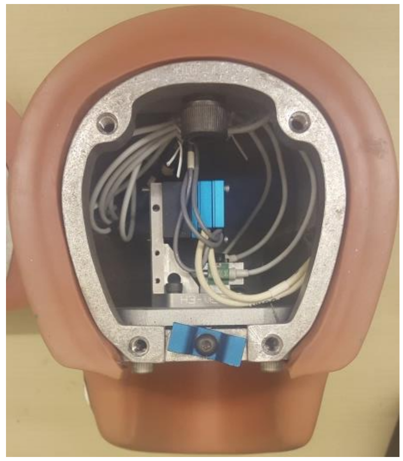


Figure 45: A view of the instrumentation mounted inside the Hybrid III headform. This configuration allows for the headform to be used for testing without being attached to external cables.

3.2 Final Design

Once all of the detailed design was completed, it was important to combine all of the components to detect any issues in integration. This was first done by creating a 3D model of all components (excluding hardware) and building a geometrically accurate apparatus in a virtual space. This process was extremely valuable to understand general form, identify overlap in tolerances and visualize constrained movements (ie. head carriage on rail; pivoting arms to lean structure back). A complete 3D rendering can be seen in Figure 46.

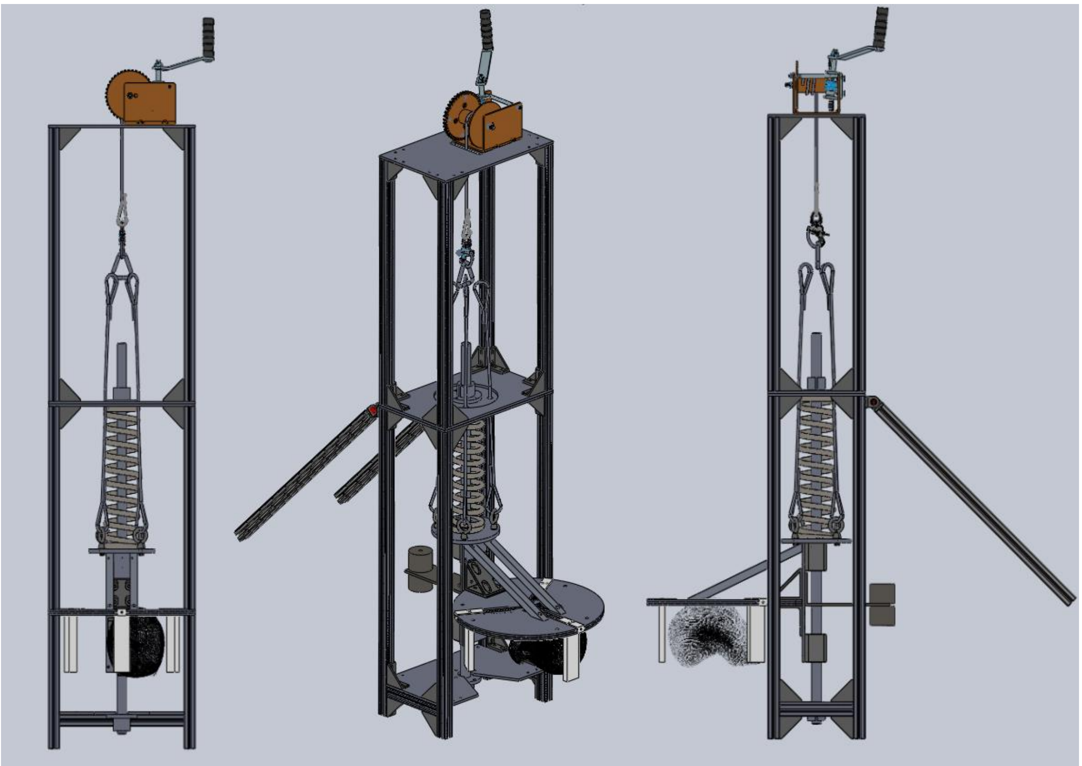


Figure 46: Complete integrated rendering of the final design for the snow sport head impact simulator. A semi-transparent headform was inserted to visualize issues with head placement.

To perform a test using the apparatus, a short procedure is followed. First, the headform should be armed using the Slice DAQ software and disconnected from all cables. It can then be places in the desired orientation within the slide clamps. Once the headform is in place, the slide clamps can be pushed radially toward the center, engaging the springs, until the 90 degree bend in the bolt can be located in the plate channel. The slide clamps can then be adjusted by loosening or tightening the flanged bolts. Next, string tethers should be tied to the bolt ends located in the plate channels. The strings can then be cut to the same length and tied to the trigger release bar. This trigger release bar is then moved up or down the structural supports according to the desired point at which the headform is to be released. To seat the head release mechanism to the base of the spring, a static lanyard should be strung between the carriage and the snap shackle trigger. Lastly, the desired angle of impact should be set by leaning the apparatus back on the pivot arms at the desired angle.

Once all wire rope lanyards are looped through the carabiner, the carabiner should then be connected to the snap shackle trigger. The system is now ready to be wound. This is done by cranking the hand winch slowly until the compression gage reaches the desired value. The apparatus can then be fired by inserting the release pin into the snap shackle trigger. The basic steps to perform a test are shown in Figure 47.

Figure 47: Schematic of the final design including the main steps to performing a test

3.3 Fabrication

Like many mechanical designs, a mix of commercially available and custom components are necessary for the physical structure to be built. As such, a full bill of materials was generated to outline the components needed for fabrication of the final design (see Appendix C: Detailed Design). The total cost of materials for this apparatus is approximately $2015.49 CAD (approximate due to variations in currency conversion). All labour, with the exception of swaging for the wire rope ($157.14; Pro-Tech Yacht Sales, Vancouver, BC) and fabrication of the instrumentation mounting bracket ($580.00; work performed by the UBC Mechanical Engineering Machine Shop), was completed independently. Machining processes for this design included waterjet cutting, milling, cutting (band saw), drilling, tapping, filing, swaging, bending and grinding as well as the use of hand tools for assembly. Figure 48 and Figure 49 show the completed design being tested in the OIBG lab while shows on snow testing, respectively.

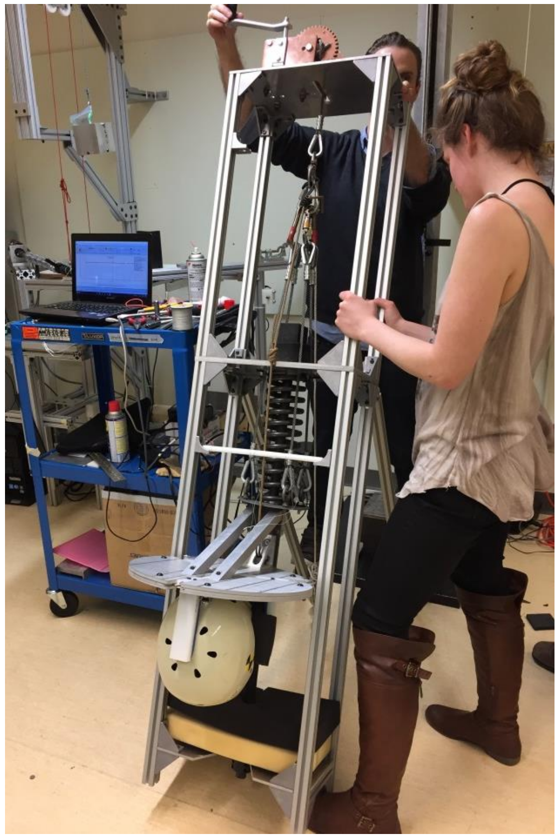


Figure 48: In-lab testing of the final apparatus design.

Figure 49: On-snow testing at Cypress Mountain of the final apparatus design. Alan Nursall (Alan Nursall Experience, Daily Planet Television Show) is shown with the production crew.

4.0 VERIFICATION OF A SNOW SPORT HEAD IMPACT TEST APPARATUS[5]

4.1 Introduction

Use of standardized testing for sport helmets dates back to 1961 where impact attenuation efficacy was investigated performing guided drops.(125–127) Although original efforts were to design protocols that would be representative of real-world impact scenarios, many simplifications were made in adapting such events to a laboratory setting. These simplifications are even more apparent for sports which involve variable impact conditions such as skiing and snowboarding.

Current snow sport helmet certification testing is generally characterized by a linear impact of a helmeted anthropomorphic test device headform to a metal anvil from heights of 1.5 m – 2.0 m (5.4 m/s – 6.3 m/s). Acceleration in the drop axis, at the head at the center of gravity, is measured and compared to a prescribed pass/fail threshold. (72–75) Figure 50 illustrates a schematic of a test apparatus to be used in such shock absorption tests. (72) With only small variations in the acceleration threshold defined in these standards (250 g – 300 g peak linear acceleration), the magnitude of most standards criteria is representative of severe head injury such as skull fracture.(62) Although higher severity, linear injuries are important to prevent against, head injury suffered from snow sports participation includes a spectrum of mechanisms and severities including minor and more severe concussions; arguably something test standards should reflect.

[5] A portion of this chapter has been submitted to the an international conference for consideration to be resented and be published in the conference proceedings.

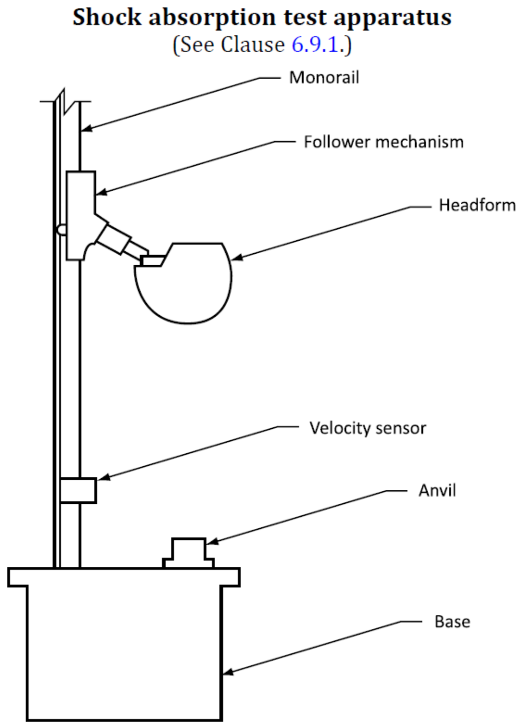


Figure 50: Schematic of a test apparatus used in a snow sport helmet impact attenuation test. This image was taken from the Canadian Standards Association standard Z263.1-14 Recreational alpine skiing and snowboarding helmets. (72)

Although many studies investigate the epidemiology of snow sport head injury, this lacks specific information detailing the mechanism of fall and correlations between mechanism and injury severity. Bailly et. al. (2016) performed a prospective study for which snow sport participants who reported to several trauma centers were surveyed to understand the nature of the accident.(67) This investigation found the top three mechanisms to be falls (54%), user-user collisions (18%) and jumps (15%) while collisions with obstacles was found to be the most common mechanism associate with severe TBI.(67) This is supported by the findings in chapter 2.0 that found jump impacts, falls from height and impact with objects to be associated with an increased risk of moderate, or worse, head injury. Further, clinical data presented in chapter 2.0 reported a high prevalence of concussive injuries among the injured ski and snow population.

With a better understanding of real-world snow sport head impact, kinematic scenarios can be developed to inform the design of more relevant test apparatuses and protocols. High tangential velocities suggest testing should include oblique impacts at variable angles as well as higher velocity impacts. As concussion was found to have a high prevalence, an injury that is associated with a lower energy threshold (ie. 53 g - 169 g; 5022 rad/s^2 – 7600 rad/s^2), a lower velocity test should also be incorporated.(91–98) As mechanisms associated with head to snow contact (ie. falls, jump impacts and falls from height) were found to be the most prevalent of all mechanisms, an argument for helmet testing to be performed on snow is made. Finally, to represent kinematics that are relevant to all injury types and severities (for the primary impact event), an anthropomorphic test device headform that is unconstrained at impact should be used. In a study by Mills and Gilchrist (2008), the influence of the neck in head impacts was investigated through full-body ATD, helmeted, head first impacts. It was observed that the neck had no influence on the head's kinematics in the first 40 ms of the impact and that the force experienced by the helmet was equal to the acceleration of the headform multiplied by the mass of the headform.(128) With head to snow impulse duration generally being 10 ms – 20 ms, use of an untethered, free motion headform is found to be appropriate.(90)

The objective of this work is to investigate the test apparatus outlined in chapter 3.0 for its suitability in representing snow sport head impact. Suitability will be evaluated based on the design requirements and the associated metrics set forth in chapter 3.0. Design requirements will be verified or contested by performing a series of tests. Through verification of this design, a test apparatus capable of representative head impact will be confirmed and aid in improved evaluation of snow sport head protection.

4.2 Methods

4.2.1 Apparatus

The test apparatus to be verified is described in detail in chapter 3.0 of this report and Is based on mechanics identified to be relevant to snow sport head injuries through clinical and biomechanical data. These include variable impact velocities between 3.6 m/s and 10 m/s, variable impact angles and impacts with snow-like surfaces (achieved by making the test device portable). The apparatus employs a large compression spring that can be loaded by way of a precision worm gear winch. Once the spring is loaded to the desired load, corresponding to a specific impact velocity, it can be released under load with a trigger snap shackle. A carriage, which holds the headform in the desired orientation, is accelerated by the spring and translates along a central rail. Once the carriage reaches a pre-defined height above the impact surface, a spring mechanism on the carriage is triggered, releasing the headform and allowing it to travel the remaining distance in free fall. Figure 51 shows the overall construction of the apparatus. The apparatus was designed to satisfy the novel requirements listed in Table 9 and will be evaluated accordingly.

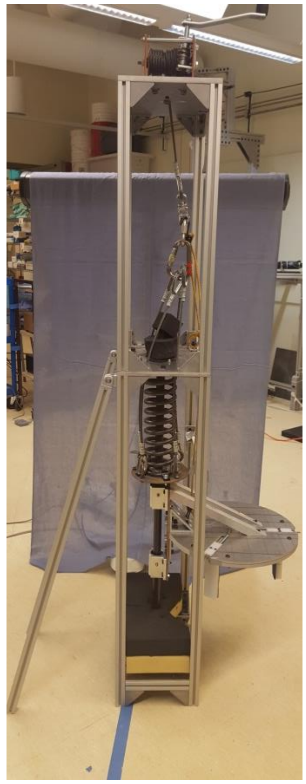


Figure 51: A side view of the test apparatus being verified.

Table 9: Summary of the design requirements of the snow sport head impact apparatus.

Protocol Requirement	**Justification**	**Metric**
Variable impact angle	High tangential, travelling velocities leading to oblique impact	15 degrees to 90 degrees (15 degree increments)
High velocity impact test	High average travelling speeds result in high velocity head impact	10 m/s
Low velocity impact test	High prevalence of concussion (low energy injury)	3.6 m/s
Impact with snow surface	High prevalence of head to snow mechanisms	Pass/fail
Unconstrained headform impacts	Measurement of biomimetic (primary impact) response	Pass/fail

4.2.2 Experimental Verification Testing

In order to verify that the test apparatus is able to meet the overall requirements listed above as well as those detailed in section 3.1.3.1, including head orientation at impact and impact velocity, a test matrix was developed. All tests were performed at 90 degrees to the ground and the impact surface was a hard linoleum ground covered by a 2" low-density foam pad. Once at least two fiducial markers, placed on the headform over the temple and the apex of the temporal region (side), were manually selected in the software, absolute velocity for each point and angular displacement and velocity of the rigid body are automatically calculated. Impact location is quantified by comparing the relative angular displacement of the two points, compared to a fiducial marker placed on the apparatus support structure, at the time the head is released and the time of impact. In addition to investigating these parameters, repeatability was investigated through three successive tests for each configuration. In order to be deemed repeatable in the context of this testing apparatus, the following criteria are to be satisfied for the three consecutive tests:

- Impact velocity must be within +/- 5%
- Impact location on the head must be within a 2 cm radius

To investigate the angles for which the apparatus is capable of being used, it was set up in several scenarios from 90 degrees (to the horizontal) to 15 degrees, at 15 degree intervals. Angle was measured between the ground and the most posterior support structure on the apparatus.

4.2.3 Instrumentation

Given the overall aim to have the test apparatus be portable for on-slope testing and facilitate high velocity, oblique impacts, instrumentation was selected to allow for all components to be contained within the headform and free from cable attachments. A Hybrid III ATD (Humanetics, Plymouth, MI) was modified to include a rigid aluminum plate and several gaskets to seal the headform from exposure to moisture. A DTS Slice Nano Data Acquisition System (DAQ) (Diversified Technical Systems, Seal Beach, CA) was fixed to a custom mounting bracket and installed inside the head near the center of gravity. Three, single-axis, Endevco accelerometers (7264C-2K, Meggitt PLC, Christchurch, UK) were mounted near the COG on the custom mounting bracket and connected to the SliceNano DAQ. The instrumentation mounted in the Hybrid III headform can be seen in Figure 45 in section 3.1.7.7.

Using a DTS USB Interface Kit (Diversified Technical Systems, Seal Beach, CA), and SliceWare DTS software (Version 1.06.0491), the sensors were armed to a circular buffer with an acceleration trigger threshold of 30 g, all cables were detached and the headform was sealed. Data was collected at a rate of 20 kHz. Following the test, the DAQ was plugged back in and data 0.5 seconds pre-trigger (exceeding a 30 g threshold) and 2.0 seconds post-trigger was downloaded. Post processing was done using Matlab software (Natick, MA). Signal conditioning and data filtering was consistent with SAE J211.(129) Once the data was filtered, resultant linear acceleration was calculated and plotted to determine the peak value.

4.2.4 Analysis

Impact velocity was measured using post-test analysis of high speed video (sampled at 2000 frames per second) of the sagittal plane was performed using TEMA motion tracking software (Linkoping, Sweden). Fiducial markers on the ATD were then used to determine the number of pixels per meter. This calibration was applied to measure the velocity of the headform in the 10 frames prior to impact. Relative orientation of fiducial markers was tracked and impact location was compared across the three trials. This method also allowed for impact angle to be quantified and compared by observing the trajectory of the markers.

Each requirement set forth with respect to angle, velocity and location was investigated to ensure desired values and range was achieved. For all measured variables (angle, location, velocity), standard deviation and percent from the desired value was calculated for repeated impact scenarios.

4.2.5 Spring Rate Investigation

In an effort to verify the spring rate defined by the manufacturer matches the actual spring rate of the spring, testing was performed. The spring was loaded in a materials testing machine (Instron 8800; Norwood, MA). The program involved position controlled loading of the spring to a maximum of 40 mm, relative to the preload compression. A linear line of best fit on a plot of load vs. displacement was used to determine the slope, and therefore spring rate.

4.3 Results

In total, twenty-one tests were performed in seven different orientations. The test matrix performed as well as the average impact velocities and standard deviations is shown in Table 10. Figure 52 shows a still frame just prior to impact captured from the high speed video for a test performed with a spring deflection of 0.08 m.

Table 10: Test results highlighting the varied test parameters, the desired velocity and measured velocity. Note: all tests were performed at 90 degrees to horizontal

Test No.	Head Orientation	Desired Impact Velocity (m/s)	Spring Deflection (m)	Measured Impact Velocity (m/s)	Average Measured Impact Velocity (m/s)	Meas. Vel. Standard Deviation (m/s)	Percent Deviation from Mean
1	Frontal	3.60	0.030	2.3754	2.509	0.152	6.1%
2	Frontal	3.60	0.030	2.6753			
3	Frontal	3.60	0.030	2.4777			
4	Frontal	5.00	0.045	2.3994	2.393	0.028	1.2%
5	Frontal	5.00	0.045	2.3623			

Test No.	Head Orientation	Desired Impact Velocity (m/s)	Spring Deflection (m)	Measured Impact Velocity (m/s)	Average Measured Impact Velocity (m/s)	Meas. Vel. Standard Deviation (m/s)	Percent Deviation from Mean
6	Frontal	5.00	0.045	2.4164			
7	Frontal	6.30	0.060	3.094	3.094	0.116	3.7%
8	Frontal	6.30	0.060	2.9776			
9	Frontal	6.30	0.060	3.2094			
10	Frontal	8.15	0.080	4.2677	4.344	0.082	1.9%
11	Frontal	8.15	0.080	4.3342			
12	Frontal	8.15	0.080	4.4311			
13	Side	5.00	0.045	3.2024	3.046	0.192	6.3%
14	Side	5.00	0.045	3.1033			
15	Side	5.00	0.045	2.8318			
16	Occipital	5.00	0.045	2.8055	2.949	0.160	5.4%
17	Occipital	5.00	0.045	3.1216			
18	Occipital	5.00	0.045	2.9202			
19	Crown	5.00	0.045	3.2764	3.106	0.162	5.2%
20	Crown	5.00	0.045	3.0874			
21	Crown	5.00	0.045	2.9537			

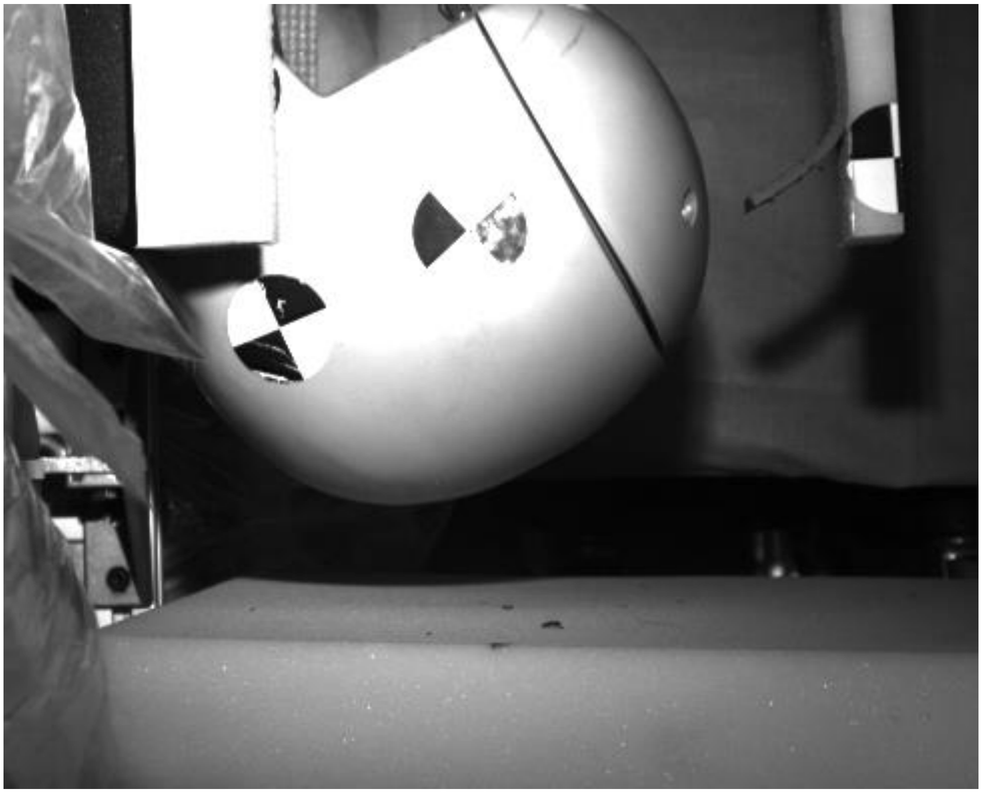


Figure 52: Still frame extracted from high speed video (2000 fps) of the headform prior to impact. The test involved frontal impact at 90 degrees with a spring deflection of 0.08m equating to 4.43 m/s at impact.

Linear acceleration data in three axes was collected and the resultant linear acceleration was calculated. Figure 53 illustrates a time plot of the resultant linear acceleration for the test shown in Figure 52. The two peaks in the plot represent the impulse of the spring acting on the head release mechanism and the head impacting the ground, respectively. The peak linear resultant acceleration for this test was found to be 185.06 g's.

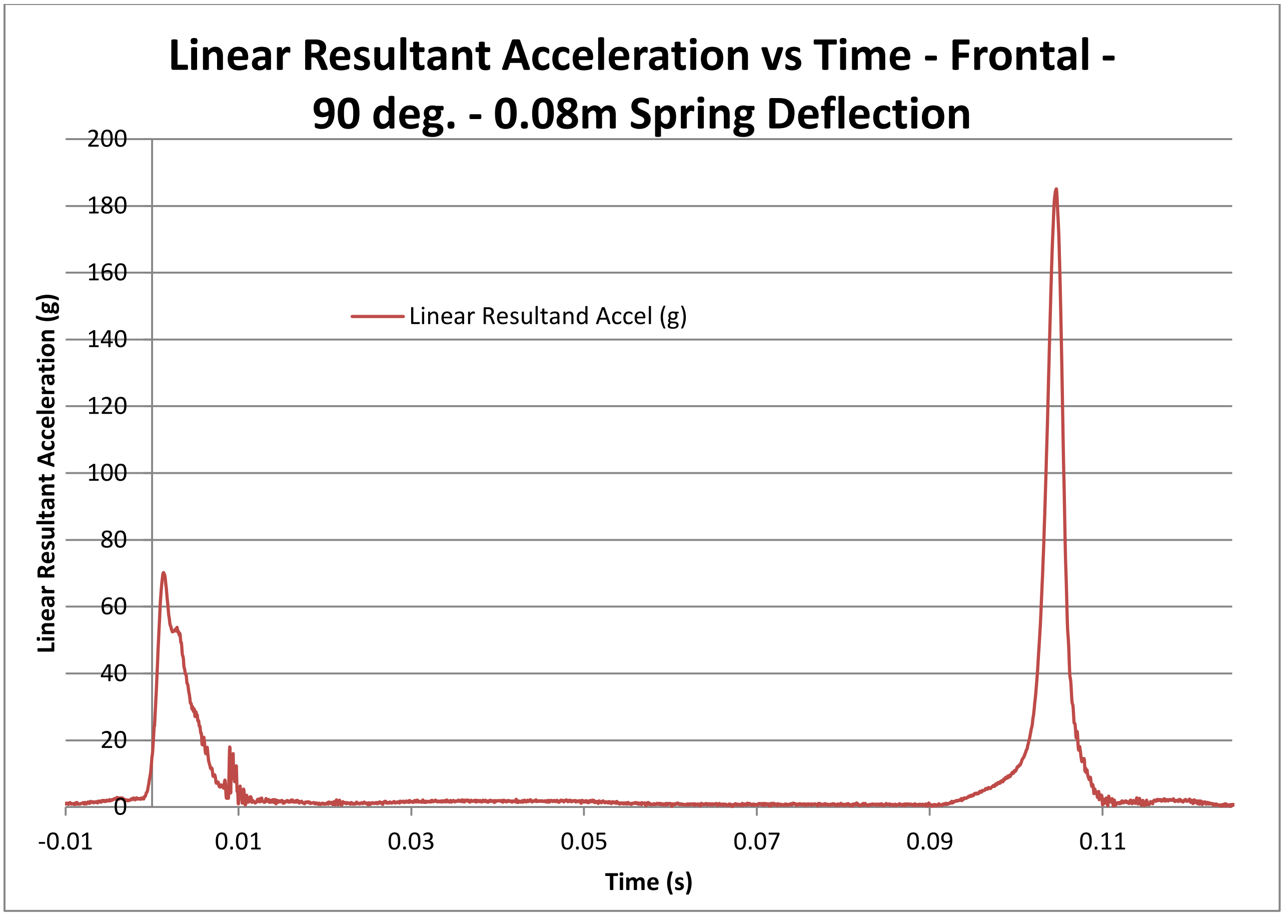


Figure 53: Time versus linear resultant acceleration for a 4.43 m/s frontal impact. The first spike represents triggering of the apparatus and the second spike represents the primary impact event. No filter was applied to this data

The configurations highlighting the capability of the apparatus to be set up for testing at oblique angles are shown in Figure 54.

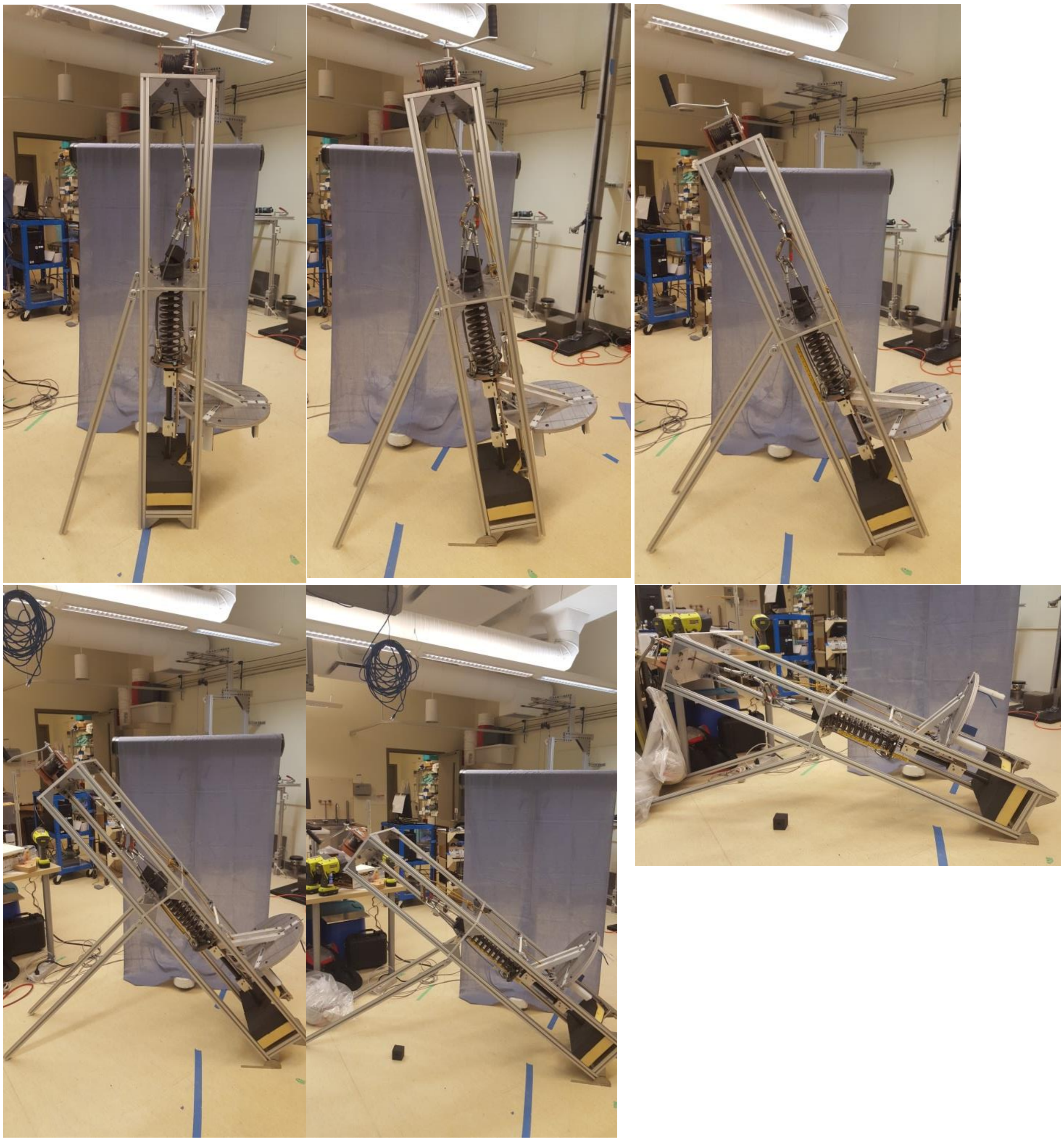


Figure 54: The test apparatus shown at variable angles (90 degrees to 15 degrees; 15 degree intervals).

In investigating the spring rate using the materials testing machine, a spring rate of 47.47 kN/m was determined. Figure 55 illustrates the spring's force response from position controlled loading.

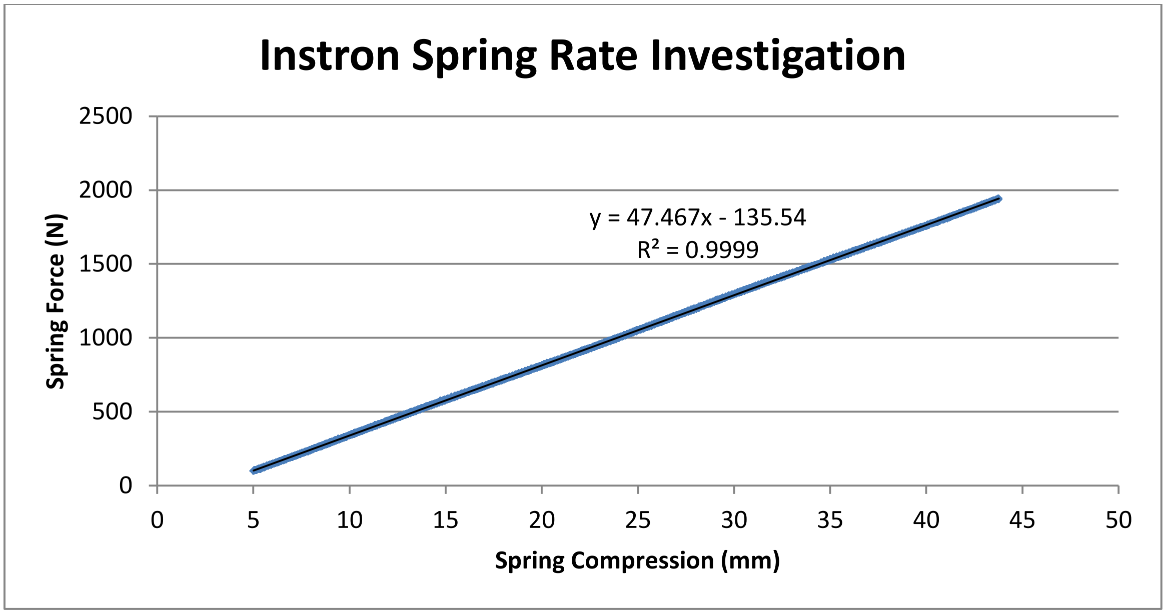


Figure 55: Force versus position for compressive loading of the spring using an Instron materials testing machine. A linear line of best fit is applied with the equation shown in the figure.

4.4 Discussion

All requirements for the design of this apparatus are revisited in Table 11. Further elaboration of unmet requirements is discussed in subsequent paragraphs.

Table 11: Revisiting the comprehensive list of design requirements and identification of status.

Requirement	Metric			Status	Comments
	Measure	Lower Threshold	Upper Threshold		
Test apparatus/ equipment must be carried by two people.	Overall Mass	N/A	50 kg (25kg each)	Met	The overall mass of the apparatus is 43.6 kg without the mass of necessary tools for assembly
Test apparatus/ equipment must be transported in a car and on a chair lift.	Overall Volume (all pieces)	N/A	0.8 m^3 (~25 ft^3)	Met	The overall volume is 0.22 m^3
Test apparatus can be assembled by 1 person	Pass/Fail	Pass/Fail	Pass/Fail	Met	
Test can be performed by 1 person	Pass/Fail	Pass/Fail	Pass/Fail	Met	All verification testing was performed by 1 person
Apparatus can be assembled/ disassembled quickly.	Total assembly time	N/A	45 min	Met	Due to the modular nature, the apparatus can be assembled/ disassembled in

					<15 min.
Requirement	**Metric**			**Status**	**Comments**
Time between same-series tests must be short	Total time between impacts	N/A	3 min	Unmet	Although the test itself can be performed and reset within this time, the critical path is downloading data and re-arming the DAQ. Current time between tests is <5 min.
Apparatus must allow for variable impact angle	Impact angle	15°	90°	Met	The lean arms accommodate virtually any impact angle between 15° and 90°.
Apparatus must allow for variable impact locations on the head. This must include those locations detailed in the CSA snow helmet standard.	Pass/Fail	Pass/Fail	Pass/Fail	Met	Virtually any impact location can be accomplished given the freeform nature of the headform and the clamp design
Apparatus must allow for variable impact speeds	Impact Velocity	3.6 m/s	10 m/s	Partially met	Due to loss of energy during firing, the top end range was not met.
Test must be initiated manually when desired	Pass/Fail	Pass/Fail	Pass/Fail	Met	Accomplished using a snap shackle
Apparatus must have the ability to measure the impact velocity (within 5cm of impact)	Percent deviation	-0.5% of impact velocity	+0.5% of impact velocity	Partially met	Collected data allows for acceleration integration to determine velocity however, this can be improved
Apparatus must be capable of repeatable velocity at impact	Percent deviation between tests	-5% m/s	+5% m/s	Partially met	Velocity repeatability has been confirmed but can be improved
Apparatus must be capable of repeatable impact locations	Radial distance between tests	N/A	2cm	Partially met	Qualitatively confirmed but further testing is required for confirmation

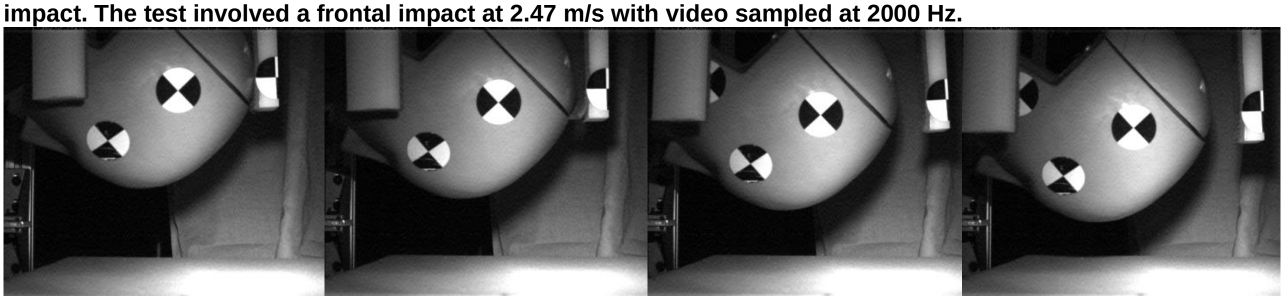
Requirement	Metric			Status	Comments
Apparatus must be capable of repeatable impact angle	Angle difference between tests	-2.5°	+2.5°	Partially Met	Qualitatively confirmed but further testing is required for confirmation
Headform must not escape the near vicinity of the apparatus after impact	Radial distance from impact site	N/A	1m	Met	Padding to contain the headform will be used
Apparatus must be able to be set up on variable impact angles	Slope angles to accommod ate	0°	30°	Partially met	Further on-snow testing needed to confirm
Apparatus must be able to be set up on uneven surfaces	Max surface height difference	N/A	5cm	Partially met	Further on-snow testing needed to confirm
Apparatus must have a camera mount	Pass/Fail	Pass/Fail	Pass/Fail	Unmet	To be recommended for future work
Apparatus camera mount must be adjustable to visualize the point of impact	Distance in XY axes	-2.5cm	+2.5cm	Unmet	To be recommended for future work
Test protocol must allow for characterization of impact surface (snow) as it pertains to the impact	Pass/Fail	Pass/Fail	Pass/Fail	Met	Objective snow hardness measurement tool to be used.
Apparatus and test protocol must not permanently damage test site	Time required to return test site to original conditions	N/A	10 min	Met	Confirmed during on-snow testing
Apparatus and test protocol must not permanently damage test equipment	Pass/Fail	Pass/Fail	Pass/Fail	Met	Confirmed during on-snow testing
Apparatus must be able to endure variable temperatures	Ambient Temp.	-30°C	30°C	Partially met	Further testing at more extreme temperature needed to confirm
Apparatus must not harm anyone using or near to the apparatus	Pass/Fail	Pass/Fail	Pass/Fail	Partially met	Formal safety protocol to be developed

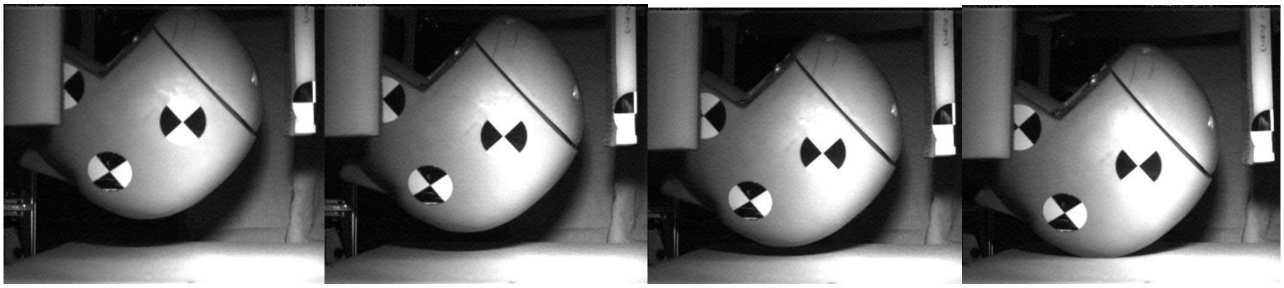
Requirement	Metric			Status	Comments
Apparatus must be affordable (independent of headform and instrumentation)	Total Cost (CAD)	$0	$5,000	Met	Final apparatus cost $2752.63 (not including labour)

In investigating the repeatability of the impact velocity, three trials for each test scenario were conducted and the average values and standard deviations calculated. The standard deviations were then compared to the average value to determine the percent difference for one standard deviation. In general, most scenarios resulted in repeatable impact velocity within approximately 5% of the average value. It is expected that once modifications are made to ensure all of the spring's energy is transferred to the headform, the repeatability of the impact velocity will be further improved.

To gain an understanding of the repeatability of the impact location, high speed video was used to understand the kinematics of the head while the head release mechanism was triggered. By using motion tracking software and fiducial markers on the headform, rotation of the head can be quantified. However, due to the unreliable nature of this mechanism, this metric was not possible to measure for many tests. Qualitatively, it was observed that when the head release mechanism triggered, the headform was projected linearly downwards with very little rotation (see Table 12). One the reliability issues are corrected, high speed video in two planes will allow for relative motion of the head to be investigated in detail. It was also found that initial placement of the head in the clamps introduced more variability than post-release of the head and therefore, an accurate, repeatable method of placing the head must be developed.

Table 12: High speed image sequence (over 35 ms at 5 ms intervals) highlighting triggering of the head release mechanism and linear translation of the headform with very little rotation between release and impact. The test involved a frontal impact at 2.47 m/s with video sampled at 2000 Hz.





Impact angle was another aspect of the protocol that was investigated through static placement of the apparatus in the desired orientation. Due to the lean arms being capable of 180 degrees rotation as well as translation in the vertical axis of the apparatus, virtually any impact angle between 15 and 90 degrees can be accomplished. In a laboratory setting with a hard, impenetrable floor, the lean arms were found to slip out at lower angles however, on snow-testing will allow for the arms to penetrate into the snow to secure the rig. To further investigate the repeatability of the apparatus angle, high speed video of each test angle increment should be performed to determine the vector that the headform approaches the ground on.

The most apparent unmet requirement from this test series is the overall magnitude of the impact velocity not being near to the theoretical value calculated using conservation of energy. For the four different spring displacements tested (0.03 m to 0.08 m), the measured impact velocity was at least 30% lower than the expected value. This discrepancy necessitates review of the possible modes of energy loss in the system. As mentioned, after triggering the apparatus, the spring imparts a significant impulse and due to the rig not being rigidly tethered to the floor, the spring accelerates the head mechanism down as well as the apparatus as a whole up. Even with sandbags being employed to increase the mass of the system, the spring was still able to impact a substantial upwards impulse to the test frame. This mode is considered to be the biggest attribute of energy loss. Figure 56 illustrates the vertical displacement by comparing two time points in the firing sequence. Secondarily, friction in the linear bearings is also anticipated to contribute to less than theoretical impact velocities.

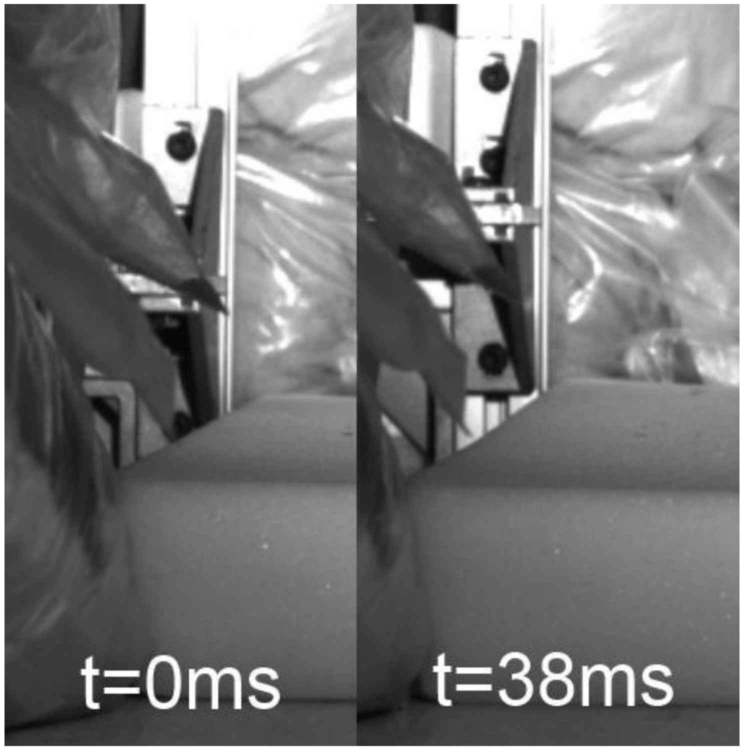


Figure 56: Still frames taken from the high speed video analysis to investigate the vertical displacement of the apparatus

To confirm the primary mode of energy loss, high speed video investigating the vertical displacement was performed to allow for the energy to be calculated for the apparatus to be raised. For a 4.47 m/s, frontal impact, the apparatus was found to travel 27.6 mm in the vertical direction. Using the equation for potential energy, this was found to be equal to 29.9 J. Compared to the overall potential energy in the spring (~160 joules when compressed 0.08 m), the energy loss from moving the mass of the apparatus was found to be approximately 20% of the total energy. This analysis is shown in Appendix C: Detailed Design.

Characterization of the spring involving position controlled loading using a materials testing machine determined that the actual rate of the spring is 47.47 kN/m despite being specified to have a rate of 50 kN/m. This finding provides additional justification as to why the theoretical impact velocity does not match the experimental value. For a test where the spring is compressed 0.08 m, this is equal to a 202 N difference and in turn approximately 8 J of potential energy in the spring (~5% of the spring's total energy). With this improved understanding of the actual spring rate, more accurate spring forces can be predicted to achieve the desired load.

To address the significant energy loss from these two modes, design modifications should be considered. The largest recovery of energy will be realised by rigidly, or effectively, tethering the apparatus to the ground to prevent movement. In a laboratory setting, this can be accomplished by physically mounting the apparatus to a plate of significant mass, as is prescribed in current test standards.(119) For field testing, more creative means must be employed. This could be a combination of digging and packing the base of the apparatus into the snow as well as using snow pickets/flukes with static cable to act as anchors. Finally, to reduce the friction in the linear bearings, a maintenance schedule to inject new lubricant must be followed and the central shaft must be inspected for burrs or scratches.

Several partially met requirements listed above involve further investigation (as outlined in Table 11) and modifications to the existing design in order to confirm they have been addressed. Other unmet requirements include minimal time between tests and inclusion of a camera mount and can be dealt with through familiarity with test protocols and minor additions to the apparatus.

Although it was not defined as a requirement of this test apparatus design, the ability to measure and collect data pertaining to the rotational kinematics of the head is important for a full understanding of the impact severity. As noted in section 1.2.2.2, rotational inertia imparted on the head can result in significant injury. With current helmet technology not investigating the rotational response of the head during impact, it is important that future research and certification standards adopt testing protocols that represent both linear and rotational injury mechanisms. Integration of angular rate sensors in the headform and oblique impact testing will allow for an improved understanding of the rotational kinematics.

As the end goal for this test apparatus is for integration into safety certification testing for snow sport helmets, it is also necessary to verify that the kinematics the rig is capable of producing are representative of clinical injury observed. To do this, further testing is necessary to compare the impact responses in several different scenarios to injury threshold data from existing literature. As an example, consider a snowboarder is involved in a high energy jump impact in which their helmet is cracked. The patient is diagnosed with multiple, diffuse, small haemorrhagic lesions. The haemorrhagic lesions are consistent with diffuse axonal injury, indicating that a significant rotational acceleration induced a shearing force on the brain. Existing biomechanics literature has found that average falls of this nature result in a peak head velocity of approximately 10.3 m/s perpendicular to the snow as well as a peak tangential velocity of 13.9m/s. [21] Biomechanical thresholds for DAI have been estimated between 8 $krad/s^2$ and 20 $krad/s^2$.(103,130,131) Through impact testing on snow surfaces at impact velocities upwards of 10 m/s, rotational kinematics can be measured and compared to these DAI threshold values to confirm the test apparatus is truly representative of such scenarios.

4.5 Conclusion

Through verification testing of an apparatus design to recreate injurious ski and snowboard head impacts, the first steps in proposal of a revised protocol for improved snow sport helmet testing are achieved. Modifications to the apparatus as well as additional tests will further strengthen confidence in the proposed design. Overall, implementation of a clinically informed helmet testing protocol will give researchers and manufacturers an effective tool to understand the influence of changes to the technology and ultimately improve protective measure for snow sport participants.

5.0 RECOMMENDATIONS

5.1 Future Work and Recommendations

Although this work aims to present justification for re-evaluation of current snow sport helmet certification testing protocols through clinical data, suggest a test apparatus design that is capable of better representing real-world head injury mechanisms and verify the requirements, a number of considerations must be made for future work.

5.1.1 Apparatus Modifications

As shown through the verification testing performed in chapter 4.0, the apparatus was able to meet most of the major requirements with the exception of impact velocity magnitude for which design modifications are suggested. Further steps are necessary to verify partially met requirements with emphasis on repeatability of impact location and testing at variable angles.

The most important modification is to ensure that energy stored in the spring be more efficiently transferred to acceleration of the headform. To do this, an improved method of tethering the apparatus to the ground is necessary. This can be accomplished by a mounting plate of significant mass (more appropriate in a lab setting) or by digging the apparatus or anchors into the ground (for on-snow testing) which are rigidly attached to the rig.

With the current means of seating the head control carriage against the lower spring plate being a static cord, an improve method of achieving this could be considered. This may involve breakaway cables, capable of being set a prescribed height, to hold the carriage up. As the head release mechanism was found to occasionally stick and therefore not release all clamp arms simultaneously, alternative designs may be considered. Plastic inserts to reduce the friction of the spring loaded threaded rod or rigid fixtures attached to the bent threaded rod ends could trigger the mechanism more reliably.

Other physical modifications to the apparatus may include additional supports to the pivot arms to improve overall rigidity of the structure. Support bars between the two pivot arms as well as between each pivot arm and the main structure would allow for stable attachment while still allowing for full range of movement. Also, to more easily determine the angle of the device with respect to gravity, an inclinometer could be fixed to one of the platforms. By addition threaded pivot feet to the base of the apparatus, small adjustment can be made for uneven surfaces. To improve the risk of pinch points and the overall safety of the apparatus, the upper and lower frames can be enclosed in removable plexi-glass.

To address these deficiencies as well as further improve the design of the apparatus, several modifications can be made with respect to the measurement and capture of the event. To allow for real time impact velocity feedback, a velocity gate can be added to the apparatus. In addition, a camera mount on the device would allow for easy capture of the impact.

As one limitation of this device is its inability to produce meaningful secondary or tertiary impacts given the head being free of the any neck, or torso, an adaptation could be made to allow for a surrogate neck to be incorporated. One possibility would be to design an independent carriage that could replace the head release carriage. Such a design could remain tethered to the rail or break away with a follower mass representative of the torso's inertia.

5.1.2 Instrumentation Modifications

As mentioned, rotational kinematics are an important consideration for the future of helmet testing given current certification standards only measuring and prescribing thresholds for linear kinematics. To do this, angular rate sensors should be incorporated into the headform. Given the current accelerometer block can already accommodate three angular rate sensors in addition to the three linear accelerometers, integration will be simplified. Generally, these sensors have a long cable which needs to be cut in order to minimize additional weight inside the headform. It is important to ensure that proper calibration of these sensors is carried out after the cables have been cut. Due to the modular nature of the Slice Nano DAQ currently used in the headform, one DTS bridge stack, capable of accommodating three strain based signals, can be added to collect the additional data.

The same post processing as is used for the linear accelerometer signals can be applied to the angular rate sensor output data. However, the Matlab code will need to be modified to include calculation of the resultant angular rate.

5.1.3 Further Testing

With several partially met requirements, extensive additional testing is necessary for full verification of the design. As suggested in Section 4.0, the focus of this testing should be to confirm efficacy of the proposed modifications to address the issue of energy being lost in movement of the rig during firing. This can be done by performing a test matrix similar to the one found in section 4.0. To investigate repeatability of impact location, high speed video in the sagittal and frontal planes should be used in conjunction with motion tracking. With two points being tracked in each plane, relative motion can be accurately quantified from the moment the head is released to the moment of impact. In further confirming the apparatus' ability to vary impact angle, repeated tests at various angles should be performed with high speed video in the sagittal plane to compare the angle of the apparatus to the headform's trajectory. Given the apparatus requirements were investigated in a lab setting, the next step is to conduct similar testing on hill to ensure that the full range of requirements are satisfied in a less controlled environment.

Next, and perhaps most importantly, the apparatus must be tested in conjunction with the isolated headform to recreate injurious impacts. With biomechanics literature currently available which characterises various head injuries through kinematic thresholds, testing with a surrogate headform allows for improved understanding of the circumstances of each injury. Using this apparatus, investigative testing should be performed to determine the influence of impact velocity, angle and surface on the head kinematics and therefore, the injury type and severity. Table 13 outlines a possible test matrix to be followed to understand the influence of various test parameters on reported injury outcomes.

Table 13: Test matrix describing test configurations for verification of biomechanically relevant outcome measures. Each test described will involve three impacts within +/- 5% of the prescribed impact velocity.

Test No.	Head Orientation	Impact Velocity (m/s)	Impact Angle (deg.)
1	Frontal	3.6	90
2	Side	3.6	90
3	Occipital	3.6	90
4	Crown	3.6	90
5	Frontal	3.6	60
6	Side	3.6	60
7	Occipital	3.6	60
8	Crown	3.6	60
9	Frontal	6.3	90
10	Side	6.3	90
11	Occipital	6.3	90
12	Crown	6.3	90
13	Frontal	6.3	60
14	Side	6.3	60
15	Occipital	6.3	60
16	Crown	6.3	60
17	Frontal	10	90
18	Side	10	90
19	Occipital	10	90
20	Crown	10	90
21	Frontal	10	60
22	Side	10	60

Test No.	Head Orientation	Impact Velocity (m/s)	Impact Angle (deg.)
23	Occipital	10	60
24	Crown	10	60

Lastly, extensive data will need to be collected with the snow hardness tool described in section 3.1.7.6.3 in order to characterize the snow pack as it relates to different test scenarios. As there is no data available to date that correlates the output of the tool (measured in Pascals) to known snow characteristics, this database will need to be established within the context of impact testing.

6.0 CONCLUSION

6.1 Summary

The overarching objective of this work is to advance the current understanding of snow sport head injury to improve prevention of real world injuries. To accomplish this, justification was provided for re-evaluation of current snow sport helmet testing standards and a test apparatus capable of more representative snow sport head impacts is proposed.

To accomplish the first objective, a 6-year retrospective clinical case study was performed, investigating snow sport head injuries that were reported to two major trauma centers as well as the BC Coroner's Office. Several mechanism categories were observed and related to injury severity in addition to the frequency of specific injury types being highlighted. Overall, snow sport head injury mechanisms were observed to be complex, particularly in relation to impact velocity, angle and surface, and cannot be represented through a single impact scenario.

To address the second objective, this clinical data, in conjunction with existing biomechanics literature, was used to inform the design of a test apparatus to better represent the possible pre-impact kinematics as well as impact surface characteristics of such head impacts. Through stakeholder discovery and secondary research, an informed list of needs was generated. For design application, this list was converted into requirements with measureable metrics. With an understanding of the top level functions of the apparatus, the next step involved generating as many concepts as possible and then evaluating those through established design tools such Pugh charts and Weighted Decision Matrices. From this objective process, a full integrated design was selected and detailed design commenced. Each major component was broken down to understand the critical design elements for which failure analysis was necessary. Utilizing engineering principles and stress analysis software, a final design was decided upon and fabricated.

The final design features a large, stiff spring (50 kN/m) that can be compressed to a prescribed displacement that correlates to a desired impact velocity. A head control mechanism, which is free to translate axially along a central rail, is then seated against the loaded spring. To release the spring force and accelerate the head control mechanism, a trigger snap shackle is used. At a predefined distance from the ground, the head control mechanism releases the headform to allow for an untethered impact. The portable design allows for variable impact velocity, angle and head orientation. Verification testing confirmed that the many of the major requirements set forth at the beginning of the design process were met as well as highlighted a few aspects of the design that require modification in order to satisfy the remaining requirements.

6.2 Strength and Limitations

6.2.1 Strengths

As current helmet certification standards represent single, oversimplified impact scenarios, informed re-evaluation is necessary. A significant strength of this work is the use of clinically relevant head injury data from skiing and snowboarding to understand the most relevant mechanisms of injury. Through a large clinical case study, relationships between injury severity and nature, helmet use and mechanism were investigated. By forming a basis for how head injuries occur on the slopes, a novel approach to the design of a helmet test apparatus and protocol was performed, drawing from real-world clinical and biomechanics data. The final apparatus that emerged from this process is capable of repeatable, on-snow testing, which enables helmet evaluation on the exact surfaces which head injuries occur on. In the end, a verified, relevant and novel test apparatus is proposed for use in development and evaluation of head protection equipment, ultimately improving snow sport participant safety.

6.2.2 Limitations

Challenges in implementation and interpretation of this work are both inherent based on the nature of the study and design as well as being a result of decision made as issues arose. The retrospective nature of the clinical study limited the resolution of data available and could only be addressed with a prospective study design. In some cases, data was unavailable however, existing data is believed to be representative of the spectrum of the sample. In addition, because the clinical study focused on those snow sport participants who reported to emergency departments, only the injured population could be investigated. Despite this, a full spectrum of injury severities were represented and meaningful conclusions were be made about injury characteristics and correlation with mechanism and helmet use.

In the design and construction of a test apparatus to represent real world snow sport head impact scenarios, limitations are generally associated with design decisions and were therefore considered at length and justified. As is the case with many test protocols, the proposed apparatus simplifies snow sport head impact to a linear trajectory prior to impact. Back edge trip mechanisms are an example of a fall scenario that cannot be truly represented using this test apparatus. This is accepted as a limitation as it is difficult to represent all possible mechanisms with a single apparatus. With that said, it is necessary to include such mechanisms for a comprehensive understanding of helmet performance. Additionally, the proposed apparatus allows for an untethered headform which can undergo rotation. This is often criticised for not representing natural impact response of the head and to be more representative it should incorporate "tethering" by the neck and additional loading, via the neck, by the torso (ie. follower mass). Given that this test method is only meant to represent the primary impact and the fact that the first 40 ms of head impact are said to be uninfluenced by the presence of the neck or torso, this was dismissed.(128)

Specific design limitations include higher than ideal overall mass, some parts being made from steel and predisposed to rust, a high number of fasteners and the design not including some of the aspects of in-lab test apparatuses (ie. velocity gate, remote test reset and trigger, camera mount etc.). These elements were all considered and determined to be unrealistic for an on-snow test apparatus, cost inhibitive and/or necessary for overall safety. To address some of these, recommendations were made in section 5.0.

6.3 Conclusion

By characterizing snow sport head injury by way of clinical data and existing literature, common mechanisms of injury were determined. This data also highlighted the need for current helmet testing standards to be re-evaluated given their oversimplification. With additional stakeholder discovery, a comprehensive list of design requirements for an apparatus capable of recreating injurious head kinematics was generated. Following a formal design process, several concepts were considered with the final design including a compression spring to accelerate an isolated headform at the ground at various angles and velocities. Through verification testing, confirmation of the design requirements met and modification recommendations for those unmet were made.

The outcome of this work is a test apparatus that is capable of improving the design and evaluation of head protection through impact testing which is more representative of real world snow sport head injury scenarios.

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Appendix A: Stakeholder Communications

Skype Call with Peter Halldin

Date: December 11, 2014 @ 08:00 PST (17:00 CET)

Attendance: Peter Halldin (Assistant Professor, KTH; CTO MIPS), Peter Cripton (Professor and Associate Head, UBC), Cam Stuart (MASc Cand., UBC)

Purpose: Discuss snow sport relevant helmet testing protocol thesis project and the potential for collaboration.

Minutes:

- Cam: brief background and introduction to thesis project (see attached proposal)
- Peter H. has been working on an unfunded study with the FIS for a couple of years
    - Competitive skiing snow properties most similar to ice
    - Perhaps just higher velocity linear drops may suffice for competition helmets?
- Peter H. has done some snow sport helmet testing at a resort to mimic real world conditions
    - Found competition helmets to have a low friction and therefore low rotational accelerations (helmet design to be round and smooth)
- Peter H. and Svein K. hoping to continue helmet work in other sport scenarios (ie. snowboarding, ski cross etc.)
- What causes rotation if not tangential force from friction?
    - Recreational helmets: anchor points (ie. Cameras or goggle anchor points)
- Great interest in collaboration
    - Either work in parallel on similar aspects of the investigation and compare the approaches/results or work on individual aspects of the study that would complement each other
    - Improve funding application with international collaboration
- Funding possibilities
    - Peter H. has some funding from the FIS to conduct a small study but funding limited
    - Worthwhile looking into Canadian skiing and snowboarding organisations/federations as well as 'Own the Podium' initiative.
    - Possibility of funding from NOCSAE?
- Svein Kleiven is working to validate an FEA snow model. Difficulty in coefficient of friction etc.
    - Real accidents are important to inform this
    - Could our clinical study help to inform this by characterising a 'real ski accident'?
- It would be interesting to have a mobile test apparatus incorporated into testing standards
    - Challenge of making the testing feasible for industry and realistic that standards organisations adopt such a protocol.
    - Could design an on hill certification test

  - How could we get address the challenge of geographically variable snow characteristics?
- Peter H. has investigated variation in snow surface friction properties
  - Competition snow has a low friction coefficient
- Certification testing requirements and insights
  - Impact surface for certification test is very important (ie. Surface needs to represent snow impact)
  - Reproducible, simple and cheap
- Peter H. looking to collect video footage from both competition and recreational accidents
- What is the best instrumentation for such testing?
  - 9 accel array; angular rate sensor (helmet dependent?)
- The new DTS sensor is (Slice Pro) is meant to be better for ~100g impacts
- Peter H. is the CTO for MIPS
  - Very popular (particularly in Europe); effective reduction of rotational acceleration

Action:

- Cam will put together a research proposal to send to Peter H. prior to the next skype call in the middle of January. Once a better understanding of the test methods proposed is achieved, we will discuss the approach and how to improve it.
- Everyone will brainstorm ideas for collaboration.
- Schedule a meeting in the New Year (middle of January)

Possible Collaborative Projects:

- Peter H. has a great amount of understanding of the impact surface (snow) properties and helmet testing protocols which could inform the design phase of the process. We could elaborate on his on snow testing (ie. Protocol, apparatus design)
- With different variations of test equipment (ie. Drop rail with a basket, impactor, monorail, drop tower, linear drive…etc.), a comparison of different test methods/approaches could be achieved.

Call with Irving Scher

Date: December 16, 2014 @ 09:40 PST

Attendance: Irving Scher (Principal and Biomechanical Engineer, Guidance Engineering), Bethany Suderman (Associate Biomechanist, Guidance Engineering), Peter Cripton (Professor and Associate Head, UBC), Cam Stuart (MASc Cand., UBC)

Purpose: Discuss snow sport relevant helmet testing protocol thesis project and the potential for collaboration.

Meeting Minutes:

- Introduction to Cam's thesis (see attached proposal)

- Beth: sent ISSS abstract
- NEISS database and Sugarbush study
    - Working with Jake Shealy
    - Sugarbush – 'case controlled prospective study'
        - Looking at head injuries from the ski hill
        - Limited as serious injuries are sent to hospital and not treated at the hill
    - Serious head injuries in 20-75% of cases w/ helmet use
    - NEISS Database analysis found a ~62% drop in skiing/snowboarding head injury in longitudinal investigation
- Robert Kennedy (lawyer) – external council representing Whistler Blackcomb

ACTION: would be interesting to try and think how our study could benefit from or be informed by data/collaboration with this study

- Irv: advocate of sport specific helmet testing and interested in the many mechanisms that lead to head injury
    - Found in research that there was a significant rotational acceleration induced even prior to impact (ie. Snowboard backwards trip study with Exponent)
- Irv: agrees with the need to identify the best instrumentation and headforms for such a study
    - NOCSAE, HIII, Angular rate, accelerometers, Kistler device
    - Also mentioned several different test apparatus that are currently used and the need to identify the best for this type of testing (ie. Linear impactor, moving anvil, angled anvil, guiderails loose, HIII neck on carriage, loose wires, drop)
    - How many different test/apparatus' are necessary?
- 10 year study with the National Ski Area Association
    - Every 10 years, select ski hills give ski patrol reports, allowing for investigation of injury
    - Canadian equivalent to NSAA is the Canada West Ski Areas Association
- Swiss and Austrian groups performing good quality ski safety research
- International Society for Skiing Safety (ISSS)
    - Worthwhile group to develop ski safety network
    - This year's meeting in Cortina, Italy
    - Student Scholarships can help subsidize travel
    - Abstracts due yesterday but they may still accept
- ASTM F27 similar in the sense of getting more familiar with the ski safety community but F08 is the helmet specific group
    - Looking at things such as AT bindings/boots, alpine gear, jump design
- Roald Bahr and involvement with ACL study
- Emphasis on pre-impact kinematics and how that influences the head/brain in the primary and tertiary impacts
- Peter: hesitant to use current brain models without further validation
- Terry Smith is working on angular acceleration prior to impact (angular impact)

- Research question: How can subsequent impact be addressed in testing protocol? Situational variability for severity

Action:

- Cam will put together a research proposal to send to Irv prior to the next skype call in the New Year. Once a better understanding of the test methods proposed is achieved, we will discuss the approach and how to improve it.
- Everyone will brainstorm ideas for collaboration.
- Cam will look into the ISSS with the potential of attending the next meeting in Italy (March 2015)
- Schedule a meeting in the New Year

Possible Collaborative Projects:

- The involvement that Irv has had with the '10 year study' and the 'Sugarbush/NCHS' study may help to identify relevant injury mechanisms and strengthen the evaluation of the current test protocol.
- Irv has many contacts in the NSAA (and potentially the CWSAA) which may be helpful to utilize some of their injury data. Ultimately, this could bring better resolution to injury mechanisms
- Long term, a prospective study could be undertaken for which specific injury mechanism information could be gathered

Notes From ASTM F08 Meeting

Date: November 13-15, 2014

Location: New Orleans, LA\

Football

- SI Variable? (football testing)
- Progressive weakening using steel anvil
- EN drop ring v. constraint (NOCSAE)
    - Argument that the drop ring is not a good way to measure rotational acceleration
- Mg Head no easy to use for ASTM football standard
- Adding rotational acceleration

Motorcycle

- ACT esting – helmet, chem., toys
- BRG sports
- New motorcycle standard – still linear w/ no rot.
- DOT standard? 400g req. – dwell time? Functionally 250g
- Issues: rot. Accel., additional metrics (>300g), youth, neck brace compatibility, freestyle, breakaways, max limit for retention, compliant impact surface (relevant to skiing), low energy threshold

- *soccer proposal for rot. Accel.
- *rotational acceleration sub-committee
- Rotational acceleration (alpha) vs rotational velocity (omega)
- Injuries of people that impact below the test line

Shirtsleeves

- MLSH heaform?
- Southern Impact Research Centre
- Azimuth – angle from sag. Plane
- Need for e-bike helmet standard
    - Based on average speed difference
- Stephanie Bonin – MEA – cadaveric v. headform for helmet def.
    - CoG for instrumentation in cadavers?
        - Resolved accel. To CoG
    - *HIII v. cadaver was not statistically different for acceleration
    - Fracture?
    - Why cap type helmet?
    - Living v. cadaveric brain mass and how brain flop effects
    - NOCSAE headform?
- Chris Whitnall
    - Draft for CSA hockey
    - Issues for rotational acceleration
        - Headform weight, shape, moment of inertia, instrumentation capability (array set up, angular rate (delta omega) – noisy)
    - Repeatability
    - How do you hit the head? (sport specific)
    - Risk of concussion – what in the acceleration curves causes a rotational acceleration injury?
    - Threshold
    - Neck…
- *material properties changing over time (ie. elastic neck)
- Peter Halldin
    - Rotational Test Methods (CTO of MIPS)
    - 5-10 m/s, 30 to 60 degrees, hard impact surface
    - WG11 – working group in Europe
    - HIII head – no neck (check study comparing HIII w/ to w/o neck and cadaver)
    - Strain to aid in defining threshold
        - Increased duration of rotational acceleration no acceptable…ehy?
    - Black box model for threshold determination
  - Attend WG11 March 2015 – Germany
  - *Basket for Peter's drop rail? (EU meeting)
- 12 manufacturers implementing MIPS
- Test method for testing MIPS efficacy (20-66% reduction in strain)
    - Published thesis?

- MIPS using Svein Kleiven's KTH finite element model
- $9.50 per helmet decreasing with volume
- Dr. Peter Cripton
    - *what about 3D printing test equipment? Vertebrae?
    - Snow sport task force

F08.53 Committee Meeting

- *variable mass headforms being implemented
- Playground surfaces @ 200g w/ HIC 700
- Roy Burek
- E-mail Chris Whitnall re: CSA and Thom Parks
- Time duration of impulse to be considered
    - Maddux
- HECC – meeting (ISO) in Florida Dec. 3-5

Appendix B: Design Phase Documentation

Requirements

Table 14: Requirements, metrics and justification for the test apparatus based on the needs statements.

Need Category	Requirement	Justification	Metric			Reference
			Measure	Lower Threshold	Upper Threshold	
Storage and Handling (mass)	Test apparatus/ equipment must be carried by two people.	Given the goal of the apparatus is to be used for field testing, the apparatus must be carried up a chairlift by 1-2 people	Overall Mass	N/A	50 kg (25kg each)	
Storage and Handling (volume)	Test apparatus/ equipment must be transported in a car and on a chair lift.	Given the goal of the apparatus is to be used for field testing, the apparatus must fit in a vehicle and on a chair lift in order to get the equipment.	Overall Volume (all pieces)	N/A	0.8 m^3 (~25 ft^3)	http://www.consumerreports.org/cro/cars/types/exterior-and-cargo-comparison.htm
Useability (assembly personnel)	Test apparatus can be assembled by 1 person	Given the goal of the apparatus is to be used for field testing, the apparatus must be easily assembled.	Pass/Fail	Pass/Fail	Pass/Fail	

Need Category	Requirement	Justification	Metric			Reference
Useability (test personnel)	Test can be performed by 1 person	Although the protocol may be expedited with additional assistance, the test should be possible with 1 person	Pass/Fail	Pass/Fail	Pass/Fail	
Useability (assembly time)	Apparatus can be assembled/ disassembled quickly.	The in-field test duration should not be limited by assembly of the apparatus. Weather changes may necessitate quick disassembly.	Total assembly time	N/A	45 min	
Useability (test time)	Time between same-series tests must be short	Many certification standards require a defined maximum amount of time between tests to investigate the helmets toughness. This may also be necessary to ensure impact surface does not change significantly between tests	Total time between impacts	N/A	3 min	Eg. CSA Recreational alpine skiing and snowboarding helmets - Toughness Test (30-90s)

Need Category	Requirement	Justification	Metric			Reference
Functional (impact angle)	Apparatus must allow for variable impact angle	To be most representative of real world snow sport head impact, impact angle must be variable. This is justified by video analysis of real world accidents as well as parametric analysis of the influence of traveling speed on impact angle. Increments of 10 degrees are acceptable.	Impact angle	15°	90°	
Functional (impact location)	Apparatus must allow for variable impact locations on the head. This must include those locations detailed in the CSA snow helmet standard.	All tests detail prescribed and unprescribed test locations on the headform. This ability would also allow for better representation of real world head impact.	Pass/Fail	Pass/Fail	Pass/Fail	Existing helmet standards
Functional (impact velocity)	Apparatus must allow for variable impact speeds	More representative of real world snow sport head impact as justified in section 2.0.	Impact Velocity	3.6 m/s	10 m/s	See section 2.0

Need Category	Requirement	Justification	Metric			Reference
Functional (test trigger)	Test must be initiated manually when desired	To ensure that the instrumentation is prepared and the battery life is maximized, manual, remote triggering is necessary (ie. Headform held stationary until test is initiated)	Pass/Fail	Pass/Fail	Pass/Fail	
Functional (quantify velocity)	Apparatus must have the ability to measure the impact velocity (within 5cm of impact)	To be consistent with standards, impact velocity will be used to confirm impact energy and therefore must be measured accurately	Percent deviation	-0.5% of impact velocity	+0.5% of impact velocity	Existing helmet standards
Functional (repeatability of velocity)	Apparatus must be capable of repeatable velocity at impact	To be consistent with test standards and to be able to perform tests efficiently (ie. No repeats), impact velocity must be repeatable and predictable	Percent deviation between tests	-5% m/s	+5% m/s	Existing helmet standards

Need Category	Requirement	Justification	Metric			Reference
Functional (repeatability of impact location)	Apparatus must be capable of repeatable impact locations	To be consistent with test standards and to be able to perform tests efficiently (ie. No repeats), impact location must be repeatable and predictable	Radial distance between tests	N/A	2cm	Existing helmet standards
Functional (repeatability of impact angle)	Apparatus must be capable of repeatable impact angle	To be consistent with test standards and to be able to perform tests efficiently (ie. No repeats), impact angle must be repeatable and predictable	Angle difference between tests	-2.5°	+2.5°	
Functional/ Durability (contain headform)	Headform must not escape the near vicinity of the apparatus after impact	To prevent the free motion headform from being damaged, to expedite multiple tests and to prevent injury to nearby people, the headform should not be allowed to escape the vicinity of the test apparatus	Radial distance from impact site	N/A	1m	

Need Category	Requirement	Justification	Metric			Reference
Functional (ground angle)	Apparatus must be able to be set up on variable impact angles	To allow for testing to take place on several different areas on the ski hill, it will need to be set up on various slope angles	Slope angles to accommodat e	0°	30°	http://www.gondyline.com/angle-of-ski-trails.php
Functional (uneven surface)	Apparatus must be able to be set up on uneven surfaces	To allow for testing to take place on several different areas on the ski hill, it will need to be set up on uneven snow surfaces	Max surface height difference	N/A	5cm	
Functional (camera mount)	Apparatus must have a camera mount	To capture video of the impact (HS or otherwise), a camera mount is necessary. Preference to isolated designs.	Pass/Fail	Pass/Fail	Pass/Fail	Can allow for impact speed verification
Functional (camera mount adjustability)	Apparatus camera mount must be adjustable to visualize the point of impact	As the impact location and direction may be variable, the camera angle and location must be adjustable	Distance in XY axes	-2.5cm	+2.5cm	

Need Category	Requirement	Justification	Metric			Reference
Functional (snow characteristics)	Test protocol must allow for characterization of impact surface (snow) as it pertains to the impact	With the impact surface being an important part of how energy is experienced by the head, characterizing the necessary parameters that relate to the impact is necessary .	Pass/Fail	Pass/Fail	Pass/Fail	External device used: http://www.snowpak.net/
Durability (damage to test area)	Apparatus and test protocol must not permanently damage test site	To ensure good stakeholder relations and maintain consistent test conditions, long lasting damage to the test site is not permitted	Time required to return test site to original conditions	N/A	10 min	
Durability (damage to test equipment)	Apparatus and test protocol must not permanently damage test equipment	To maintain consistent and valid tests, test equipment must not be damaged during testing. Consideration must be taken to insure all equipment is being tested within the defined limits. Safe guards should also be put in place to minimize interaction of equipment with other apparatus structures.	Pass/Fail	Pass/Fail	Pass/Fail	

Need Category	Requirement	Justification	Metric			Reference
Durability (temperature)	Apparatus must be able to endure variable temperatures	Testing may be performed in the winter or in the summer and therefore should be able to endure a variety of temperature ranges	Ambient Temp.	-30°C	30°C	
Safety (personal)	Apparatus must not harm anyone using or near to the apparatus	Safe operation with all potential hazards identified and mitigated within reason. This may include sharp surfaces, trip hazards, projectiles, pinch points etc.	Pass/Fail	Pass/Fail	Pass/Fail	Mechanism safeguards Ie. Minimum radius, distance between moving members
Desirable (cost)	Apparatus must be affordable (independent of headform and instrumentation)	In order to make testing accessible to those interested, the device must not be too expensive to build or purchase.	Total Cost (CAD)	$0	$5,000	

Brainstorming

Basic structure of Group Brainstorming Session

Date: Tuesday, October 4th, 2017 @12:00pm

Location: 5th Flr., East Conference Room, Blusson Spinal Cord Centre

Attendance: Dr. Peter Cripton, Ingmar Fleps, Angela Melnyk, Hannah Gustafson

Rules:

1) No stupid ideas
2) Speak your mind (all ideas; from very simple to very technical)
3) Open conversation

Format:

- Quick explanation of project
- Summarize functional decomposition
- Go through functional decomposition one-by-one
    - 2-3 mins for each person to write down all the ideas individually
    - 5-7 mins to go around the table and list each idea
    - 4-5 mins to build on listed ideas
- Brainstorm integrated solutions

Functional Decomposition

- Hold headform relative to ground
- Initiate headform acceleration relative to ground
- Control headform orientation at impact
- Contain headform within test zone
- Adjust impact orientation of headform
- Release headform from test apparatus prior to impact
- Quantify headform impact velocity
- Maintain consistent impact surface between tests

Concept Evaluation

Table 15: Comprehensive list of concepts as well as results of winnowing. Concepts highlighted in green indicate those that passed to the next stage of evaluation while red indicates elimination of that concept.

Function	Concept	Winnowing			Comments
		Feasibility	Requirements	Technical Readiness	
Hold headform relative to ground	Rail with Hard Stop	Y	Y	Y	
	Tensioned tether with release pin (similar to drop rail)	Y	Y	Y	
	Suspension cables on a drop frame	Y	Y	Y	
	Mesh bag	Y	Y	Y	May have slight influence on impact (ie. Friction, standoff, surface irregularity
	Table/shelf	Y	Y	Y	
	Clamp	Y	Y	Y	
	Hold with hands	Y	Y	Y	
	Magnet	Y	Y	Y	
	Adhesive	Y	Y	Y	

	Air foil	Y	N	Y	Jet turbine air velocity ~500m/s (7000hp motor required); mass biggest consideration
	Pole with bowl (ie. T-Ball stand)	Y	Y	Y	
Function	**Concept**	**Winnowing**			**Comments**
Induce known acceleration to headform relative to ground	Engage clutch from flywheel (flywheel could be brought up to speed via a hand crank, power drill, rip cord, counter weight…)	Y (See below for calc)	Y	Y	Mass of motor a consideration
	Hydraulic impact ram	Y	N	Y	Failed on mass and size requirement
	Pneumatic impact ram	Y	N	Y	Failed on mass and size requirement
	Chemical reaction (ie. Airbag)	Y	Y	Y	
	Loaded spring (linear or pendulum (could use a linear spring for the pendulum or a torsional spring))	Y	Y	Y	See calculation below (used Adams simulation)
	Freefall drop	Y	Y	Y	For 10 m/s, a drop height of ~5.1m
	Trebuchet with late deploy	Y	N	Y	Unpredictable impact location and requires a significant horizontal distance. Used online simulator (http://virtualtrebuchet.com/#simulator)
	Inverted pendulum (pole)	Y	Y	Y	

	Electric motor driven (linear drive)	Y	N	Y	Cannot reach the necessary impact speed
	Electromagnet (railgun)	Y	N	Y	F=i (current) * L (length of rail) * B (magnetic field); car battery = 12V (~45Ahrs; 45 A for 12hr); dangerous for the current necessary to project the headform mass
	Electromagnet (solenoid)	Y	Y	Y	
	Slingshot (either pushing or pulling to the ground)	Y	N	Y	Cannot get the necessary propulsion force from bungee/elastic cords alone
	Spinning disc with a high friction cable that gets quickly tensioned (similar to a clutch)	Y	Y	Y	
	Blast of air/water	Y	N	Y	Cannot achieve enough force with air; water too heavy to carry and difficult to source onsite.
	Throw (human powered)	Y	N	Y	Not repeatable within the impact velocity requirement
	Pulley system with mechanical advantage	Y	Y	Y	
	See-saw launch	Y	Y	Y	
	Zipline (gravity)	Y	N	Y	Spring force alone cannot induce high enough magnitude

					acceleration; Not contained in test area
	Using a T-Bar mechanism (already at the ski hill)	Y	N	Y	Spring force alone cannot induce high enough magnitude acceleration
	Sled (pull line or gravity)	Y	N	Y	Not contained in test area
	Winch	Y	Y	Y	
Function	**Concept**	**Winnowing**			**Comments**
Control headform orientation at impact	Pendulum with rotation axis height adjustment	Y	Y	Y	
	Mesh bag tethered to rotation axis	Y	Y	Y	Centripetal acceleration could be used to seat the headform and maintain orientation;
	Constrained tube (Linear cannon with release of headform at desired orientation)	Y	Y	Y	Impact would need to be soon after deployment
	Extendable pole (inverted pendulum) that is manually controlled	Y	Y	Y	
	Set screws	Y	Y	Y	
	Linear bearing	Y	Y	Y	
	Breakaway pins	Y	Y	Y	

	Air foil	Y	N	Y	Failed because the irregularity of the headform would cause unpredictable rotation of headform
	Foils to induce laminar flow (ie. Dart feathers)	Y	N	Y	Too much variability in impact site and stability is related to velocity
	Robot	Y	Y	Y	
	Guided free fall (throw)	Y	N	Y	Not repeatable for impact location
	Electric Field	Y	N	Y	Susceptible to perturbation causing inconsistent impact location; high power requirement
	Basket	Y	Y	Y	
	Release close to ground	Y	Y	Y	Minimum distance?
Function	**Concept**	**Winnowing**			**Comments**
Contain headform within test zone	Plexi glass	Y	Y	Y	
	Netting	Y	Y	Y	
	Tether to the headform	Y	Y	Y	
	Mounted on rail	Y	Y	Y	
	Padding	Y	Y	Y	
	Person to catch	Y	Y	Y	
	Electric Field	Y	N	Y	Large power requirement causing high mass

	Magnet	Y	N	Y	Extremely strong (expensive) magnet necessary to overcome; may damage DAQ
	Dog	Y	N	Y	Likely cause damage to the headform
	Box	Y	Y	Y	
	Elastic	Y	Y	Y	
	Air/water/snow blast	Y	N	Y	Required equipment for strong enough blast is too heavy and voluminous
	Snow barrier	Y	Y	Y	
	Controlled environment (ie. Halfpipe)	Y	N	Y	Limits place testing can take place; construction of a barrier using natural elements (below) may be an alternative
	Shunting mechanism (ie. J shape)	Y	Y	Y	
	Blanket	Y	Y	Y	
	Glue	Y	N	Y	Not strong enough on their own; may be helpful in conjunction with another concept
	Velcro	Y	N	Y	Not strong enough on their own; may be helpful in conjunction with another concept

Function	Concept	Winnowing			Comments
Adjust impact orientation of headform	Ball arm secured with fasteners	Y	Y	Y	
	Cage that releases/drops away before impact	Y	Y	Y	
	Freefall release in desired impact orientation	Y	Y	Y	Allows for variable impact locations but is not repeatable
	Suspension cables	Y	Y	Y	
	Constrained tube	Y	Y	Y	
	Mesh bag (placed in bag in desired orientation)	Y	Y	Y	
	Clamp	Y	Y	Y	
	3D Printed part	Y	Y	Y	Standardized for each defined impact location
	Wedges	Y	Y	Y	Concern about repeatability
	Magnets	Y	N	Y	Placing magnets on the head will change the mass properties and create surface irregularity leading to variability
	Robots	Y	Y	Y	
	Set screws (x-mas tree stand)	Y	Y	Y	
	Locking Hinge	Y	Y	Y	

	Power screw (2 DOF)	Y	Y	Y	May need to use in combination with another concept
	6 DOF arm (ask Kurt)				
	Air foil	N	N	Y	Perturbation causes significant movement
Function	**Concept**	**Winnowing**			**Comments**
Release headform from test apparatus prior to impact	Manual release (trigger, cable pull)	Y	Y	Y	
	Shear pin at desired velocity	Y	Y	Y	
	Trip wire that engages release mechanism	Y	Y	Y	
	Free fall (release at top of drop height)	Y	Y	Y	
	Release mechanism triggers at specified distance (eg. finite length of cord that when tensioned, pulls pin)	Y	Y	Y	
	Gravitational release (for rotational means of acceleration)			Y	Cannot conceptualize
	Exit blast tube	Y	Y	Y	
	Push off table	Y	Y	Y	
	Release from hands	Y	Y	Y	
	Guide ends (ie. Rail)	Y	Y	Y	

	Launcher (ball launcher)	Y	Y	Y	
	String cut	Y	Y	Y	
	Stop air flow	Y	Y	Y	
	Release C-clamp via impulse to screw	Y	Y	Y	Would need another mechanism to
Function	**Concept**	**Winnowing**			**Comments**
Quantify headform impact velocity	Velocity gate (optic)	Y	Y	Y	
	Integrate resultant linear acceleration	Y	Y	Y	
	Shear pin that breaks at known force (ie. Force exerted at velocity threshold)	Y	Y	Y	Question as to the error range for failure and how that compares to the allowable range of velocity (ie. %5)
	Video replay and marker analysis	Y	N	Y	Not possible to perform analysis on the hill to determine if the test was valid.
	Radar gun/ultrasonic motion sensor	Y	Y	Y	
	Burst membrane	Y	Y	Y	
	Stopwatch/visual	Y	N	Y	Not precise enough
	Sensors (force, accelerometers on apparatus)	Y	Y	Y	Would be time intensive to verify the velocity for each test
	Validation protocol with a look up	Y	N	Y	Variability in environmental

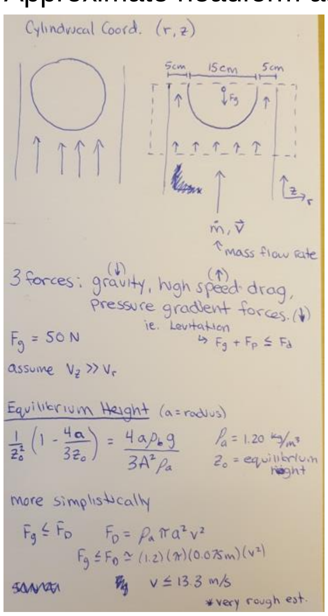
	table				conditions introduces too many variables to anticipate
	Time/height calc	Y	N	Y	Not precise enough
Function	**Concept**	**Winnowing**			**Comments**
Maintain consistent impact surface between tests	Rake impact area	Y	Y	Y	
	Move apparatus finite amount laterally	Y	Y	Y	
	Deposit finite amount of nearby snow over impact surface	Y	Y	Y	
	Develop protocol for impact site preparation (include prescribed radius from impact point; test of compaction, granularity, moisture content, hardness?, angle)	Y	Y	Y	
	Hardness gauge (Fraser)	Y	Y	Y	
	Temperature controlled chamber	Y	N	Y	Defeats purpose of in-field testing
	Flatrod (consistent profile)	Y	Y	Y	
	Blow snow over site	Y	N	Y	Inconsistent and unnatural characteritics/profile
	Don't maintain; characterize	Y	Y	Y	
	Surrogate material	Y	N	Y	Defeats purpose of in-field testing

Concept Feasibility Calculations

Flywheel Energy Calc:

- E=(1/2)*I*omega^2
- Let's say we can get the flywheel to a speed of 1500 rpm (25 rps = 157 rad/s) with a cordless power drill
- For a 10 m/s drop, we need the headform to have an energy of 252.5 joules (K=(1/2)mv^2)
- This means our moment of inertia (I) needs to be at least (given ideally, Eflywheel transferred to Ehead):
    - 252.2 Joules = (1/2) * I * 157 rad/s^2
    - I = 0.020 kg*m^2
- Approximate flywheel as a hollow cylinder (inside radius = 5cm; outside radius = 8cm; I=(1/2)*mass*(R1^2 + R2^2))
    - 0.020 Kg*m^2 = (1/2)*mass*(0.08m^2 + 0.05m^2)
    - Mass = 4.494 kg
- Note: This calculation is an ideal situation in which no energy is lost when transferred from the flywheel to the headform. It also does not account for potential energy of the headform.

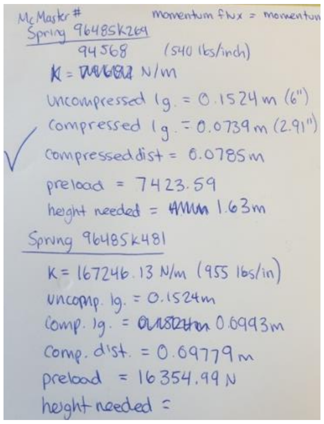
AirFoil Force Calc

- Resource : http://www.physics.princeton.edu/~mcdonald/examples/beachball.pdf
- Force required to hold up head form (ie. Overcome gravity) → F = ma = 5.05kg * 9.81 m/s^2 = 49.54 N
- Approximate headform as a sphere with diameter of 15 cm
- 

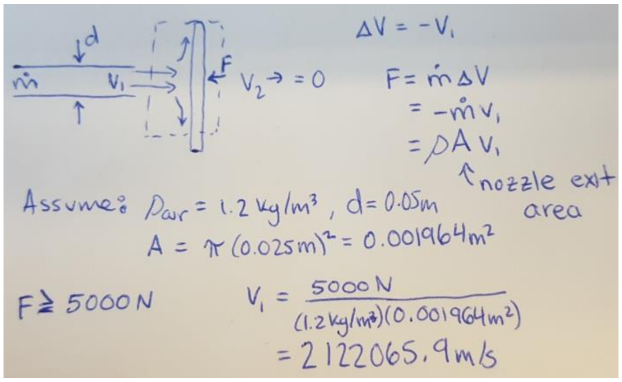
Freefall drop height calc

- Assume no air drag
- Kinetic energy = 1/2 * m * v^2; potential energy = mgh
- KE = PE (conservation of energy); 1/2 mv^2=mgh; mass cancels; v = 10 m/s
- Height (for 10 m/s impact speed) = $v^2/2g$ = 100/2*9.81m/s^2 → height = 5.097m

Linear spring on monorail calc (used Adams simulation)



Airjet Propulsion Force Calc



Pugh Charts

Table 16: 1-1 Hold Headform Relative to Ground (Datum)

Evaluation Criteria	Rail with Hard Stop	Tensioned tether with release pin	Suspension cables on a drop	Suspended Mesh bag	Table/shelf	Clamp mounted on post	Hold with hands	Magnet	Adhesive	Pole with bowl (ie. T-Ball stand)
Cost	S	+	S	+	+	+	+	-	+	+
Precision	S	S	S	S	S	-	-	S	-	-
Weight	S	+	S	S	S	S	+	+	+	+
Ease of Use	S	S	S	S	S	S	+	S	S	+

Evaluation Criteria	Rail with Hard Stop	Tensioned tether with release pin	Suspension cables on a drop	Suspended Mesh bag	Table/shelf	Clamp mounted on post	Hold with hands	Magnet	Adhesive	Pole with bowl (ie. T-Ball stand)
Durability	S	-	-	-	-	S	-	-	-	-
Set-Up Time	S	S	S	-	-	S	+	S	S	S
Size	S	+	S	S	-	S	+	+	+	S
Repeatability	S	-	-	-	S	-	-	S	-	-
Safety	S	S	S	S	S	S	-	-	-	-
Σ+	-	+3	+0	+1	+1	+1	+5	+2	+3	+3
ΣS	-	4	7	5	5	6	0	4	2	2
Σ-	-	-2	-2	-3	-3	-2	-4	-3	-4	-4
Net Score	-	0	-2	-2	-2	-1	+1	-3	-1	-1
Rank	-	2nd	4th	4th	4th	3rd	1st	5th	3rd	3rd

Table 17: 1-2 Hold Headform Relative to Ground

Evaluation Criteria	Rail with Hard Stop	Tensioned tether with release pin	Suspension cables on a drop	Suspended Mesh bag	Table/shelf	Clamp mounted on post	Hold with hands	Magnet	Adhesive	Pole with bowl (ie. T-Ball stand)
Cost	-	-	-	-	-	-	S	-	-	-
Precision	+	+	+	+	+	+	S	+	+	+
Weight	-	-	-	-	-	-	S	-	-	-
Ease of Use	-	-	-	-	S	-	S	S	S	S
Durability	+	+	+	+	+	+	S	+	S	+
Set-Up Time	-	-	-	-	-	-	S	-	-	-
Size	-	-	-	-	-	-	S	-	-	-
Repeatability	+	+	+	+	+	+	S	+	+	+
Safety	+	+	+	+	S	+	S	+	+	+

Evaluation Criteria	Rail with Hard Stop	Tensioned tether with release pin	Suspension cables on a drop	Suspended Mesh bag	Table/shelf	Clamp mounted on post	Hold with hands	Magnet	Adhesive	Pole with bowl (ie. T-Ball stand)
Σ+	+4	+4	+4	+4	+3	+4	-	+4	+2	+4
ΣS	0	0	0	0	2	0	-	1	3	1
Σ-	-5	-5	-5	-5	-4	-5	-	-4	-4	-4
Net Score	-1	-1	-1	-1	-1	-1	-	0	-2	0
Rank	2nd	2nd	2nd	2nd	2nd	2nd	-	1st	3rd	1st

Table 18: 1-3 Hold Headform Relative to Ground

Evaluation Criteria	**Rail with Hard Stop**	**Tensioned tether with release**	Suspension cables on a drop	**Suspended Mesh**	Table/shelf	**Clamp mounted on post**	**Hold with hands**	**Magnet**	Adhesive	**Pole with bowl (ie. T-Ball**
Cost	S	S	-	+	-	+	+	S	+	S
Precision	S	-	-	-	S	S	-	S	-	S
Weight	-	S	S	S	-	S	+	S	S	S
Ease of Use	S	S	S	S	S	S	+	S	S	S
Durability	S	S	S	-	+	S	-	S	-	S
Set-Up Time	+	+	S	+	S	S	+	S	-	S
Size	S	S	S	S	-	S	+	S	S	S
Repeatability	S	-	-	-	-	-	-	S	-	-
Safety	+	+	+	+	-	+	-	S	+	+
Σ+	+2	+2	+1	+3	+1	+2	+5	-	+2	+1
ΣS	6	5	5	3	3	6	0	-	3	7
Σ-	-1	-2	-3	-3	-5	-1	-4	-	-4	-1
Net Score	+1	0	-2	0	-4	+1	+1	-	-2	0
Rank	1st	2nd	3rd	2nd	4th	1st	1st	-	3rd	2nd

From the above Pugh charts, we can exclude the concepts that were consistently ranked low. These include table/shelf, adhesive and suspension cables on a drop frame.

Table 19: 2-1 Induce Known Acceleration to Headform Relative to Ground

Evaluation Criteria	Flywheel and Clutch (power drill)	Flywheel and Clutch (hand crank/ripcord	Chemical Reaction	Loaded Spring	Gravity Drop	Inverted Pendulum	Powered Disc with	Pulley System	Seesaw Launch	Winch
Cost	S	+	-	+	+	+	S	+	+	S
Precision	S	S	-	+	+	+	S	+	-	S
Weight	S	S	+	+	+	+	+	+	+	S
Ease of Use	S	-	S	-	S	S	S	S	-	S
Durability	S	-	-	+	+	S	S	-	-	-
Set-Up Time	S	-	S	S	S	S	S	S	+	S
Size	S	S	+	+	-	S	+	+	S	S
Repeatability	S	S	-	S	S	S	S	S	-	S
Safety	S	-	-	S	S	S	S	-	-	S
Σ+	-	+1	+2	+5	+4	+3	+2	+4	+3	0
ΣS	-	4	2	3	4	6	7	3	1	8
Σ-	-	-4	-5	-1	-1	0	0	-2	-5	-1
Net Score	-	-3	-3	+4	+3	+3	+2	+2	-2	-1
Rank	-	6th	6th	1st	2nd	2nd	3rd	3rd	5th	4th

Table 20: 2-2. Induce Known Acceleration to Headform Relative to Ground

Evaluation Criteria	**Flywheel and Clutch (power drill)**	Flywheel and Clutch (hand crank/ripcord	Chemical Reaction	**Loaded Spring**	**Gravity Drop**	**Inverted Pendulum**	**Powered Disc with**	**Pulley System**	Seesaw Launch	**Winch**
Cost	-	-	-	-	S	S	-	S	-	-

Evaluation Criteria	**Flywheel and Clutch (power drill)**	Flywheel and Clutch (hand crank/ripcord	Chemical Reaction	**Loaded Spring**	**Gravity Drop**	**Inverted Pendulum**	**Powered Disc with**	**Pulley System**	Seesaw Launch	**Winch**
Precision	-	+	-	S	S	S	+	S	-	+
Weight	S	S	+	+	S	S	+	+	+	-
Ease of Use	S	-	S	S	S	S	+	+	+	+
Durability	-	-	-	-	S	S	-	-	-	-
Set-Up Time	S	-	S	S	S	S	S	-	+	S
Size	+	S	+	+	S	S	+	+	S	-
Repeatability	S	S	-	S	S	S	S	-	-	+
Safety	-	-	-	S	S	S	-	-	-	-
Σ+	+2	+1	+2	+3	-	0	+4	+3	+3	+3
ΣS	4	4	2	4	-	9	2	3	1	1
Σ-	-3	-3	-5	-2	-	0	-3	-3	-5	-5
Net Score	-1	-2	-3	+1	-	0	+1	0	-2	-2
Rank	3rd	4th	5th	1st	-	2nd	1st	2nd	4th	4th

From the above Pugh charts, we can exclude the concepts that were consistently ranked low. These include flywheel (manual), chemical reaction and seesaw launch.

Table 21: 3-1. Control Headform Orientation at Impact

Evaluation Criteria	Inverted Pendulum w/height	Mesh Bag (rotating)	Constrained Tube	Set Screws	Linear Bearing	Breakaway Pin	Robot	Release close to ground	Basket	Ball arm
Cost	S	+	-	+	S	-	-	S	S	S
Precision	S	S	-	S	S	S	S	-	S	S
Weight	S	+	-	S	S	S	-	+	S	S

Evaluation Criteria	Inverted Pendulum w/height	Mesh Bag (rotating)	Constrained Tube	Set Screws	Linear Bearing	Breakaway Pin	Robot	Release close to ground	Basket	Ball arm
Ease of Use	S	S	-	-	S	S	+	+	+	S
Durability	S	-	-	-	S	-	-	S	S	S
Set-Up Time	S	+	S	S	S	S	-	S	-	S
Size	-	+	-	+	S	-	-	S	S	S
Repeatability	S	-	-	S	S	-	+	-	S	S
Safety	S	S	+	S	S	-	+	-	S	S
Σ+	0	+4	+1	+2	0	0	+3	+2	+1	-
ΣS	8	3	1	5	9	4	1	4	7	-
Σ-	-1	-2	-7	-2	0	-5	-5	-3	-1	-
Net Score	-1	+2	-6	0	0	-5	-2	-1	0	-
Rank	3rd	1st	6th	2nd	2nd	5th	4th	3rd	2nd	-

Table 22: 3-2. Control Headform Orientation at Impact

Evaluation Criteria	**Inverted Pendulum w/height adjust**	**Mesh Bag (rotating)**	Constrained Tube	**Set Screws**	**Linear Bearing**	Breakaway Pin	Robot	**Release close to**	**Basket**	**Ball arm**
Cost	-	S	-	S	-	-	-	S	-	-
Precision	+	S	S	+	+	-	+	-	+	+
Weight	-	S	-	S	-	S	-	S	-	-
Ease of Use	S	S	-	-	S	S	-	S	S	S
Durability	+	S	S	+	-	-	-	+	+	+
Set-Up Time	S	S	-	S	+	S	-	S	+	+
Size	S	S	-	+	S	S	-	+	-	-

Repeatability	+	S	-	+	+	S	+	-	+	+
Safety	S	S	+	S	S	-	+	-	S	S
Σ+	+3	-	+1	+4	+3	0	+3	+2	+4	+4
ΣS	4	-	2	4	3	5	0	4	2	2
Σ-	-2	-	-6	-1	-3	-4	-6	-3	-3	-3
Net Score	+1	-	-5	+3	0	-4	-3	-1	+1	+1
Rank	2nd	-	7th	1st	3rd	6th	5th	4th	2nd	2nd

From the above Pugh charts, we can exclude the concepts that were consistently ranked low. These include constrained tube, breakaway pin and robot.

Table 23: 4-1. Contain Headform Within Test Zone

Evaluation Criteria	Netting	Plexi Glass	Tether	Rail Mount	Padding	Person to Catch	Box	Elastic	Shunting Mechanism	Blanket	Snow Barrier
Cost	S	S	+	-	S	+	S	S	-	S	+
Weight	S	-	+	-	S	+	-	S	-	S	+
Effectiveness	S	-	S	+	S	-	S	-	+	S	-
Ease of Use	S	S	S	S	S	-	S	S	S	S	-
Durability	S	-	S	+	S	-	-	S	+	S	-
Set-Up Time	S	S	S	-	S	+	S	S	-	S	-
Size	S	-	S	-	S	+	-	S	-	-	+
Repeatability	S	S	S	+	S	-	S	S	+	S	S
Safety	S	-	S	+	+	-	S	-	+	S	-
Σ+	-	0	+2	+4	+1	+4	0	0	+4	0	+3
ΣS	-	4	7	1	8	0	6	7	1	8	1
Σ-	-	-5	0	-4	0	-5	-3	-2	-4	-1	-5

Net Score	-	-5	+2	0	+1	-1	-3	-2	0	-1	-2
Rank	-	7th	1st	3rd	2nd	4th	6th	5th	3rd	4th	5th

Table 24:4-2. Contain Headform within Test Zone

Evaluation Criteria	**Netting**	Plexi Glass	**Tether**	**Rail Mount**	**Padding**	**Person to Catch**	Box	Elastic	**Shunting Mechanism**	Blanket	**Snow Barrier**
Cost	-	-	S	-	-	+	-	-	-	-	+
Weight	-	-	S	-	-	+	-	-	-	-	+
Effectiveness	S	-	S	+	S	-	S	-	+	S	-
Ease of Use	S	S	S	S	S	-	S	S	S	S	-
Durability	S	-	S	+	S	-	-	S	+	S	-
Set-Up Time	S	S	S	-	S	+	S	S	-	S	-
Size	S	-	S	-	-	+	-	S	-	-	+
Repeatability	S	S	S	+	S	-	S	S	+	S	S
Safety	S	-	S	+	S	-	S	-	+	S	-
Σ+	0	0	-	+4	0	+4	0	0	+4	0	+3
ΣS	7	3	-	1	6	0	5	5	1	6	1
Σ-	-2	-6	-	-4	-3	-5	-4	-4	-4	-3	-5
Net Score	-2	-6	-	0	-3	-1	-4	-4	0	-3	-2
Rank	3rd	6th	-	1st	4th	2nd	5th	5th	1st	4th	3rd

From the above Pugh charts, we can exclude the concepts that were consistently ranked low. These include box, elastic, blanket and plexi glass.

Table 25: 5-1. Adjust Impact Orientation of Headform (Constrained tube and robot excluded based on previous Pugh analysis)

Evaluation Criteria	Ball arm w Fasteners	Dropaway Cage	Freefall	Suspension Cable	Power Screw	Mesh Bag	Clamp	3D Printed Part	Wedges	Set Screws	Locking Hinge
Cost	S	S	+	+	S	+	+	S	+	+	+
Weight	S	S	+	S	+	+	S	+	S	+	+
Precision	S	S	-	-	S	-	S	S	-	S	S
Ease of Use	S	+	S	S	S	S	S	S	-	S	S
Durability	S	S	-	-	S	-	S	-	-	-	S
Set-Up Time	S	S	+	-	S	S	-	S	-	S	S
Size	S	S	+	+	S	+	S	+	S	+	S
Repeatability	S	S	-	-	S	-	-	-	-	-	S
Safety	S	S	-	S	S	-	-	-	-	S	S
Adjustability	S	+	+	-	-	+	S	-	S	S	-
Σ+	-	+2	+5	+2	+1	+4	+1	+2	+1	+3	+2
ΣS	-	8	1	3	8	2	6	4	3	5	7
Σ-	-	0	-4	-5	-1	-4	-3	-4	-6	-2	-1
Net Score	-	+2	+1	-3	0	0	-2	0	-5	+1	+1
Rank	-	1st	2nd	5th	3rd	3rd	4th	3rd	6th	2nd	2nd

Table 26: 5-2. Adjust Impact Orientation of Headform

Evaluation Criteria	**Ball arm w Fasteners**	**Dropaway Cage**	**Freefall**	Suspension Cable	**Power Screw**	**Mesh Bag**	Clamp	**3D Printed Part**	Wedges	**Set Screws**	**Locking Hinge**
Cost	-	-	S	-	-	-	-	-	-	-	-
Weight	-	-	S	-	-	-	-	-	-	-	-

Evaluation Criteria	**Ball arm w Fasteners**	**Dropaway Cage**	**Freefall**	Suspension Cable	**Power Screw**	**Mesh Bag**	Clamp	**3D Printed Part**	Wedges	**Set Screws**	**Locking Hinge**
Precision	+	+	S	+	+	+	+	+	+	+	+
Ease of Use	S	+	S	-	S	S	-	+	-	S	S
Durability	+	+	S	+	+	+	+	+	+	+	+
Set-Up Time	-	S	S	-	S	S	S	S	S	-	S
Size	S	S	S	S	S	S	S	-	S	S	S
Repeatability	+	+	S	+	+	+	+	+	+	+	+
Safety	+	+	S	+	+	+	+	+	+	+	+
Adjustability	+	+	S	S	-	+	S	-	S	+	S
Σ+	+5	+6	-	+4	+4	+5	+4	+5	+4	+5	+4
ΣS	2	2	-	2	3	3	3	1	3	2	4
Σ-	-3	-2	-	-4	-3	-2	-3	-4	-3	-3	-2
Net Score	+2	+4	-	0	+1	+3	+1	+1	+1	+2	+2
Rank	3rd	1st	-	5th	4th	2nd	4th	4th	4th	3rd	3rd

From the above Pugh charts, we can exclude the concepts that were consistently ranked low. These include suspension cables, clamp, and wedges.

Table 27: 6-1. Release Headform from Test Apparatus prior to Impact

Evaluation Criteria	Manual Release	Shear Pin	Trip Wire	Release from Hands	Exit Blast Tube	Push off Table	Distance Dependent	Guide Ends	String Cut	Stop Air Flow	C-clamp impulse
Cost	S	+	S	+	-	+	S	+	-	-	-
Weight	S	S	S	+	-	+	S	+	S	-	-
Precision	S	S	S	-	S	-	S	S	S	-	-

Evaluation Criteria	Manual Release	Shear Pin	Trip Wire	Release from Hands	Exit Blast Tube	Push off Table	Distance Dependent	Guide Ends	String Cut	Stop Air Flow	C-clamp impulse
Ease of Use	S	S	S	S	+	S	S	+	+	S	S
Durability	S	+	S	-	S	-	S	+	-	-	S
Set-Up Time	S	S	S	+	S	-	S	S	S	-	-
Size	S	-	S	+	-	+	S	+	S	-	-
Repeatability	S	+	+	-	S	-	+	-	-	-	S
Safety	S	S	S	-	-	-	S	-	-	+	-
Σ+	-	+3	+1	+4	+1	+3	+1	+5	+1	+1	0
ΣS	-	5	8	1	4	1	8	2	4	1	3
Σ-	-	-1	0	-3	-4	-5	0	-2	-4	-7	-6
Net Score	-	+2	+1	+1	-3	-2	+1	+3	-3	-6	-6
Rank	-	2nd	3rd	3rd	5th	4th	3rd	1st	5th	6th	6th

Table 28:6-2. Release Headform from Test Apparatus prior to Impact

Evaluation Criteria	**Manual Release (Trigger**	**Shear Pin**	**Trip Wire**	**Release from Hands**	Exit Blast Tube	Push off Table	**Distance Dependent**	**Guide Ends**	String Cut	Stop Air Flow	C-clamp impulse
Cost	-	-	-	+	-	S	-	S	-	-	-
Weight	-	-	-	+	S	S	-	S	-	-	-
Precision	S	-	-	-	-	-	S	S	-	-	-
Ease of Use	S	S	S	S	S	-	S	S	S	S	S
Durability	-	-	-	-	-	S	-	S	-	S	-
Set-Up Time	+	S	S	+	-	S	S	S	S	-	+
Size	-	-	-	S	-	-	-	S	-	-	-

Evaluation Criteria	**Manual Release (Trigger**	**Shear Pin**	**Trip Wire**	**Release from Hands**	Exit Blast Tube	Push off Table	**Distance Dependent**	**Guide Ends**	String Cut	Stop Air Flow	C-clamp impulse
Repeatability	S	-	-	-	-	-	-	S	-	-	-
Safety	+	S	S	-	-	-	+	S	+	-	S
Σ+	+2	0	0	+3	0	0	+1	-	+1	0	+1
ΣS	3	3	3	2	2	4	3	-	2	2	2
Σ-	-4	-6	-6	-4	-7	-5	-5	-	-6	-7	-6
Net Score	-2	-6	-6	-1	-7	-5	-4	-	-5	-7	-5
Rank	2nd	5th	5th	1st	6th	4th	3rd	-	4th	6th	4th

From the above Pugh charts, we can exclude the concepts that were consistently ranked low. These include stop air flow, exit blast tube, string cut, push off table and c-clamp impulse.

Table 29: 7-1. Quantify Headform Impact Velocity

Evaluation Criteria	Velocity Gate	Integrate	Shear Pin	Radar Gun	Sensors	Burst Membrane
Cost	S	+	-	S	S	-
Weight	S	+	-	-	S	-
Precision	S	-	-	-	S	-
Ease of Use	S	-	-	S	-	-
Durability	S	+	S	S	S	-
Set-Up Time	S	-	-	+	S	-
Size	S	+	-	-	S	-
Repeatability	S	-	-	S	S	-
Safety	S	S	-	S	S	-

Evaluation Criteria	Velocity Gate	Integrate	Shear Pin	Radar Gun	Sensors	Burst Membrane
Σ+	-	+4	0	+1	0	0
ΣS	-	1	1	5	8	0
Σ-	-	-4	-8	-3	-1	-9
Net Score	-	0	-8	-2	-1	-9
Rank	-	1st	4th	3rd	2nd	5th

Table 30: 7-2. Quantify Headform Impact Velocity

Evaluation Criteria	**Velocity Gate**	**Integrate**	Shear Pin	**Radar Gun**	**Sensors**	Burst Membrane
Cost	-	S	-	-	S	-
Weight	-	S	-	-	S	-
Precision	+	S	S	+	+	-
Ease of Use	+	S	+	+	+	S
Durability	S	S	-	+	S	-
Set-Up Time	S	S	-	+	-	-
Size	-	S	-	-	S	-
Repeatability	+	S	S	S	+	-
Safety	S	S	-	S	S	-
Σ+	+3	-	+1	+4	+3	0
ΣS	3	-	2	2	5	1
Σ-	-3	-	-6	-3	-1	-8
Net Score	0	-	-5	+1	+2	-8

Evaluation Criteria	**Velocity Gate**	**Integrate**	Shear Pin	**Radar Gun**	**Sensors**	Burst Membrane
Rank	3rd	-	4th	2nd	1st	5th

From the above Pugh charts, we can exclude the concepts that were consistently ranked low. These include shear pin and burst membrane.

Table 31: 8-1. Maintain consistent impact surface between tests

Evaluation Criteria	Rake	Move Apparatus	Deposit new snow	Protocol	Flatrod	Hardness Gauge	Characterize
Cost	S	+	+	-	S	-	-
Weight	S	+	+	+	S	S	S
Precision	S	-	-	+	S	+	+
Ease of Use	S	-	-	-	S	S	-
Durability	S	+	+	S	S	-	-
Set-Up Time	S	-	S	-	S	S	-
Size	S	+	+	S	S	+	S
Repeatability	S	-	-	+	S	+	+
Safety	S	-	S	S	S	S	S
Σ+	-	+4	+4	+3	0	+3	+2
ΣS	-	0	2	3	9	4	3
Σ-	-	-5	-3	-3	0	-2	-4
Net Score	-	-1	+1	0	0	+1	-2
Rank	-	3rd	1st	2nd	2nd	1st	4th

Table 32: 8-2. Maintain consistent impact surface between tests

Evaluation Criteria	**Rake**	**Move Apparatus**	**Deposit new snow**	**Protocol**	**Flatrod**	**Hardness Gauge**	Characterize
Cost	-	S	S	-	S	-	-
Weight	-	S	S	-	-	-	-
Precision	+	+	S	+	+	+	+
Ease of Use	+	-	S	-	S	+	S
Durability	S	-	S	-	S	-	-
Set-Up Time	S	-	S	-	S	S	-
Size	S	+	S	-	S	+	-
Repeatability	+	S	S	+	+	+	+
Safety	S	-	S	S	S	S	S
Σ+	+3	+2	-	+2	+2	+4	+2
ΣS	4	3	-	1	6	2	2
Σ-	-2	-4	-	-6	-1	-3	-5
Net Score	+1	-2	-	-4	+1	+1	-3
Rank	1st	2nd	-	4th	1st	1st	3rd

Analytical Hierarchical Process

This method of determining the weight of each evaluation criteria relies on relative importance. All criteria were put as both row and column headers with the table's diagonal (intersecting box where the row and column are the same criteria) being populated with the value '1'. Next, each criteria was compared to all others and scored from 1-9 based on the relative importance as seen in Table 33.

Table 33: Analytical Hierarchical Process ranking rubric (121)

Value	Ranking
1	Equally important
3	Slightly more important
5	Moderately more important
7	Much more important
9	Absolutely more important

When the criterion was determined to be more important than another criterion, the ranking value was entered in the box corresponding to the row of the more important criteria and the column of the less important criteria. Once this comparison was completed for each combination, the remainder of the boxes were filled in with the inverse value of the partner comparison (ie. precision is much more important than cost so the box where precision is the row header and cost is the column header was entered as 7 while the box with cost as the row header and precision as the column header was entered as 1/7). Table 34 shows the raw rank assigned for each criteria.

Once the ranking table was filled in, each value was then normalized by dividing each value by the sum of the column that value belonged to. Next, all of the rows were summed. The final weight was then determined by dividing each of the row totals by the sum of the row totals column.

Table 34: AHP showing the raw rank for each evaluation criteria

Evaluation	Cost	Precisio	Weigh	Ease	Durability	Set-	Size	Repeatabilit	Safety

Criteria		n	t	of Use		Up Time		y	
Cost	1.00	0.14	0.33	0.20	0.33	0.20	0.33	0.14	0.20
Precision	7.00	1.00	3.00	5.00	5.00	5.00	5.00	1.00	1.00
Weight	3.00	0.33	1.00	0.33	0.33	0.20	1.00	0.14	0.20
Ease of Use	5.00	0.20	3.00	1.00	3.00	0.33	3.00	0.20	0.33
Durability	3.00	0.20	3.00	0.33	1.00	3.00	3.00	0.20	0.33
Set-Up Time	5.00	0.20	5.00	3.00	0.33	1.00	3.00	0.14	0.20
Size	3.00	0.20	1.00	0.33	0.33	0.33	1.00	0.14	0.20
Repeatability	7.00	1.00	7.00	5.00	5.00	7.00	7.00	1.00	1.00
Safety	5.00	1.00	5.00	3.00	3.00	5.00	5.00	1.00	1.00
Total	39.00	4.28	28.33	18.20	18.33	22.07	28.33	3.97	4.47

Table 35: Normalized rankings and overall weightings for each evaluation criteria using the AHP

Evaluation Criteria	Cost	Precision	Weight	Ease of Use	Durability	Set-Up Time	Size	Repeatability	Safety	Row Total	Weight	Weight (%)
Cost	0.026	0.033	0.012	0.011	0.018	0.009	0.012	0.036	0.045	0.202	0.02	2.24
Precision	0.179	0.234	0.106	0.275	0.273	0.227	0.176	0.252	0.224	1.945	0.22	21.62
Weight	0.077	0.078	0.035	0.018	0.018	0.009	0.035	0.036	0.045	0.352	0.04	3.91
Ease of Use	0.128	0.047	0.106	0.055	0.164	0.015	0.106	0.050	0.075	0.745	0.08	8.28
Durability	0.077	0.047	0.106	0.018	0.055	0.136	0.106	0.050	0.075	0.669	0.07	7.44
Set-Up Time	0.128	0.047	0.176	0.165	0.018	0.045	0.106	0.036	0.045	0.766	0.09	8.52
Size	0.077	0.047	0.035	0.018	0.018	0.015	0.035	0.036	0.045	0.327	0.04	3.63
Repeatability	0.179	0.234	0.247	0.275	0.273	0.317	0.247	0.252	0.224	2.248	0.25	24.98
Safety	0.128	0.234	0.176	0.165	0.164	0.227	0.176	0.252	0.224	1.746	0.19	19.40
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	9.000	1	

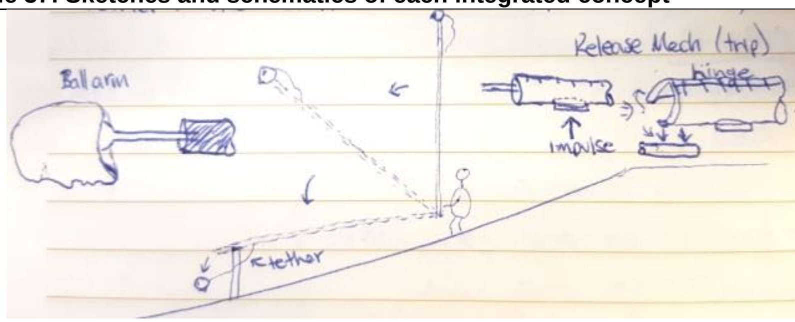
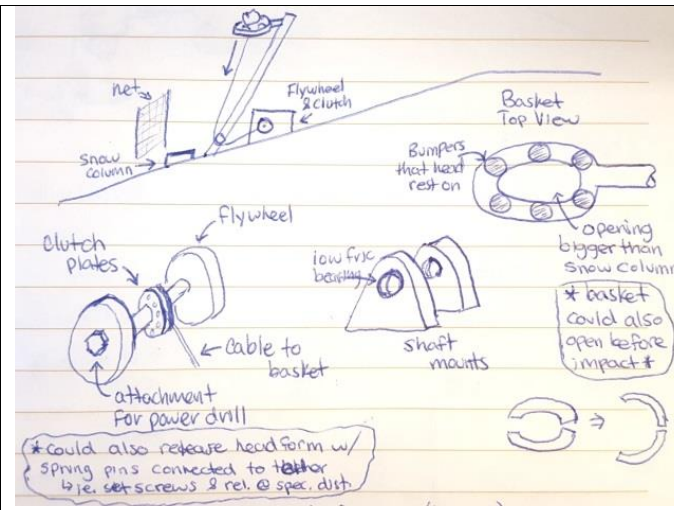
Integrated Concepts

Table 36: Summary of concept fragments chosen for each integrated concepts

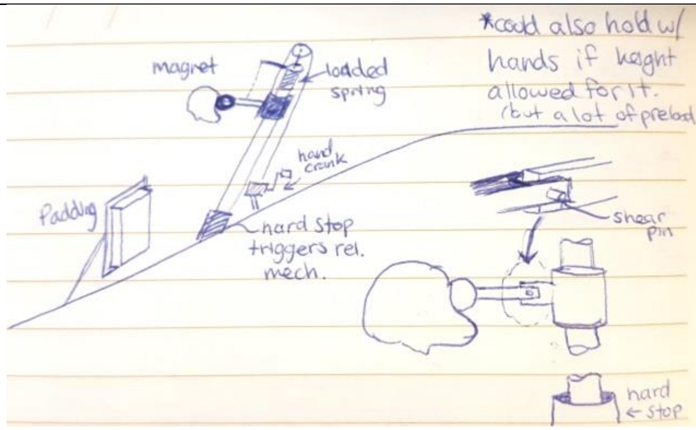
	Descriptor	Top Level Functions							
		Hold headform relative to ground	**Induce known acceleration to headform relative to ground**	**Control headform orientation at impact**	**Contain headform within test zone**	**Adjust impact orientation of headform**	**Release headform from test apparatus prior to impact**	**Quantify headform impact velocity**	**Maintain consistent impact surface between tests**
A	Inverted Pendulum (gravity)	Clamp	Inverted Pendulum	Ball Arm	Tether to Headform	Ball Arm w Fasteners	Trip Wire	Sensors (meas. Vel.)	Move Laterally
B	Flywheel w Clutch (powered)	Rail w Hard stop	Flywheel/Clutch (powered)	Basket	Netting	Cage (drops away)	Guide Ends	Velocity Gate	Hardness Gauge/Protocol
C	Loaded Spring (linear)	Ball Arm (rail)	Loaded Spring (linear)	Release close to grnd/ball arm	Padding	Ball Arm w Fasteners	Release Mechanism @ Spec. Distance	Integrate Acceleration	Rake Impact Area
D	Freefall Drop	Magnet (Solenoid)	Freefall	Mesh Bag	Snow Barrier	Mesh Bag (in desired orientation)	Manual Release (Solenoid)	Velocity Gate	Move Laterally
E	Pulley System (4:1)	Rail w Hard stop	Pulley System	Basket/Set Screws	Person to Catch	Set Screws	Trip Wire	Radar Gun	Flat rod
F	Inverted Pendulum (spring)	Clamp	Inverted Pendulum (torsional spring)	Ball Arm	Tether to Headform	Ball Arm w Fasteners	Shear Pin/Trip Wire	Integrate Acceleration	Rake Impact Area
G	Winch	Tether w Release Pin	Winch Motor	Release close to grnd/linear bearing	Netting	3D Printed Part	Guide Ends	Velocity Gate	Deposit Snow

	Descriptor	**Top Level Functions**							
		Hold headform relative to ground	**Induce known acceleration to headform relative to ground**	**Control headform orientation at impact**	**Contain headform within test zone**	**Adjust impact orientation of headform**	**Release headform from test apparatus prior to impact**	**Quantify headform impact velocity**	**Maintain consistent impact surface between tests**
H	Electromagnet	Magnet (Solenoid)	Electromagnet (Rail Gun)	Linear Bearing	Snow Barrier	Locking Hinge	Shear Pin/Trip Wire	Radar Gun	Characterize/Move Laterally

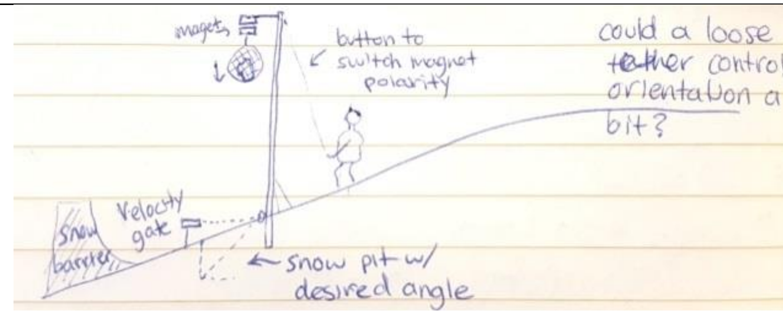
Table 37: Sketches and schematics of each integrated concept

A		B	

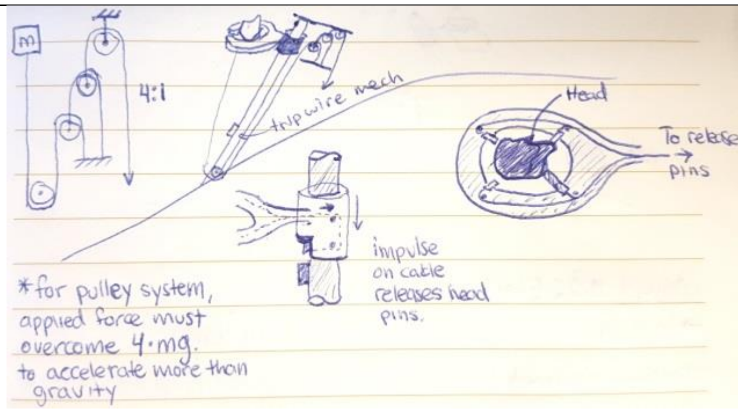
C


*could also hold w/ hands if height allowed for it. (but a lot of preload
magnet
loaded spring
hand crank
Padding
hard stop triggers rel. mech.
shear pin
hard stop

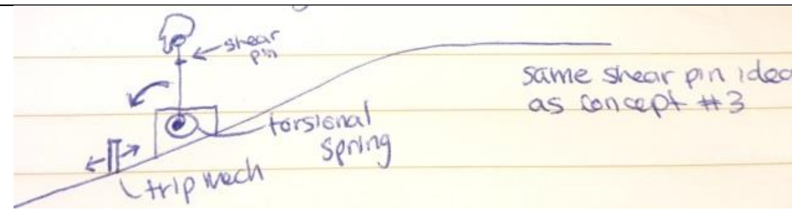
D

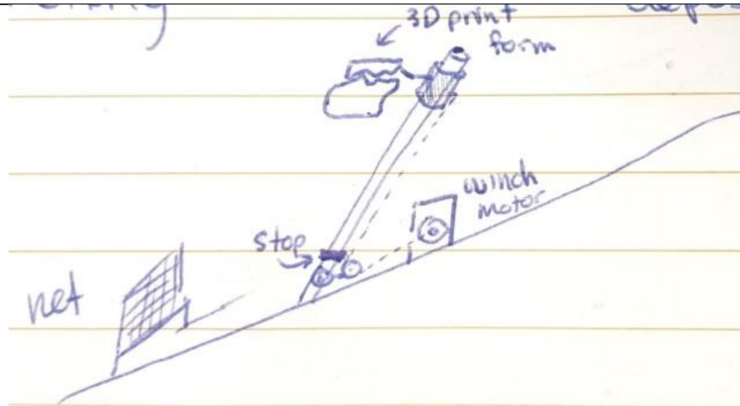

magnets
button to switch magnet polarity
could a loose tether control orientation a bit?
Snow barrier
Velocity gate
snow pit w/ desired angle

E


m
4:1
tripwire mech
Head
To release pins
impulse on cable releases head pins.
*for pulley system, applied force must overcome 4·mg. to accelerate more than gravity

F


shear pin
torsional spring
trip mech
same shear pin idea as concept #3

G		H	

Weighted Decision Matrices

Component-by-Component Evaluation

Table 38: Summary of scoring rubrics for each of the evaluation criteria in the component-by-component scoring

Cost Level Breakdown ($)	1	<10	Volume Level Breakdown (ft^3)	1	<0.2
	2	10-50		2	0.2-0.5
	3	50-100		3	0.5-1
	4	100-200		4	1-2
	5	200-500		5	2-5
	6	500-1000		6	5-10

Weight Level Breakdown (kg)	1	<0.5
	2	0.5-1
	3	1-2
	4	2-5
	5	5-10
	6	10-25

Set Up Time (min)	1	<1
	2	1-5
	3	5-10
	4	10-20
	5	20-45
	6	45+

Ease of Use Breakdown (Qualitative)	1	very easy and fast
	2	very easy but more time consuming
	3	moderatelty difficult and more time consuming
	4	moderately difficult and quite time consuming
	5	difficult and quite time consuming
	6	extremely difficult and time consuming

Precision	1	Extremely precise (+/- 1%)
	2	Fairly precise (+/- 2.5%)
	3	Moderately precise (+/- 5%)
	4	Moderately imprecise (+/- 7.5%)
	5	Fairly imprecise (+/- 10%)
	6	Extremely imprecise (+/- 15%)

Durability	1	Most durable; no moving parts; easy to fix; no critical parts
	2	Quite durable; few moving parts; moderately easy to fix; no critical parts
	3	Fairly durable; few moving parts; moderately easy to fix; few critical parts
	4	Mediocre durability; several moving parts; moderately easy to fix; few critical parts
	5	Not very durable; many moving parts; moderately easy to fix; several critical parts
	6	Least durable; many moving parts;difficult to fix; many critical parts
Repeatability	1	Extremely repeatable (+/- 1%)
	2	Fairly repreatable (+/- 2.5%)
	3	Moderately repreatable (+/- 5%)
	4	Moderately unrepreatable (+/- 7.5%)
	5	Fairly unrepreatable (+/- 10%)
	6	Extremely unrepreatable (+/- 15%)

Safety	1	Very Safe to Operators and Public; No Extra Measures
	2	Moderately Safe to Operators; Very Safe to Public; No Extra Measures
	3	Moderately Safe to Operators; Moderately Safe to Public; Some Extra Measures
	4	Moderately Safe to Operators; Moderately Safe to Public; Some Extra Measures
	5	Dangerous to Operators; Moderately Safe to Public; Many Extra Measures
	6	Dangerous to Operators; Dangerous to Public; Many Extra Measures

Table 39: Component based scoring for the Inverted Pendulum concept

	Inverted Pendulum (gravity)									
Components	**Item**	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set Up Time**	**Volume**	**Weight**	**Cost**
	Long pole (rigid)	4	4	3	3	3	3	5	6	3
	Clamp			2			1	2	1	2
	Hinge release mechanism			3			2	2	2	4
	Tether cable			2			1	1	1	1
	Ball arm			1			2	2	2	4
	Additional sensor to measure velocity			3			2	1	1	4

	Power supply for sensor			3			1	2	2	2
	Trip Block			2			2	4	3	2
Components	**Item**	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set Up Time**	**Volume**	**Weight**	**Cost**
Special Set Up Eq.	shovel (trip block)			2			1	3	2	3

Table 40: Component based scoring for the Flywheel with Clutch concept

	Flywheel w Clutch (powered)									
	Item	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
	Net			2			1	2	1	2
	Support frame for net			2			2	4	3	2
	Rail (~2m)			3			3	6	5	5
	Basket			2			2	3	3	4
Components	Power Drill			2			1	4	3	4
	Guide Follower	3	2	3	2	3	1	3	3	4
	Cable			2			1	2	1	2
	Flywheel			2			3	4	5	3
	Clutch Plates			3			2	2	2	4
	Shaft			2			2	3	3	3
	Shaft Mounts			2			2	4	3	2
	rot. Bearings (x2)			3			2	2	3	3

	Assembly Frame			2			2	5	4	3
	Velocity Gate			3			2	3	2	4
	Power Supply for Vel. Gate			3			1	2	2	3
	Rail stop block			2			2	1	1	2
	Various hardware			1			2	1	1	2
	Hardness Gauge			3			2	2	1	4
	lubricant			1			1	1	1	1
	pulley			2			1	1	1	1
Components	**Item**	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
Special Set Up Eq.	shovel/column tool			2			1	3	2	3

Table 41: Component based scoring for the Linear Spring concept

	Loaded Spring (linear)									
Components	**Item**	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
	Padding	2	1	2	1	2	2	4	2	2
	Support frame for padding			2			2	4	3	2
	rigid shaft (~2m)			3			3	6	5	5
	pulley			2			1	1	1	1
	crank			2			2	2	2	3

	linear spring (high stiffness)			3			2	2	2	5
	ball arm			1			2	2	2	4
	shaft collar (low fric)			3			1	3	3	4
	cable			2			1	2	1	2
	spring mount			1			1	2	2	2
	lubricant			1			1	1	1	1
Special Set Up Eq.	shear pins			1			1	1	2	2
	rake			2			1	2	2	2

Table 42: Component based scoring for the Freefall Drop concept

	Freefall Drop									
	Item	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
Components	solenoid (5kg force)	3	4	3	4	2	2	2	1	4
	pole (5.5m; rigid; not rail stiffness)			4			3	5	4	5
	solenoid cable			2			1	2	1	2
	velocity gate			3			2	3	2	4
	power			3			1	2	3	3

	source									
	mesh bag			1			2	2	1	2
	stabilizing posts			2			2	3	2	2
	mount for solenoid			1			1	1	1	2
Special Set Up Eq.	shovel			2			1	3	2	3

Table 43: Component based scoring for the Pulley System concept

	Pulley System (4:1)									
	Item	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
Components	rigid shaft (~3m)	3	3	3	2	3	3	6	6	4
	pulley (x5)			2			2	2	3	3
	basket			2			2	3	3	4
	shaft collar			3			1	3	3	4
	spring pins			3			2	1	1	3
	cable (double length)			2			1	2	1	3
	trip block (mounted on shaft)			2			2	3	3	2
	flatrod			2			1	2	1	2
	radar gun			2			1	4	4	5
	mechanism in shaft collar			3			2	1	1	2

	mount for pulley system			1			1	1	1	2
	lubricant			1			1	1	1	1
Components	**Item**	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
Special Set Up Eq.	person to catch			1			-	1	-	2

Table 44: Component based scoring for the Inverted Pendulum with Spring concept

	Inverted Pendulum (spring)									
Components	**Item**	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
Components	pendulum frame	3	2	2	2	3	2	4	4	4
	pendulum arm (~1.5m)			3			3	4	3	3
	torsional spring (high stiffness)			3			2	2	2	5
	crank			2			2	2	2	3
	clamp			1			1	2	1	2
	ball arm			1			2	2	2	4
	tether cable			2			1	1	1	1
	trip block			2			2	4	3	2
	shaft			2			1	3	3	3
	rot. Bearing			3			2	2	2	4
	gear mech. Engage			3			1	2	2	4

Components	Item	Safety	Repeatability	Durability	Precision	Ease of Use	Set up Time	Volume	Weight	Cost
Special Set Up Eq.	shear pin			1			1	1	2	2
	rake			2			1	2	2	2
	shovel (trip block/frame)			2			1	3	2	3

Table 45: Component based scoring for the Winch concept

	Winch									
Components	**Item**	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
	tether			2			1	1	1	1
	release pin mech			2			1	1	1	2
	winch motor			4			1	4	4	6
	netting			2			1	2	1	2
	net frame			2			2	4	3	2
	3D printed parts (~6)			3			2	4	2	2
	velocity gate	3	2	3	3	1	2	3	2	4
	power for vel. Gate			3			1	2	2	3
	frame for winch			2			2	3	4	4
	pulleys (x2)			2			2	2	2	2
	shaft (~2m; low fric)			3			3	6	5	5
	shaft collar			3			1	3	3	4

	3d printed part mount			1			1	1	1	2
	mechanical stop			2			2	2	2	2
	power supply for winch			4			2	4	4	4
	cable			2			1	2	1	2
Components	**Item**	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
Special Set Up Eq.	shovel (impact surf.)			2			1	3	2	3

Table 46: Component based scoring for the Electromagnet concept

	Electromagnet									
Components	**Item**	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
	capacitor bank			3			1	5	4	3
	railgun rails			2			2	2	3	2
	insulated wire			2			-	1	1	2
	locking hinge mechanism (x2)			3			2	2	2	2
	rail mount box	5	3	2	4	4	1	4	2	2
	metal frame for headform			2			2	3	3	2
	shaft (~1.5m; low fric)			3			3	5	5	4
	trip collar			2			2	3	3	2
	radar gun			2			1	4	4	5

	magnet			1			2	1	1	3
	railgun frame			2			2	4	4	2
	power source to charge railgun			4			2	3	5	4
	shaft collar			3			1	3	3	4
Components	**Item**	**Safety**	**Repeatability**	**Durability**	**Precision**	**Ease of Use**	**Set up Time**	**Volume**	**Weight**	**Cost**
Special Set Up Eq.	snow characterization tools			3			2	2	2	4
	shear pins			1			1	1	2	2
	shovel			2			1	3	2	3
	safety equipment to handle railgun			1			1	3	2	3

Appendix C: Detailed Design

Spring Parametric Analysis

Table 47: Parametric Analysis of Phase 1 - Moment at which the Spring is at Preload and Static. Bold values represent manipulated variables

Deflection (m)	Spring Rate (N/m)	Spring Preload (N)	Rail Length (m; to bottom of unloaded spring)	Distance btwn Bearing and Head COG (m)	Slope Angle (deg)	Rail Angle to Horizontal (deg)	Effective Height (m)	Friction Loss (5% Etot; kinetic)	PE Head (J)	KE Head (J)	PE Spring (J)	Head Velocity (m/s)
0.1	50000	5000	1.5	0.5	15	90	1.73	16.80	85.90	0	250	0
0.1	50000	5000	1.5	0.5	15	**45**	1.62	16.51	80.20	0	250	0
0.1	50000	5000	1.5	0.5	15	**60**	1.77	16.88	87.67	0	250	0
0.1	50000	5000	1.5	0.5	15	**15**	1.03	15.05	51.08	0	250	0
0.12	50000	6000	1.5	0.5	15	60	1.79	22.43	88.53	0	360	0
0.08	50000	4000	**2**	0.5	15	60	2.19	13.41	108.26	0	160	0
0.09	50000	4500	**2**	0.5	15	**15**	1.16	12.99	57.36	0	202.5	0
0.1	50000	5000	**0.5**	0.3	15	90	0.68	14.19	33.71	0	250	0

Table 48: Parametric Analysis of Phase 2 - Moment at which the spring reaches a displacement of zero. Bold values represent manipulated variables

Deflection (m)	Spring Rate (N/m)	Spring Preload (N)	Rail Length (m; to bottom of unloaded spring)	Distance btwn Bearing and Head COG (m)	Slope Angle (deg)	Rail Angle to Horizontal (deg)	Effective Height (m)	Remaining Height (m)	Vertical Distance Traveled (m)	PE Head (J)	KE Head (J)	PE Spring (J)	Ideal Head Velocity (m/s)
0.1	50000	5000	1.5	0.5	15	90	1.73	1.63	0.10	80.95	254.95	0.00	10.05
0.1	50000	5000	1.5	0.5	15	**45**	1.62	1.55	0.07	76.70	254.95	0.00	10.05
0.1	50000	5000	1.5	0.5	15	**60**	1.77	1.68	0.09	83.38	254.95	0.00	10.05
0.1	50000	5000	1.5	0.5	15	**15**	1.03	1.01	0.03	49.80	254.95	0.00	10.05

Deflection (m)	Spring Rate (N/m)	Spring Preload (N)	Rail Length (m; to bottom of unloaded spring)	Distance btwn Bearing and Head COG (m)	Slope Angle (deg)	Rail Angle to Horizontal (deg)	Effective Height (m)	Remaining Height (m)	Vertical Distance Traveled (m)	PE Head (J)	KE Head (J)	PE Spring (J)	Ideal Head Velocity (m/s)
0.12	50000	6000	1.5	0.5	15	60	1.79	1.68	0.10	83.38	365.94	0.00	12.04
0.08	50000	4000	**2**	0.5	15	60	2.19	2.12	0.07	104.83	163.96	0.00	8.06
0.09	50000	4500	**2**	0.5	15	15	1.16	1.13	0.02	56.21	206.96	0.00	9.05
0.1	50000	5000	**0.5**	0.3	15	90	0.68	0.58	0.10	28.75	254.95	0.00	10.05

Table 49: Spring Parametric Analysis Pase 3 - Moment at which the head first makes contact with the ground. Bold values represent manipulated variables

Deflection (m)	Spring Rate (N/m)	Spring Preload (N)	Rail Length (m; to bottom of unloaded spring)	Distance btwn Bearing and Head COG (m)	Slope Angle (deg)	Rail Angle to Horizontal (deg)	Effective Height (m)	Vertical Distance Traveled (m)	Friction Loss (5% Etot; kinetic)	PE Head (J)	KE Head (J)	PE Spring (J)	Ideal Head Velocity (m/s)	Head Velocity after Frictional Losses (m/s)
0.1	50000	5000	1.5	0.5	15	90	1.73	1.73	16.80	0.00	335.90	0.00	11.53	11.24
0.1	50000	5000	1.5	0.5	15	**45**	1.62	1.62	16.58	0.00	331.65	0.00	11.46	11.17
0.1	50000	5000	1.5	0.5	15	**60**	1.77	1.77	16.92	0.00	338.33	0.00	11.58	11.28
0.1	50000	5000	1.5	0.5	15	**15**	1.03	1.03	15.24	0.00	304.75	0.00	10.99	10.71
0.12	50000	6000	1.5	0.5	15	60	1.79	1.79	22.47	0.00	449.32	0.00	13.34	13.00
0.08	50000	4000	**2**	0.5	15	60	2.19	2.19	13.44	0.00	268.79	0.00	10.32	10.06
0.09	50000	4500	**2**	0.5	15	15	1.16	1.16	13.16	0.00	263.17	0.00	10.21	9.95
0.1	50000	5000	**0.5**	0.3	15	90	0.68	0.68	14.19	0.00	283.71	0.00	10.60	10.33

Assumptions made for this analysis include:

- Impact occurs a horizontal distance of 50 cm from base of rail

- The mass of the head and ball arm is 5.05 kg
- Ideal Spring (no losses and transfer all PE to KE of head)
- Frictional losses on the rail are accounted for by applying a 5% reduction in final velocity

Support Plate Analysis

Table 50: Simple beam bending analysis for design of support plates to fix the spring and winch

Variable	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Material	Aluminum 6061	Aluminum 6061	Aluminum 6061	Aluminum 6061
Young's Modulus	69000000000	69000000000	69000000000	69000000000
Mat. Prop. Source	Mechanics of Materials	Mechanics of Materials	Mechanics of Materials	Mechanics of Materials
Height (m)	0.01	0.02	0.01	0.01
Length (m)	0.4	0.4	0.4	0.4
Depth (m)	0.25	0.25	0.25	0.25
Cross Sectional Area (m^2)	0.0025	0.005	0.0025	0.0025
Force (N; point force)	6000	6000	6000	6000
Leftmost distance to Force (m)	0.2	0.2	0.24	0.28
Force to Rightmost Distance (m)	0.2	0.2	0.16	0.12
I (cross sectional; m^4)	2.08333E-08	1.66667E-07	2.08333E-08	2.08333E-08
Max Deflection (m)	0.005565217	0.000695652	0.005277147	0.00446276

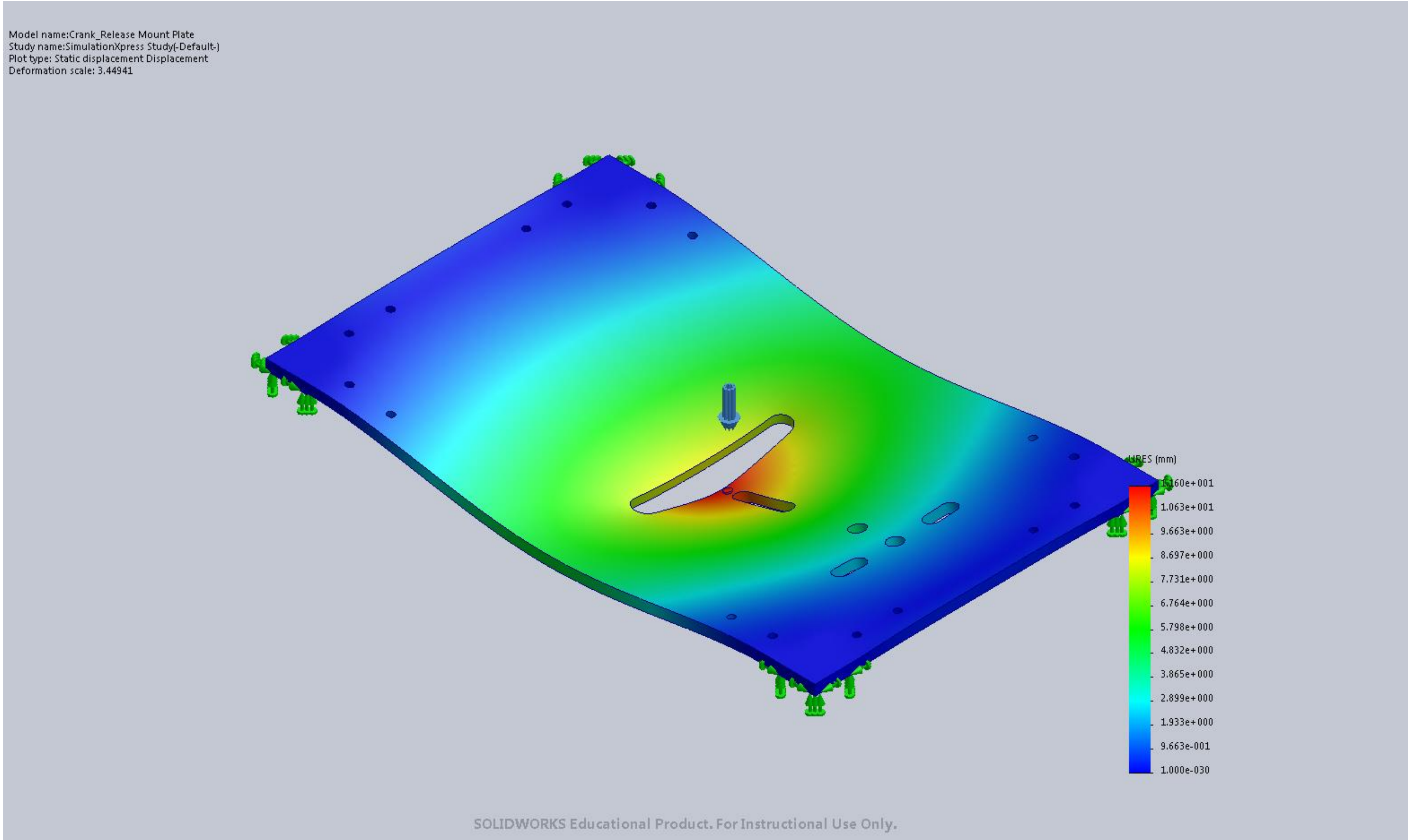


Figure 57: Solidworks simulation illustrating the displacement on the winch mount plate from a 5000 N force acting at the point of the wire rope leaving the winch. The plate is 0.25 inches thick and was found to deflect a maximum of 11.6mm

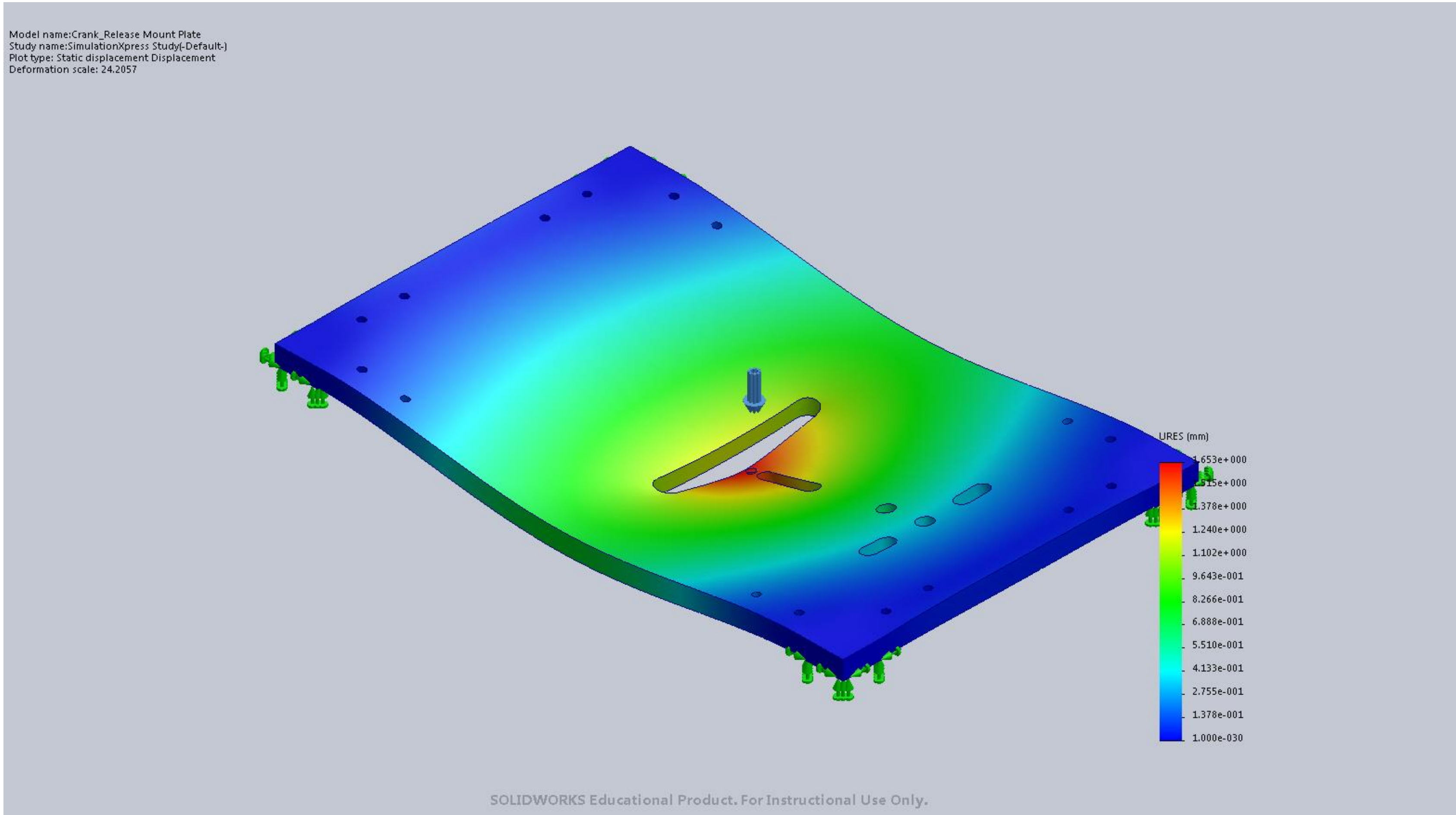


Figure 58: Solidworks simulation illustrating the displacement on the winch mount plate from a 5000 N force acting at the point of the wire rope leaving the winch. The plate is 0.5 inches thick and was found to deflect a maximum of 1.63mm

Buckling Calculations for Support Structures

Equation 13: Buckling calculation for cylindrical rods

$$F_{crit} = \frac{\pi EI}{(KL)^2} \quad where \quad I = \frac{\pi r^4}{4} \; for\ a\ rod\ and\ K = 0.5\ for\ fixed\ ends$$

Table 51: General buckling calculations for support structures. Cross-sectional areas are taken from 80/20 geometry specifications

Variable	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Force (spring; N)	6000	6000	6000	6000	6000	6000
Material Description	Aluminum 6061	Aluminum 6061	Steel; stainless	Steel; stainless	Titanium Alloy	Titanium Alloy
Material Serial No.						
Yield Strength (Pa)	255000000	255000000	260000000	260000000	825000000	825000000
Young's Modulus (Pa)	69000000000	69000000000	2E+11	2E+11	1.14E+11	1.14E+11
Radius of Support (cylinder; m)	0.01	0.01	0.01	0.01	0.01	0.01
Cross Sectional Area (m^2)	0.000314159	0.000314159	0.000314159	0.000314159	0.000314159	0.000314159
Applied Stress (Pa)	19098593.17	19098593.17	19098593.17	19098593.17	19098593.17	19098593.17
I (cross sectional; smallest; m^4)	**7.85398E-09**	**7.85398E-09**	**7.85398E-09**	**7.85398E-09**	**7.85398E-09**	**7.85398E-09**
Length Factor	0.5	0.5	0.5	0.5	0.5	0.5
Length of Support (m)	0.4	0.5	0.4	0.5	0.4	0.5
Critical Force (N)	133714.5682	85577.32364	387578.4585	248050.2134	220919.7213	141388.6217
Source for Mat. Properties	Mechanics of Materials	Mechanics of Materials	Mechanics of Materials	Mechanics of Materials	Mechanics of Materials	Mechanics of Materials

Table 52: Buckling calculations for using threaded rods and nuts. Note: the difference from the previous analysis is the use of the effective cross-sectional area

Using Threaded Rod and Nuts - Use Equivalent Tensile Stress Area (Shigleys, pg. 412)				
Variable	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Force (spring; N)	6000	6000	6000	6000
Material Description	Steel; stainless (3/8"	Steel; stainless	Steel; stainless	Steel; stainless

	dia)	(3/8" dia)	(3/8" dia)	(3/8" dia)
Variable	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Material Serial No.	Home depot	Home depot	Home depot	Home depot
Yield Strength (Pa)	260000000	260000000	260000000	260000000
Young's Modulus (Pa)	2E+11	2E+11	2E+11	2E+11
Nominal Diameter (m)	0.009525	0.009525	0.0127	0.0127
Pitch (m)	0.0015875	0.0015875	0.001953846	0.001953846
H Value	0.001374815	0.001374815	0.00169208	0.00169208
Pitch Diameter (m)	0.008493889	0.008493889	0.01143094	0.01143094
Minor Diameter (m)	0.008150185	0.008150185	0.01100792	0.01100792
Effective Diameter (m)	0.008322037	0.008322037	0.01121943	0.01121943
Eff. Radius of Support (cylinder; m)	0.004161018	0.004161018	0.005609715	0.005609715
Cross Sectional Area (m^2)	5.43938E-05	5.43938E-05	9.88625E-05	9.88625E-05
Effective Cross Sectional Area (m^2)	5.43938E-05	5.43938E-05	9.88625E-05	9.88625E-05
Applied Stress (Effective; Pa)	110306759.7	110306759.7	60690373.45	60690373.45
I (cross sectional; smallest; m^4)	**2.35444E-10**	**2.35444E-10**	**7.77773E-10**	**7.77773E-10**
Length Factor	0.5	0.5	0.5	0.5
Length of Support (m)	0.4	0.5	0.4	0.5
Critical Force (N)	11618.71588	7435.978163	38381.57275	24564.20656
Source for Mat. Properties	Shigleys and Mechanics of Materials	Shigleys and Mechanics of Materials	Shigleys and Mechanics of Materials	Shigleys and Mechanics of Materials

Table 53: Buckling calculations for support structures using 80/20. Cross-sectional areas are taken from 80/20 geometry specifications

Variable	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Force (spring; N)	6000	6000	6000	6000	6000	6000
Material Description	80-20	80-20	80-20	80-20	80-20	80-20
Material Serial No.	40-8080-Black-FB	40-4045-Lie-Black-FB	40-4045-Lie-Black-FB	30-3030	25-2525	25-2525
Yield Strength (Pa)	241000000	241000000	241000000	241000000	241100000	241100000
Young's Modulus (Pa)	70326500000	70326500000	70326500000	70326500000	70326500000	70326500000
Cross Sectional Area (m^2)	0.002357	0.0005541	0.0005541	0.0003144	0.0002746	0.0002746
Applied Stress (Pa)	2545608.825	10828370.33	10828370.33	19083969.47	21849963.58	21849963.58
I (cross sectional; smallest; m^4)	**1.70571E-06**	**4.462E-08**	4.462E-08	**2.732E-08**	**1.77E-08**	**1.77E-08**
Length Factor	0.5	0.5	0.5	0.5	0.5	0.5
Length of Support (m)	1	1	**1.5**	1	1	0.7
Critical Force (N)	4735697.314	123882.0281	55058.67916	75850.67252	49141.90716	100289.6065
Source for Mat. Properties	https://8020.net/shop/40-4045-lite-black-fb.html					

Table 54: Bill of materials for the construction of the snow sport head impact simulator. Assorted hardware is not included.

Item	Material	Quantity	Unit Cost	Unit	Total Cost	Currency	Source	Comments
30mm x 30mm T Slotted Profile - Four Open Slots	Aluminum	11	$ 0.24	Inch	$ 105.60	USD	80-20	40" sections
30 Series 4 Hole - Inside Corner Bracket with Single Support	Aluminum	36	$ 2.95	Each	$ 106.20	USD	80-20	
M6 Slide-in Economy T-Nut - Centered Thread	Steel	60	$ 0.27	Each	$ 16.20	USD	80-20	
2 Hole Pivot Joint - 30 Series	Zinc	2	$ 17.75	Each	$ 35.50	USD	80-20	
Wire Rope - for Lifting, 1/4"	Steel	1	$ 38.00	25'	$ 38.00	USD	McMaster	

Item	Material	Quantity	Unit Cost	Unit	Total Cost	Currency	Source	Comments
Diameter							Carr	
Heavy Duty Wire Rope Thimble - for Lifting, Galvanized Steel, for 1/4" Rope Diameter	Steel	9	$ 0.67	Each	$ 6.03	USD	McMaster Carr	
Wire Rope Compression Sleeve - for Lifting for Steel Rope, Zinc-Plated Copper, for 1/4" Rope Diameter	Copper	2	$ 8.12	Pckg (5)	$ 16.24	USD	McMaster Carr	
Hex Drive Rounded Head Screw, Black-Oxide Alloy Steel, M6 x 1 mm Thread, 14 mm Long	Steel	2	$ 9.97	Pckg (100)	$ 19.94	USD	McMaster Carr	
Triangle-Shaped Threaded Connecting Link, Type 316 Stainless Steel, 3/8" Thickness, Not for Lifting	Steel	1	$ 24.34	Each	$ 24.34	USD	McMaster Carr	
Steel Eyebolt with Shoulder - for Lifting, 3/8"-16 Thread Size, 5/8" Thread Length	Steel	4	$ 3.15	Each	$ 12.60	USD	McMaster Carr	
1" dia. Annodized Aluminum 6061 Shaft	Aluminum	1	$ 113.58	Each	$ 113.58	USD	McMaster Carr	
Flange-mounted Shaft Support	Steel	2	$ 50.74	Each	$ 101.48	USD	McMaster Carr	
1" Square 6061 Aluminum Bar	Aluminum	1	$ 0.91	Inch	$ 25.48	CAD	Metal Supermarket	28" section
1/4" 6061 Aluminum Plate	Aluminum	1	$ 183.69	Each	$ 183.69	CAD	Metal Supermarket	45"x27"
0.188" 6061 Aluminum Plate	Aluminum	1	$ 117.46	Each	$ 117.46	CAD	Metal Supermarket	51"x17"
1/4" A36 Hot Rolled Steel Plate	Steel	2	$ 15.87	Each	$ 31.74	CAD	Metal Supermarket	12"x4"

Mounted Linear Ball Bearing, Self Aligns, 1" Shaft Diameter, 2-13/16" x 3-1/4" x 2-3/16"	Various	2	$ 92.88	Each	$ 185.76	USD	McMaster Carr	
Tylaska T5 Trigger Snap shackle	Stainless Steel	1	$ 280.00	Each	$ 155.40	CAD	Pro-Tech Yacht	
WG2000 Worm gear winch	Various	1	$ 84.99	Each	$ 84.99	USD	Dutton Lainson Company	
3/4" Impact-Resistant UHMW Polyethylene Sheet	UHMWPE	1	$ 19.14	Each	$ 19.14	USD	McMaster Carr	6"x12"
18-8 Steel Threaded Rod	Steel	1	$ 1.22	Each	$ 1.22	USD	McMaster Carr	3' section
Steel Compression Spring	Stainless Steel	1	$ 7.83	Pckg (6)	$ 7.83	USD	McMaster Carr	
18-8 Stainless Steel Flange Nut	Stainless Steel	6	$ 3.80	Each	$ 22.80	USD	McMaster Carr	
25 Series 8 Hole - Inside Corner Bracket	Aluminum	1	$ 5.35	Each	$ 5.35	USD	McMaster Carr	
25 Series 8 Hole - Gusseted Inside Corner Bracket	Aluminum	1	$ 7.45	Each	$ 7.45	USD	McMaster Carr	
Coil Spring Retainers	Steel	3	$ 15.79	Each	$ 47.37	CAD	North Shore Off-Road Center	
1/2" 6061 Aluminum plate	Aluminum	1	$ 81.94	Each	$ 81.94	CAD	Metal Supermarket	11"x20"
2" Steel Round	A36 Steel	1	$ 16.27	Each	$ 16.27	CAD	Metal Supermarket	4"
0.120" A1011 Hot Rolled Steel Sheet	A1011 Steel	1	$ 13.81	Each	$ 13.81	CAD	Metal Supermarket	8" x 8"
Static Cordlette	Nylon	1	$ 8.40	Each	$ 8.40	CAD	MEC	4'

Table 55: Parametric analysis using the principles of projectile motion to understand head impact angle and velocity from a representative ski or snowboard fall forward

Height (m)	Travelling Velocity (m/s)	Slope Angle (deg)	Slope Angle (rad)	Vx1 (m/s)	Vy1 (m/s)	ax1 (m/s)	ay1 (m/s)	Time to Impact (s)	Vx2 (m/s)	Vy2 (m/s)	V Impact (m/s)	Impact Angle (rad)	Impact Angle (deg)
1.4	9	0	0.00	9.00	0.00	0.00	9.81	0.53	9.00	5.24	10.41	0.53	30.21
1.45	9	0	0.00	9.00	0.00	0.00	9.81	0.54	9.00	5.33	10.46	0.53	30.65
1.5	9	0	0.00	9.00	0.00	0.00	9.81	0.55	9.00	5.42	10.51	0.54	31.08
1.55	9	0	0.00	9.00	0.00	0.00	9.81	0.56	9.00	5.51	10.56	0.55	31.50
1.6	9	0	0.00	9.00	0.00	0.00	9.81	0.57	9.00	5.60	10.60	0.56	31.90
1.65	9	0	0.00	9.00	0.00	0.00	9.81	0.58	9.00	5.69	10.65	0.56	32.30
1.7	9	0	0.00	9.00	0.00	0.00	9.81	0.59	9.00	5.78	10.69	0.57	32.69
1.75	9	0	0.00	9.00	0.00	0.00	9.81	0.60	9.00	5.86	10.74	0.58	33.07
1.8	9	0	0.00	9.00	0.00	0.00	9.81	0.61	9.00	5.94	10.78	0.58	33.44
1.6	9.5	0	0.00	9.50	0.00	0.00	9.81	0.57	9.50	5.60	11.03	0.53	30.53
1.6	10	0	0.00	10.00	0.00	0.00	9.81	0.57	10.00	5.60	11.46	0.51	29.26
1.6	10.5	0	0.00	10.50	0.00	0.00	9.81	0.57	10.50	5.60	11.90	0.49	28.08
1.6	11	0	0.00	11.00	0.00	0.00	9.81	0.57	11.00	5.60	12.34	0.47	26.99
1.6	11.5	0	0.00	11.50	0.00	0.00	9.81	0.57	11.50	5.60	12.79	0.45	25.98
1.6	12	0	0.00	12.00	0.00	0.00	9.81	0.57	12.00	5.60	13.24	0.44	25.03
1.6	12.5	0	0.00	12.50	0.00	0.00	9.81	0.57	12.50	5.60	13.70	0.42	24.14
1.6	9	5	0.09	8.97	0.78	0.00	9.81	0.66	8.97	6.39	11.01	0.53	30.47
1.6	9	10	0.17	8.86	1.56	0.00	9.81	0.75	8.86	7.17	11.40	0.51	28.95
1.6	9	15	0.26	8.69	2.33	0.00	9.81	0.84	8.69	7.93	11.77	0.48	27.38
1.6	9	20	0.35	8.46	3.08	0.00	9.81	0.93	8.46	8.68	12.12	0.45	25.75
1.6	9	25	0.44	8.16	3.80	0.00	9.81	1.01	8.16	9.41	12.45	0.42	24.07
1.6	9	30	0.52	7.79	4.50	0.00	9.81	1.10	7.79	10.10	12.76	0.39	22.35

Table 56: Test matrix and results from the acceleration calibration impact testing comparing known accelerations to data from a sensor with an unknown sensitivity. All data was post processed with a 1000Hz filter

Test No.	Drop Height (m)	Control Accel.	Peak Accel (m/s^2)	Unknown Accel.	Raw Unknown Signal (mV)	Calculated Sensitivity (mV/g)	Average Unknown Sensitivity (mV/g)	Standard Deviation (mV/g)
1	1.02	P80371	-546.5	P80374	55.20944	0.101024		
2	1.02	P80371	-530.3	P80374	53.68442	0.101234		
3	1.02	P80371	-535.3	P80374	54.0705	0.10101		
4	1.02	P80371	-510.8	P80374	51.8988	0.101603		
5	1.02	P80371	-531.4	P80374	54.43728	0.102441	0.1014	0.0005
6	0.57	P80371	-384.3	P80374	39.37051	0.102447		
7	0.57	P80371	-457.2	P80374	46.05934	0.100742		
8	0.57	P80371	-314.6	P80374	31.58134	0.100386		
9	0.57	P80371	-324.3	P80374	32.74924	0.100984		
10	0.57	P80371	-325.9	P80374	32.48863	0.099689	0.1008	0.0010
11	1.02	P80371	-548.8	P80373	47.9066	0.087293		
12	1.02	P80371	-573.9	P80373	49.85888	0.086877		
13	1.02	P80371	-562.9	P80373	49.6485	0.088201		
14	1.02	P80371	-585.7	P80373	49.5896	0.084667		
15	1.02	P80371	-507	P80373	49.16885	0.09698	0.0888	0.0047
16	0.50	P80371	-312.6	P80373	27.60962	0.088323		
17	0.50	P80371	-317.1	P80373	27.81158	0.087706		
18	0.50	P80372	-310.7	P80373	27.0374	0.087021		
19	0.50	P80373	-320.9	P80373	28.01354	0.087297		
20	0.50	P80371	-309	P80373	27.7106	0.089678	0.0880	0.0010
21	0.57	P80371	-315.6	P80375	27.29996	0.086502		
22	0.57	P80371	-334.1	P80375	29.11714	0.087151		
23	0.57	P80371	-313.2	P80375	27.4521	0.08765		
24	0.57	P80371	-327.4	P80375	28.66073	0.08754		
25	0.57	P80371	-324.5	P80375	28.47479	0.08775	0.0873	0.0005

Test No.	Drop Height (m)	Control Accel.	Peak Accel (m/s^2)	Unknown Accel.	Raw Unknown Signal (mV)	Calculated Sensitivity (mV/g)	Average Unknown Sensitivity (mV/g)	Standard Deviation (mV/g)
26	1.00	P80371	-563.2	P80375	49.41884	0.087747		
27	1.00	P80371	-535.7	P80375	46.05495	0.085972		
28	1.00	P80371	-529.9	P80375	46.67194	0.088077		
29	1.00	P80371	-506.5	P80375	43.69684	0.086272		
30	1.00	P80371	-461.7	P80375	41.26266	0.089371	0.0874	0.0013

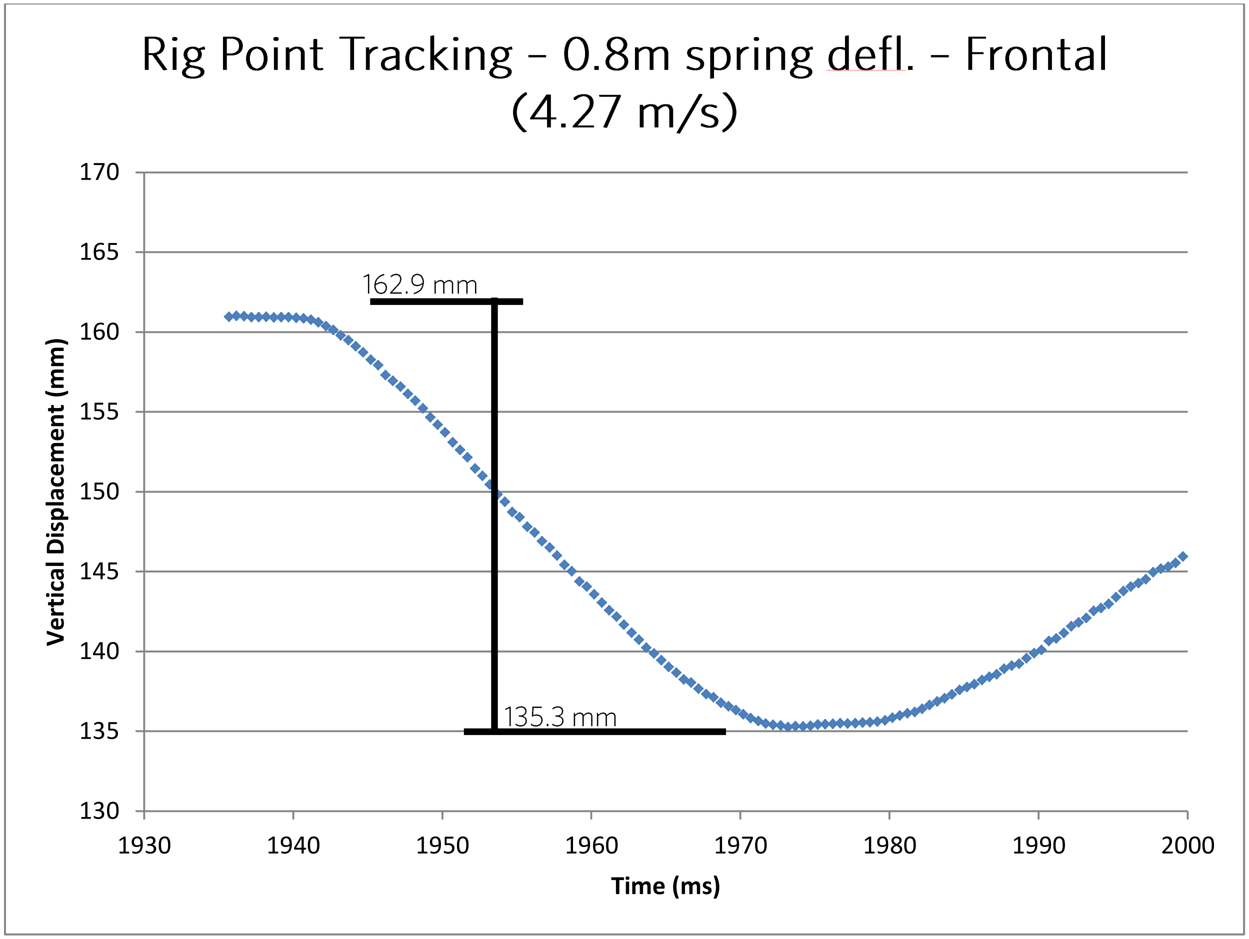


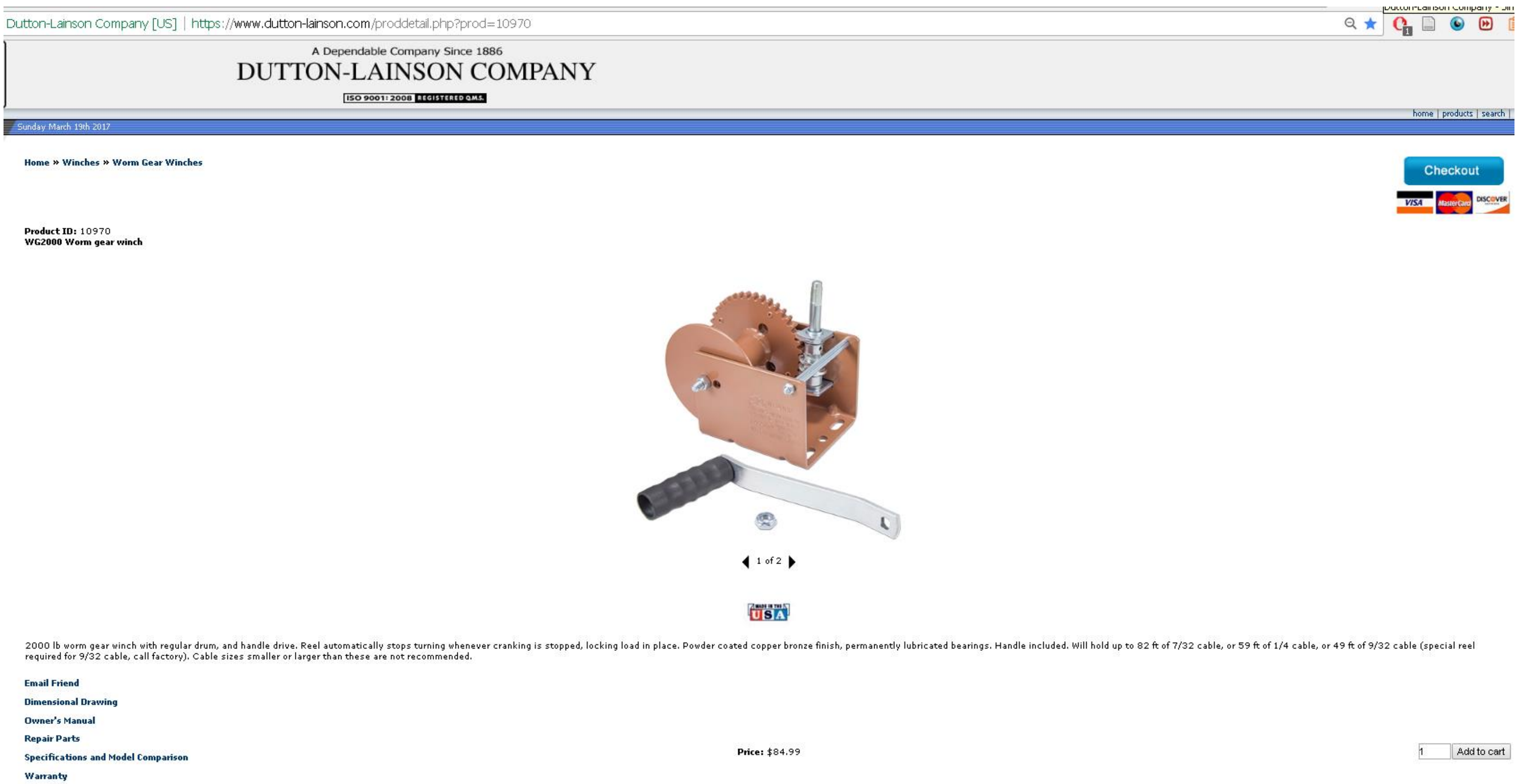
Figure 59: A plot of vertical displacement versus time to investigate the potential energy of the apparatus when lifted off the ground. The data was collected using high speed video and TEMA motion analysis software. The maximum vertical displacement was found to be 27.6 mm

$$PE_{rig} = (m_{rig} + m_{sand}) * g * h_{rig}$$

$$PE_{rig} = (50kg + 60kg) * 9.81\frac{m}{s^2} * 0.0276m$$

$$PE_{rig} = 29.8\,J$$

Appendix D: Product Specification


Dutton-Lainson Company [US] | https://www.dutton-lainson.com/proddetail.php?prod=10970

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Sunday March 19th 2017

Home » Winches » Worm Gear Winches

Checkout

Product ID: 10970

WG2000 Worm gear winch

1 of 2

2000 lb worm gear winch with regular drum, and handle drive. Reel automatically stops turning whenever cranking is stopped, locking load in place. Powder coated copper bronze finish, permanently lubricated bearings. Handle included. Will hold up to 82 ft of 7/32 cable, or 59 ft of 1/4 cable, or 49 ft of 9/32 cable (special reel required for 9/32 cable, call factory). Cable sizes smaller or larger than these are not recommended.

Email Friend

Dimensional Drawing

Owner's Manual

Repair Parts

Specifications and Model Comparison

Warranty

Price: $84.99

Add to cart

Figure 60: Specifications for the Dutton Lainson WG2000 Worm Gear Winch

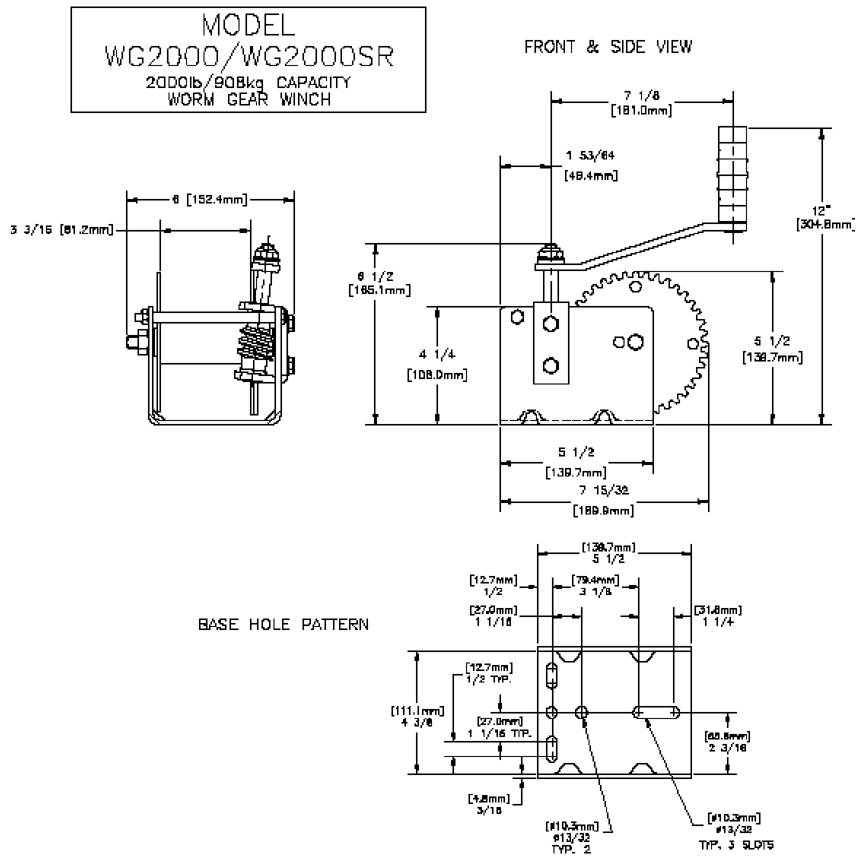


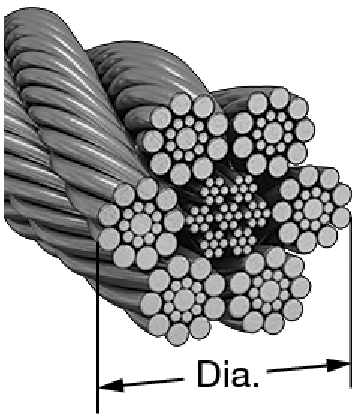
Figure 61: Dimensions for the Dutton Lainson WG2000 Worm Gear Winch

McMASTER-CARR

Find

Wire Rope - for Lifting

1/4" Diameter



Length, ft.
- 10
- 25
- 50
- 100
- Other

Each

ADD TO ORDER

$1.52 per ft.
3440T56

Application	For Lifting
Diameter	1/4"
Capacity	1,300 lbs.
Fits Pulley/Drum Diameter	9"
Material	Steel
Finish	Unfinished
Construction	6 x 19
Core Type	IWRC
Lubrication	Lubricated
Preformed	Yes
Specifications Met	ASTM A1023
Attachment Type	Plain
RoHS	Compliant

This 6x19 IWRC wire rope has a good balance of abrasion resistance and flexibility. It is preformed to prevent it from unraveling when cut, and it's lubricated to reduce wear.

Note: The safety factor for capacity is 5:1. Warning: Never use to lift people or items over people.

Figure 62: Specifications for 1.4" Wire Rope from McMaster Carr

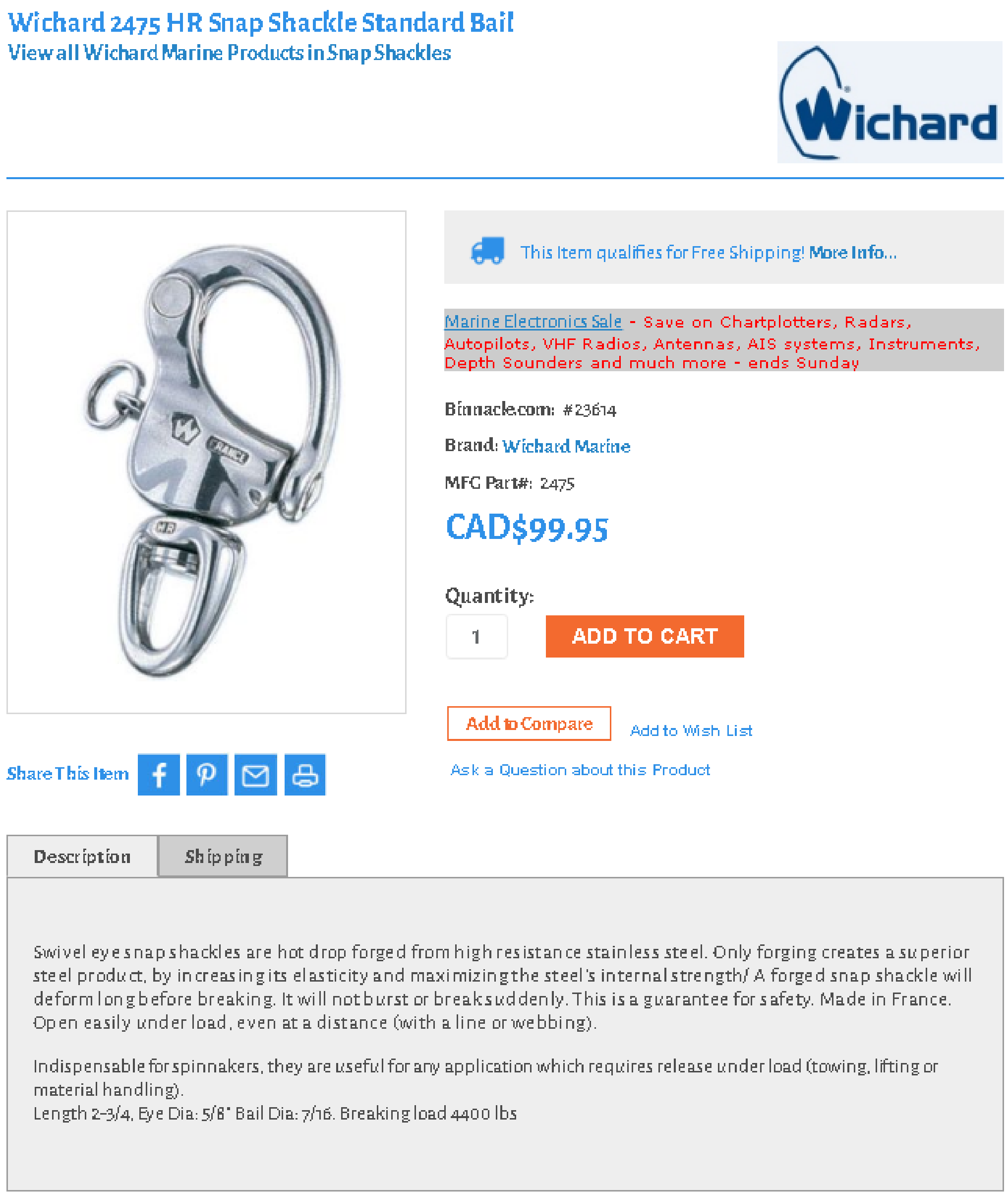


Figure 63: Wichard Snap Shackle product specifications

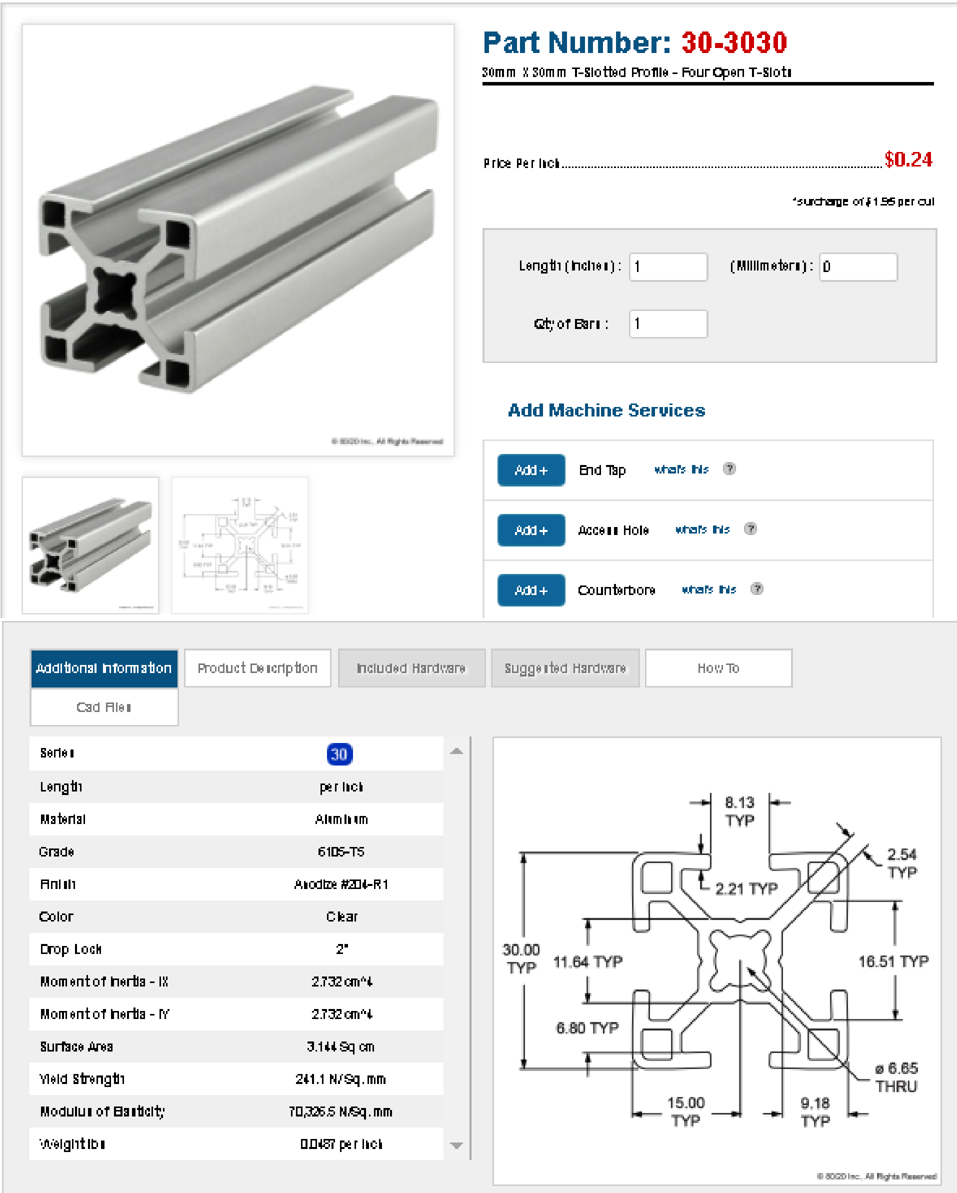


Figure 64: 80/20 extruded aluminum spec sheet - 30 mm by 30 mm t-slotted profile

Part Number: 14070

30 Series 4 Hole - Inside Corner Bracket with Single Support

Price $2.95

Qty: 1 | + Add to Cart

Add to Wish list

Additional Information | Product Description | Included Hardware | Suggested Hardware | How To | Cad Files

Material	Aluminum
Finish	Natural
A	57.00mm
B	57.00mm
C	1.98mm
D	15.62mm
E	14.00mm
F	6.00mm
G	10.80mm
H	6.20mm
J	29.90mm
K	28.00mm
L	8.00mm
Weight lbs	0.1272

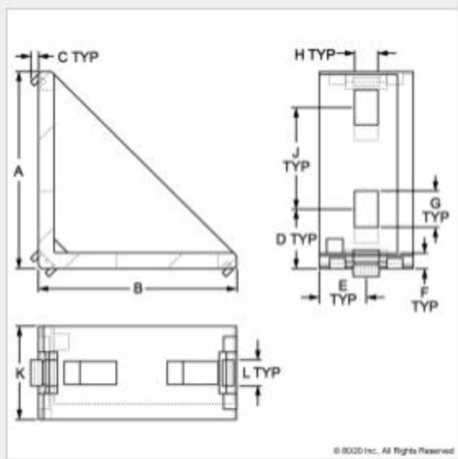


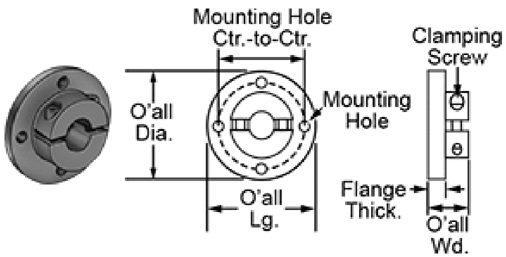
Figure 65: Specifications for 80/20 inside corner brackets

McMASTER-CARR®

Find

Easy-Access Flange-Mounted Shaft Support

for 1" Shaft Diameter, 1117 Carbon Steel



Each

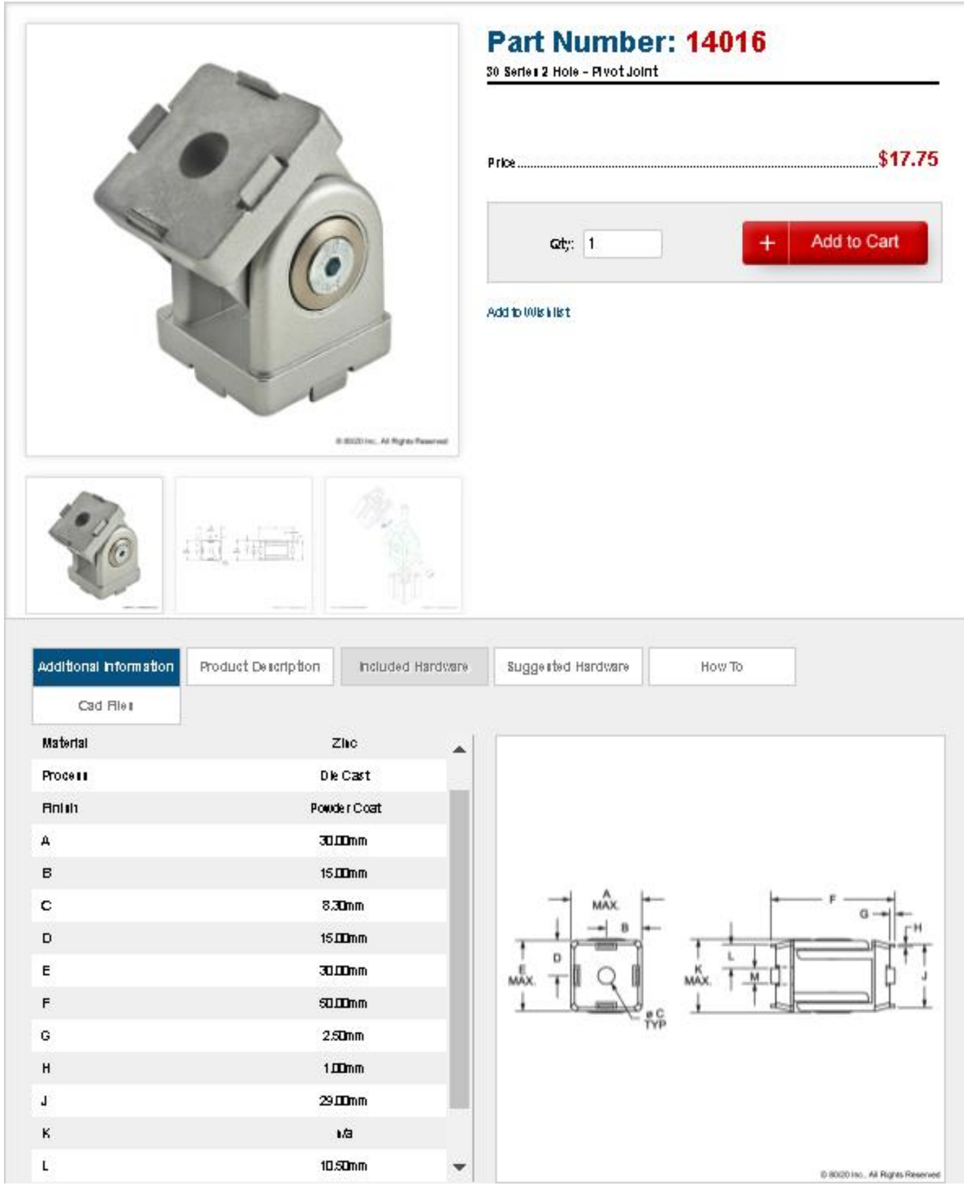
In stock
$50.74 Each
1870K6

ADD TO ORDER

Material	1117 Carbon Steel
For Shaft Diameter	1"
Overall	
Width	1 5/8"
Diameter	3 1/4"
Flange Thickness	3/8"
Bolt Circle Diameter	2 3/4"
Mounting Holes	
Number of	4
Diameter	1/4"
Clamping Screw Thread Size	1/4"-28
Shaft Support Type	Flange Mount
Construction	Two Piece
RoHS	Compliant

The two-piece design lets you remove the top of the support for access to your shaft. Supports allow you to brace the ends of your linear shafts when working with light to medium loads where shaft alignment is not critical.

Figure 66: Specifications for flange mounted shaft collars (taken from McMaster-Carr)



Material	Zinc
Process	Die Cast
Finish	Powder Coat
A	30.00mm
B	15.00mm
C	8.30mm
D	15.00mm
E	30.00mm
F	50.00mm
G	2.50mm
H	1.00mm
J	29.00mm
K	n/a
L	10.50mm

Figure 67: Pivot joint specifications (taken from 80/20) used to facilitate angled impacts

Compression Spring

Zinc-Plated, Music-Wire, Closed & Flat End, 3.5" Long, 0.48" OD

Packs of 6

ADD TO ORDER

In stock
$8.00 per pack of 6
9657K448

Spring Type	Compression
Material	Zinc-Plated Music-Wire Steel
End Type	Closed and Flat
Overall Length	3.5"
OD	0.48"
ID	0.336"
Wire Diameter	0.072"
Wire Shape	Round
Compressed Length	1.81"
Maximum Load	48.30 lbs.
Rate	28.50 lbs./in.
RoHS	Compliant

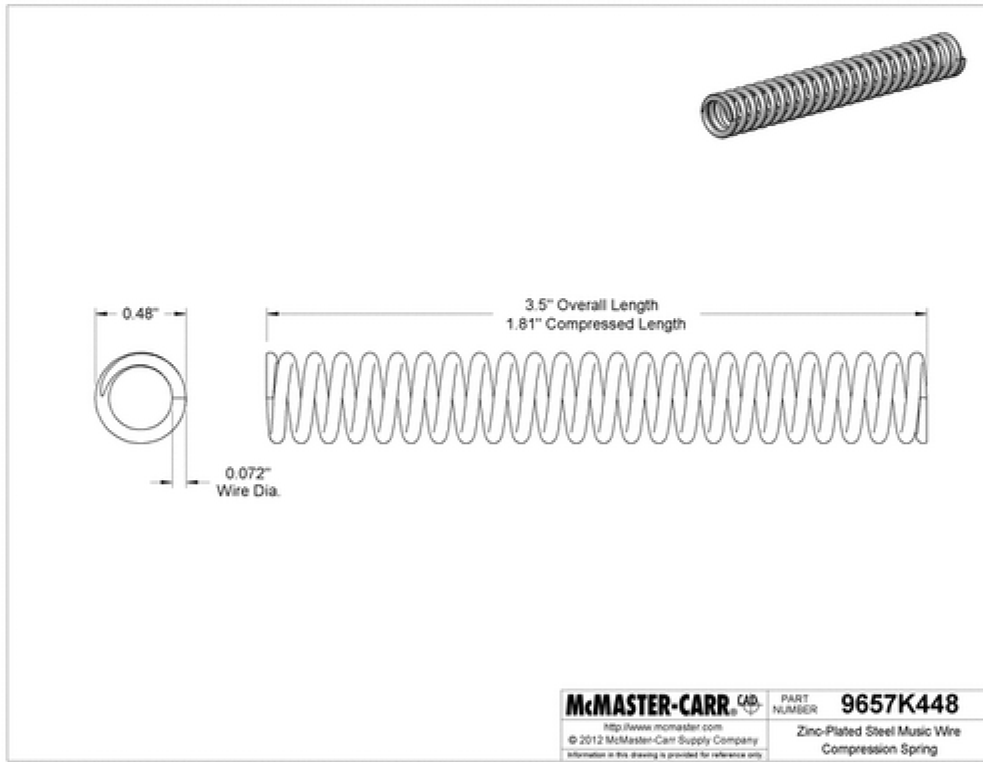
Music-wire steel springs are strong.

Zinc-plated springs provide moderate corrosion resistance.

Rate—As you push a compression spring, it gets harder to push. The higher the rate, the harder it is to compress the spring.

On springs with closed and flat ends, the last coil is ground flush so the springs stand straighter and are easier to stack.

Don't see the size you need? Additional sizes are available.

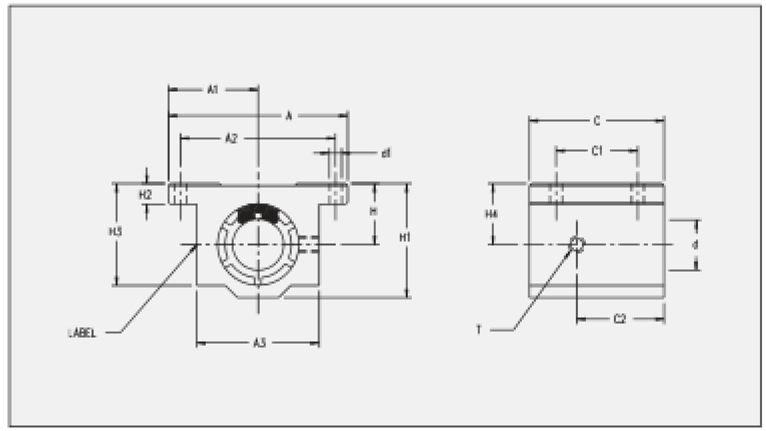


The information in this 3-D model is provided for reference only. Details

Figure 68: Zinc-coated, steel compression springs selected for use in the head release mechanism

Self-Aligning Linear Ball Bearing With Housing

Series KGNZ, KGNZ..PP



Shaft Dia.	Part Number	Seal suffix	Wt. lbs.	Dimensions in inches															Load Ratings (Lbs)	
				d	A	C	A1 ±.001	H ±.001	A3	H1	H2	H3	C2	H4	T	A2 ±.01	C1 ±.01	d1	Dynamic C	Static C_o
1/4	KGNZ 04	PP	0.10	0.250	1.63	1.188	0.813	0.437	1.000	0.813	0.188	0.750	0.590	0.437	NIP A1	1.312	0.750	.156	39	27
3/8	KGNZ 06	PP	0.14	0.375	1.75	1.313	0.875	0.500	1.125	0.938	0.188	0.875	0.660	0.500	NIP A1	1.437	0.875	.156	59	43
1/2	KGNZ 08	PP	0.29	0.500	2.00	1.688	1.000	0.687	1.375	1.250	0.250	1.125	0.844	0.690	NIP A1	1.688	1.000	.156	152	112
5/8	KGNZ 10	PP	0.53	0.625	2.50	1.938	1.250	0.875	1.750	1.625	0.281	1.437	1.260	0.700	1/4-28	2.125	1.125	.188	273	187
3/4	KGNZ 12	PP	0.64	0.750	2.75	2.063	1.375	0.937	1.875	1.750	0.313	1.563	1.340	0.937	1/4-28	2.375	1.250	.188	383	274
1	KGNZ 16	PP	1.36	1.000	3.25	2.813	1.625	1.187	2.375	2.188	0.375	1.938	1.950	1.187	1/4-28	2.875	1.750	.218	684	492
1 1/4	KGNZ 20	PP	2.86	1.250	4.00	3.625	2.000	1.500	3.000	2.813	0.437	2.500	2.430	1.500	1/4-28	3.500	2.000	.218	1,017	712
1 1/2	KGNZ 24	PP	4.19	1.500	4.75	4.000	2.375	1.750	3.500	3.250	0.500	2.875	2.750	1.750	1/4-28	4.125	2.500	.281	1,298	852
2	KGNZ 32	PP	7.92	2.000	6.00	5.000	3.000	2.125	4.500	4.063	0.625	3.625	3.420	2.125	1/4-28	5.250	3.250	.406	2,104	1,458

Figure 69: Linear bearing's selected (KGNZ-16PP). Taken from
http://www.schaeffler.com/remotemedien/media/_shared_media/08_media_library/01_publications/schaeffler_2/catalogue_1/downloads_6/kxkbz_us_us.pdf

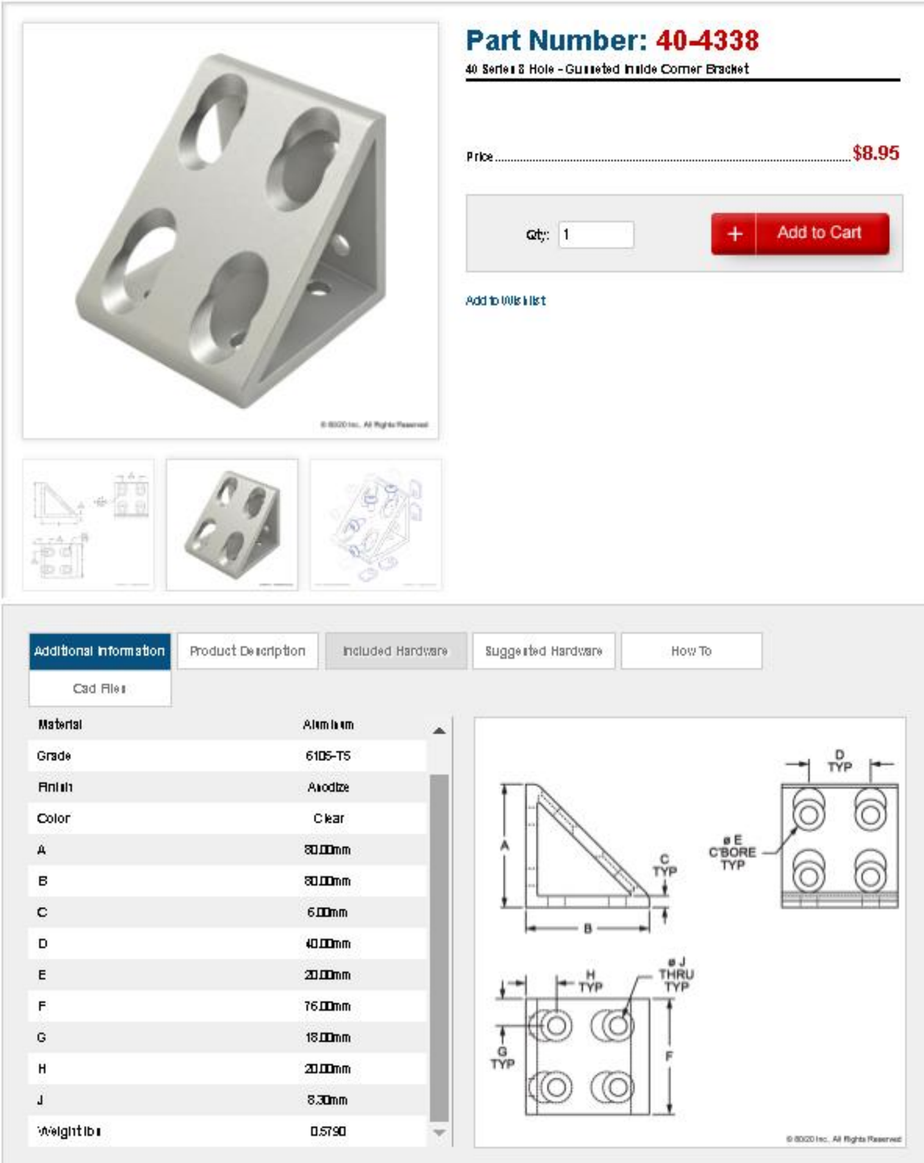


Figure 70: Specifications for the 80/20 gusseted inside corner bracket

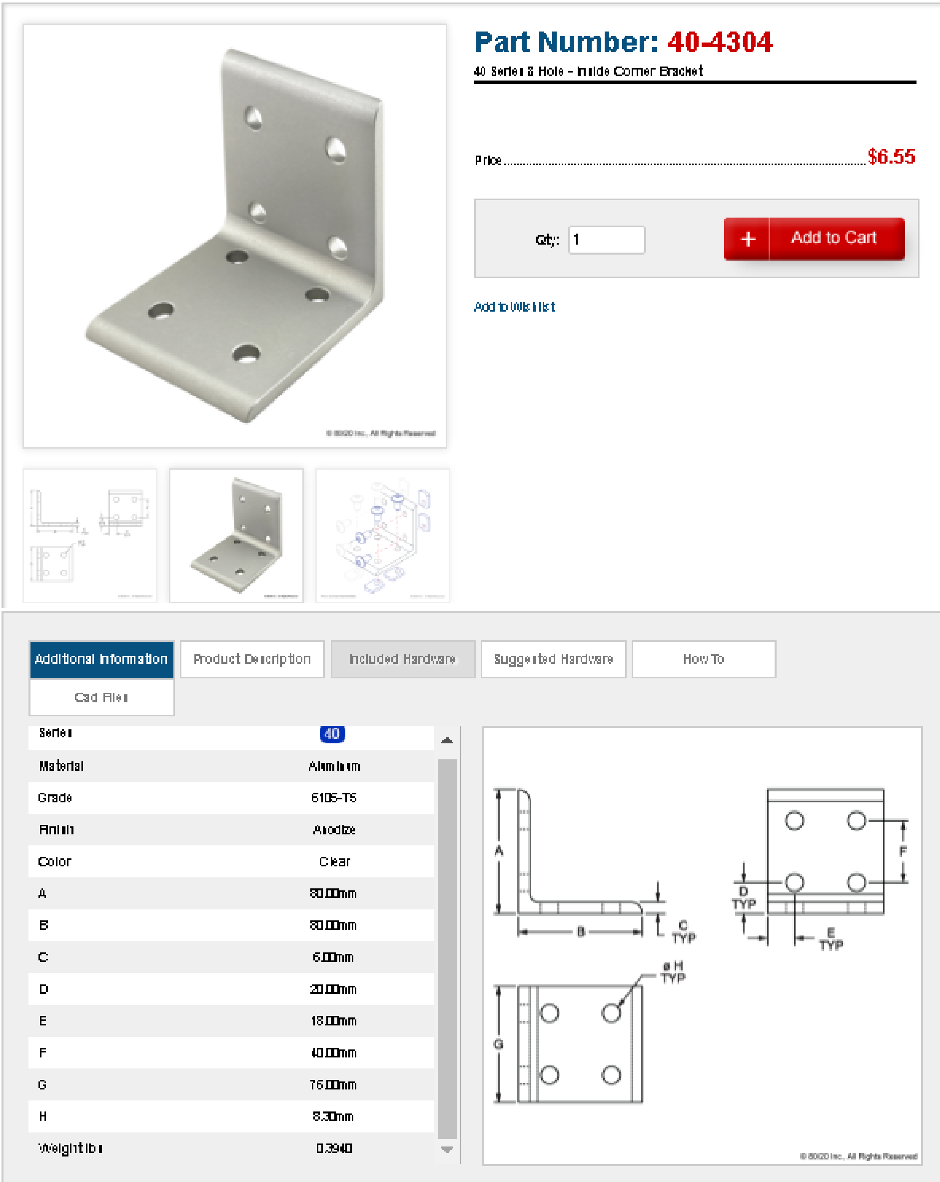


Figure 71: Specifications for the 80/20 inside corner bracket

Find

Lightweight Linear Motion Shaft

Anodized 6061 Aluminum, 1" Diameter, 48" Long

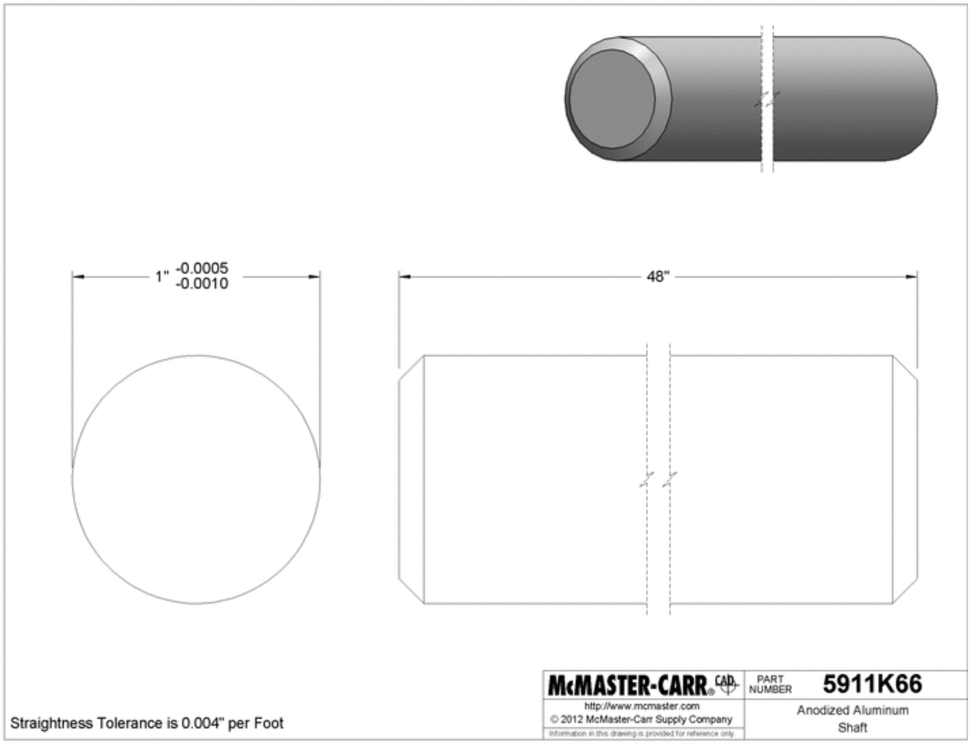
Each

ADD TO ORDER

In stock
$113.58 Each
5911K66

Material	Anodized 6061 Aluminum
Temper	T6
Diameter	1"
Length	48"
Diameter Tolerance	-0.001" to -0.0005"
Straightness Tolerance	0.004" per ft.
Length Tolerance	-0.0625" to 0.0625"
Finish Thickness	0.002"
Surface Smoothness (RMS)	16 microns
End Shape	Chamfered
Hardness Rating	Ultra Hard
Hardness	Rockwell C70
Yield Strength	46,000 psi
For Motion Type	Linear
For Linear Bearing Type	Ball, Plain
Shaft Type	Round
End Type	Straight

Aluminum shafts are lighter and more corrosion resistant than steel shafts. They're also nonmagnetic and resist chipping. Mount these shafts to a shaft support for use with linear bearings, slides, and other precision applications. All are precision ground for tight diameter and straightness tolerances.



The information in this 3-D model is provided for reference only. Details

Figure 72: Sepcification of the central shaft. Taken from McMaster Carr

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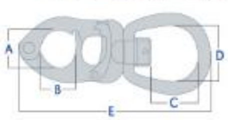
T5

Tylaska T5 Snap Shackles are perfect for small boat applications requiring high strength and low weight. They have a breaking strength of 5,000 lbs and weigh just 2.2 ounces in the standard bail configuration. Ideal for J-24s, Mumm 30s and similar boats.

SHACKLE TYPE	A in (mm)	B in (mm)	C in (mm)	D in (mm)	E in (mm)	THICKNESS in (mm)	WEIGHT oz (gm)	WORK LOAD lb (kg)	BREAKING STRENGTH lb (kg)	RECOMMENDED APPLICATIONS
T5 SB	9/16 (14.2)	9/16 (14.2)	17/32 (13.5)	9/16 (14.2)	2 15/16 (74.6)	.31 (7.9)	2.2 (59)	2,500 (1,136)	5,000 (2,273)	20-30' Boats
T5 LB	9/16 (14.2)	9/16 (14.2)	13/16 (20.6)	7/8 (22.2)	3 5/16 (84.1)	.31 (7.9)	2.8 (74)	2,500 (1,136)	5,000 (2,273)	20-30' Boats
T5 CB	9/16 (14.2)	9/16 (14.2)	19/32 (15.1)	1/2 (12.7)	3 1/4 (82.6)	.31 (7.9)	2.8 (79)	2,500 (1,136)	5,000 (2,273)	20-30' Boats



SB - Standard Bails provide ample room for attaching a line while keeping weight and overall shackle length to a minimum. Ideal for halyards and sheets.

LB - Large Bails provide room for up to three additional shackles or a combination of shackles and lines. Ideal for spinnaker sheets, guys or other multi-line applications.

CB - Clevis Bails do not require splicing and provide moveable attachments to rings, deck fittings, furlers, rolling furlers, etc. Ideal for many uses.

Every unit is pull tested and released under several different load conditions before shipping.

Figure 73: Specifications for a Tylaska T5 Snap Shackle. Taken from http://www.tylaska.com/index.php/snap-shackles/t5/