A new helmet testing method to assess potential damages in the Brain and the head due to rotational energy

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En ny hjälm testmetod för att bedöma eventuella skador i hjärnan och huvudet på grund av rotationsenergi

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Abstract

Preservation and protection of the head segment is of upmost importance due to the criticality of the functions entailed in this section of the body by the brain and the nervous system. Numerous events in daily life situations such as transportation and sports pose threats of injuries that may end or change a person’s life.

In the European Union, statistics report that almost 4.2 million of road users are injured non-fatally, out of which 18% is represented by motorcyclist and 40% by cyclists, being head injuries 34% for bicyclists, and 24% for two-wheeled motor vehicles. Not only vehicles, are a source of injuries for the human head according to the injury report, 6,1 million people are admitted in hospitals for sports related injuries, where sports such as hockey, swimming, cycling presented head injuries up to 28%, 25% and 16% respectively (European Association for Injury Prevention and Safety Promotion, 2013).

According to records the vast majority of head crashes result in an oblique impact (Thibault & Gennarelli, 1985). These types of impacts are characterized for involving a rotation of the head segment which is correlated with serious head injuries. Even though there is plenty of evidence suggesting the involvement of rotational forces current helmet development standards and regulations fail to recognize their importance and account only for translational impact tests.

This thesis contains an evaluation for a different developed method for testing oblique impacts. In consequence a new test rig was constructed with basis on a guided free fall of a helmeted dummy head striking an oblique (angled) anvil which will induce rotation.

The results obtained are intended to be subjected to a comparison with another oblique test rig that performs experiments utilizing a movable sliding plate which when impacted induces the rotation of a dropped helmeted dummy head. The outcome will solidify the presence of rotational forces at head-anvil impact and offer an alternative testing method.

After setting up the new test rig; experiments were conducted utilizing bicycle helmets varying the velocities before impact from $5\frac{m}{s}$ to $6\ \frac{m}{s}$ crashing an angled anvil of 45°. Results showed higher peak resultant values for rotational accelerations and rotational velocities in the new test rig compared to the movable plate impact test, indicating that depending on the impact situation the “Normal Force” has a direct effect on the rotational components. On the other hand a performed finite element analysis predicted that the best correlation between both methods is when the new angled anvil impact test is submitted to crashes with a velocity before impact of $6\,\frac{m}{s}$ at 45° and the movable sliding impact test to a resultant velocity vector of $7{,}6\,\frac{m}{s}$ with an angle of 30° .

In conclusion the new test method is meant to provide a comparison between two different test rigs that will undoubtedly have a part in the analysis for helmet and head safety improvements.

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Abbreviations

MPIT	Movable Plate Impact Test
AAIT	Angled Anvil Impact Test
MTBI	Mild Traumatic Brain Injury
DAI	Diffuse Axonal Injury
ASDH	Acute Subdural Hematoma
FEA	Finite Element Analysis

1 Project definition

1.1 Introduction

The criticality of head injuries has originated the manufacturing of helmet testing devices. However these testing methods are currently considered insufficient due to the fact that they disregard the presence of rotational forces at the moment of impact and therefore do not measure their contribution affecting effective helmet manufacturing.

The increasing need for helmet protection against rotationally induced head injuries have given rise to the proposal of new helmet testing methods that account for these existing forces.

Nowadays oblique test rigs are being manufactured for example behind a method of a sliding plate colliding with a dropped helmeted dummy head inducing the rotation of the segment so that the rotational effect can be accounted for.

However this methodology entails complicated calculations and the control of several variables during experimental testing, which in turn hardens the analysis of testing results. It is for this reason that the focus of this project was to construct another helmet testing rig under a different testing method, simulating a different impact situation allowing the comparison between these two possible oblique test procedures.

Through the development of the project and this report a sense of criticality will be given to this rotational aspect and is the aim of this endeavor that the results of the comparison serve the purpose of demonstrating another way to evaluate the rotational forces at head impacts. Thus provide findings in a method that is easier to duplicate around the world by other researchers. This could be achieved by simply customizing a shock absorption test rig proposed in standards such as ECE 22.05 (motorcycle helmets), EN 1078 (bicycle helmet, roller skate helmets and skateboard helmets), EN 1080 (small child helmets), EN 1077 (ski helmets) and EN 1384 (equestrian activities helmets) to an oblique impact situation.

To that extent it is imperative that in the near future emends can be applied to the current standards and regulations. Consequently promote oblique impact testing and producing the development of new versions of helmets capable to provide the market with a more effective option against rotationally induced head injuries.

1.2 Objectives

1.2.1 General objective

"Evaluate the performance of a new helmet testing method in order to prevent head and brain injuries by simulating realistic head impact situations"

1.2.2 Specific objectives

- Determine the cost /benefit of an in-house constructed test rig compared to an external supplier or constructor.
- Compare the new oblique helmet test method (AAIT) with the existent oblique helmet test method (MPIT).
- Utilize a finite element analysis to complement the comparison of methods.
- Determine the ergonomic improvements of the new oblique helmet test method AAIT.

1.3 Background

1.3.1 Human head anatomy

In order to comprehend the protective effect of helmets and their importance of usage, this section provides an insight of the anatomy of the human head; in this sense a practical overview of what is being protected is acquired and the mechanical properties utilized to achieve its protection are more easily absorbed.

The head is surrounded firstly by a thin layer of skin known as the scalp. The Scalp consist of a layer of soft tissue (Nouri, 2012)

The scalp is covering the cranium. The cranium is a hard encasing structure formed by 8 bones separated by zigzagged joints known as the cranial sutures which can be seen on a dry skull (Figure 2) (Hollins, 2012).

At birth the joints in the cranium are connected by a gelatinous cartilage that allows those structures of the roof to move freely decreasing the ability to absorb direct impacts and protect the brain but on the other hand offers the opportunity of absorbing energy by moving and avoiding in some degree concussions and cranium fractures. During the development of the person this gelatinous substance solidifies giving the cranium its common egg like shape. During adult life the roof of the cranium is the most unprotected and therefore the most injury prone to direct impacts (Cruveilhier, 1844) , requiring devices such as helmets to aid in protection.

On the inside of the skull the meninges are located; the meninges provide protection and support for the brain tissues and carry many important vessels between them (Figure 1). They serve as a cushion for violent impacts with the surrounding bones, they also border with the cerebrospinal fluid, which is in charge of supplying the brain with oxygen and nutrients and removing the metabolic waste products.

The meninges are divided in three major components the outer layer known as the Dura mater which is subdivided in the outer layer and the inner layer; these two layers are separated in order to provide a gap for the tissue fluids and blood vessels. The middle layer is known as the Arachnoid named because of its spider web appearance and is formed by connective tissue. Beneath the Arachnoid there is the Subarachnoid space filled with cerebrospinal fluid. And the last and final is the Pia mater this layer adheres itself to the surface of the brain and is filled with blood vessels providing nutrients and oxygen to the brain (Alcamo, 2003).

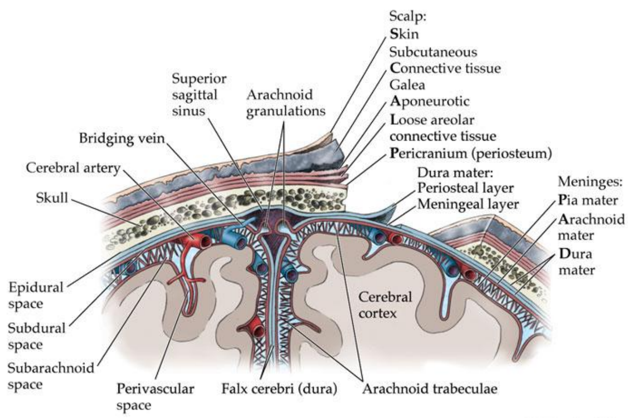


Figure 1 Image of the meninges (Blumenfeld, 2010)

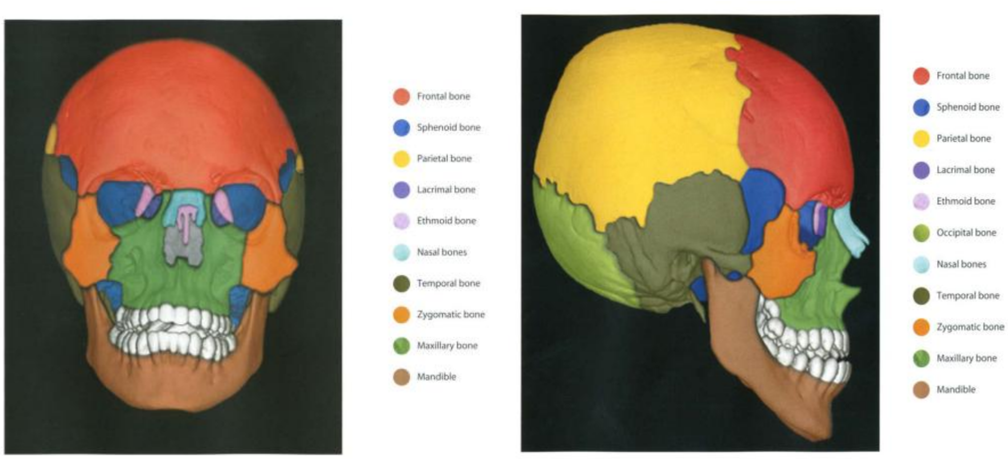


Figure 2 Overview of the Skull bones. Left image: frontal view; right image: lateral view. (Gallucci, et al., 2007)

The brain is composed by three parts; the cerebrum, the cerebellum and the brain stem (includes midbrain, pons and medulla) (Figure 3).

The cerebrum is the largest part of the brain and is divided by 2 hemispheres; the right hemisphere and the left hemisphere joined together by a group of fibers knows as the corpus callosum; whose function is to deliver and serve as a pathway of information from one hemisphere to the other. Not all functions of the brain are shared among both hemispheres the left side for example is characterized by controlling speech, comprehension and writing meanwhile the right side controls creativity, art and musical skills; to name a few (Mayfield Clinic and Spine Institute, 2013).

The cerebrum is subdivided into four lobes; the frontal lobe, parietal lobe, temporal lobe and occipital lobe (Figure 4) (American association of neurological surgeons, 2006).

- The frontal lobe functions include motor skills such as voluntary movement, speech, intellectual and behavioral functions.
- The Occipital Lobes are located at the back of the brain and allow humans to receive and process visual information also influencing how humans process colors and shapes.
- The Parietal Lobes have the function of processing information received from the other areas of the brain.
- The Temporal Lobes are located on each side of the brain at about ear level, and can be divided into two parts; the ventral located at the bottom and lateral located at the side of the lobes. The right hemisphere is associated with visual memory helping the individual to recognize objects and faces meanwhile the left side helps to understand language; finally the rear of the lobe is associated with the interpretation of other people's emotions and reactions (American association of neurological surgeons, 2006).

The brain is made up by two types of cells known as neurons (Figure 5) and glia cells. The neurons consists of a dendrite, body, and axon they are in charge of transmitting information through electrical and chemical stimuli; they communicate with each other by a chemical process known as synapses taking place in a small gap between each other (synapse). Glia cells on the other hand are in charge of nourishment, protection and providing structural support, it is speculated that the number of glia cells are 10 to 50 times more than the neurons (Mayfield Clinic and Spine Institute, 2013).

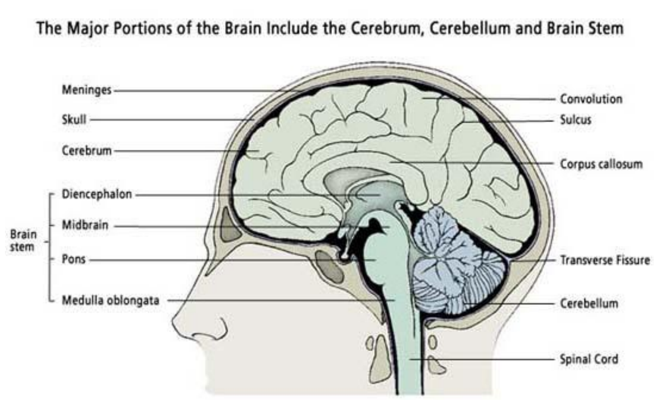


Figure 3 View of Principal parts of the brain. (Genius Intelligence, 2012)

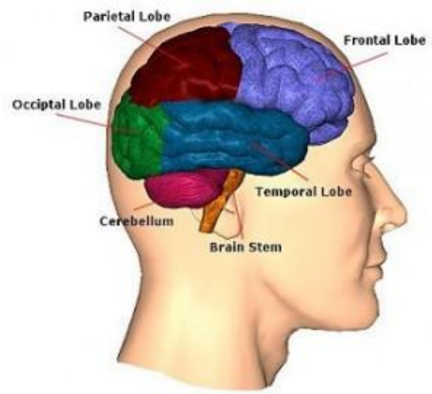


Figure 4 View of the brain lobes (McLeish, 2012)

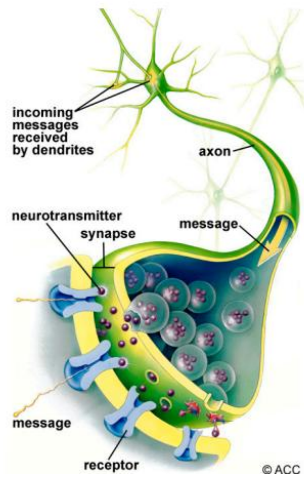


Figure 5 View of a neuron and its components. (Mayfield Clinic and Spine Institute, 2013)

1.3.2 Biomechanics of head injuries

Now that the anatomy of head is known, in order to give a better understanding of the importance of helmet testing one must acquire knowledge on the most common injuries that could be prevented with the use of this man made device.

Head injuries are related to the direction of impact in which the head segment makes contact this can be either translational or oblique. While there are injuries produced by translational kinematics such as skull fractures and pathologies derived of those injuries, these are very rare (Kleiven , 2013) and the most common impact type has shown to be an oblique impact with an estimated angle of impact of around 30°-40° (Harrison, et al., 1996) (Otte, et al., 1999) (Richter, et al., 2001) (Verschueren, 2009).

In simulations conducted by Kleiven (2007) comparing two impact situations with the same characteristics but altering the angle of impact it was shown how an angular impact would most likely produce injuries such as diffuse axonal injuries and subdural hematomas due to the incompressible properties of the brain tissue meanwhile linear impacts are closely related to skull fractures due to the high levels of stress sustained by the skull (Kleiven , 2013).

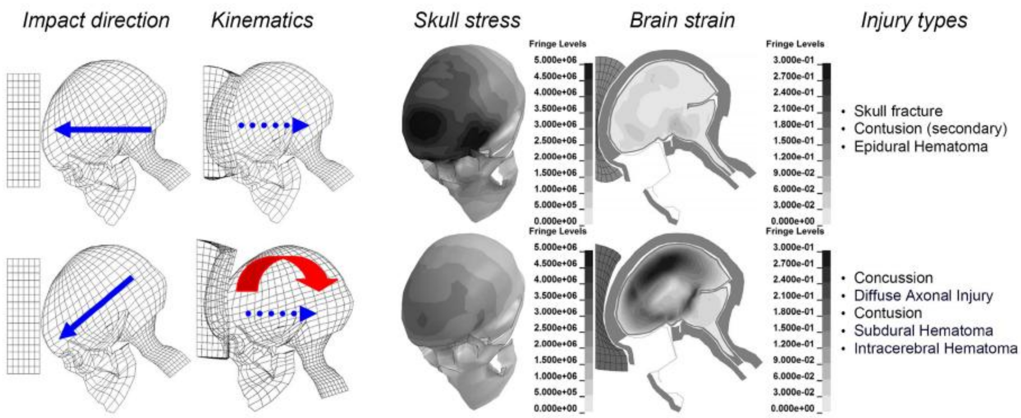


Figure 6 Illustration of the experiments conducted by Kleiven showing the biomechanics of an oblique impact (lower) compared to a translational one (upper). Obtained from: (Kleiven, 2007)

1.3.2.1 Skull fractures.

During high linear/translational energy impacts the skull can be broken and fractured; originating lesions in the head in the form of skull fractures or hematomas. The main reason of why a skull fracture appears is due to direct impacts producing high linear accelerations increasing the stresses sustained by the skull bone (Figure 6). Due to the anatomical configuration of the skull; certain areas are more prone to sustain a fracture such as the sphenoid sinus, foramen magnum, petrous temporal ridge and the middle cranial fossa (Figure 7) which is the weakest point. There is a causal relation between skull fractures and other brain injuries such as extradural hematomas this is because of the fact that the Dura mater is adhered to the skull which makes it vulnerable to lacerations by a skull fracture producing leakage of cerebro-spinal fluid to the outer part of the Dura mater producing infections (Samii & Tatagiba, 2002), nerve and blood vessel damage due to increase of internal pressure (Thibault & Gennarelli, 1985).

Studies by Mertz et.al (1997) show a correlation of linear acceleration and skull fractures where an acceleration of 180g is expected to produce 5% chance of skull fracture and 40% of chance for 250g.

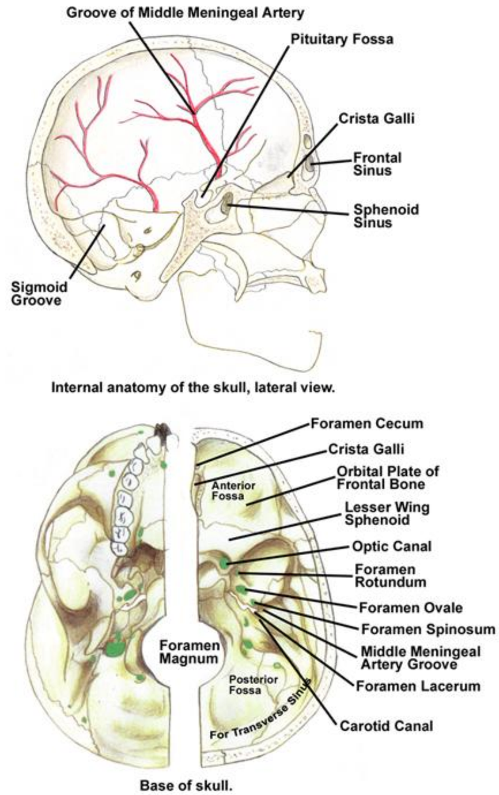


Figure 7 Top: view of the skull. Bottom: Superior view of the skull, calvaria is removed (Joshi, 2013) .

1.3.2.2 Acute subdural hematomas (ASDH)

Acute subdural hematomas are especially important to this study since according to Gennarelli and Thibault who performed studies on live primates; determined that rotational accelerations had a direct correlation with injuries such as ASDH and diffuse axonal injuries moreover than direct translational impacts. They based their conclusions on the hypothesis that these type of injuries were the result of shear strain generated by a rotational acceleration and claimed that almost every type of head injury will occur in an scenario where rotational acceleration is also present (Thibault & Gennarelli, 1985;Gennarelli, et al., 1982).

Acute subdural hematomas are usually caused by the tear of the bridging veins (Figure 8) that pass across the subdural space to the Dural sinus, if the subdural hematoma is sufficiently large it can cause the internal cranial pressure to elevate resulting in a split of the cranial sutures (McMillan, et al., 2006). The mortality rate after the evacuation of the excess fluid can vary from 30% to 60% and the recovery after survival can be complicated and dependent on several factors such as age, operating time, mechanism of injury among others (Lubin, et al., 2006).

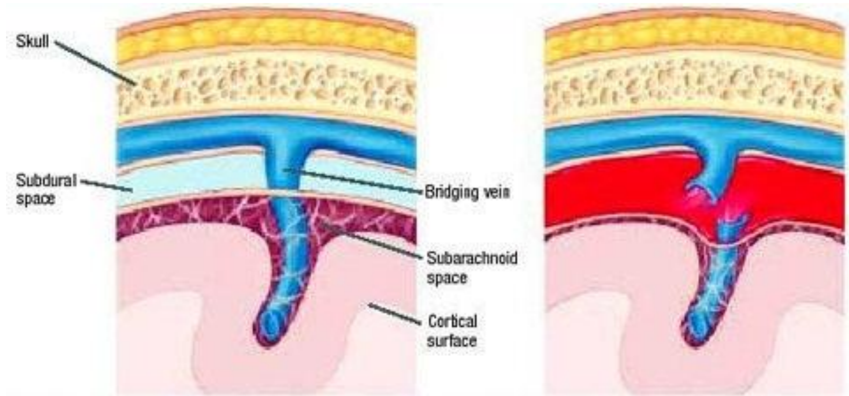


Figure 8 View of the bridging veins that produce subdural hematomas. (All About Neurology .info, 2013)

1.3.2.3 Brain contusion

Contusions form part of the most common injury sustained to the head after impacts, on a study performed by Depreitere on a case study of 86 impact situations; out of which 44 where against motor vehicles and 42 about normal falls the most frequent injuries were skull fractures (86%) and cerebral contusions (73%) (Depreitere, et al., 2004).

In the absence of skull fracture the brain contusion is an injury resulting from contact of the brain and the inner part of the skull, involving some damage of the superficial gray matter caused by excessive head rotational loading (Löwenhielm, 1975). The usual location for contusions is in the frontal and temporal lobes (Granacher, 2007) and the specific affected area is categorized in coup (under the affected area by impact) and contrecoup (distal to the area of impact) (Figure 9).

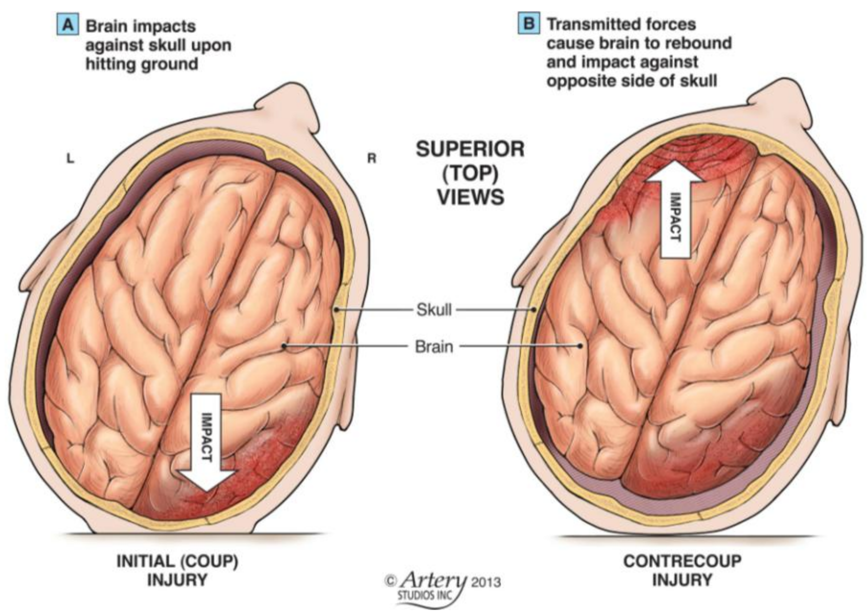


Figure 9 View of coup and contrecoup injuries. (McLeish, 2013)

1.3.2.4 Diffuse Axonal injury

Diffuse axonal injuries (DAI) are those pertaining to destruction of white brain matter and are specially related to those injuries involving shearing of the brain components due to rotational motion where there is an acceleration/deceleration oh the head (Hurley, et al., 2009). DAI injuries can only be identified postmortem. Studies in the early eighties show that the reason for these types of injuries is the inability of the axons to transport information which then leads to swelling of the axon and later axonal disconnection, due to the nature of the brain tissue when a rapid acceleration is experienced brain matter slide over one another resulting in damage on the axons which cause breakage of the axon ports, isolating them from other axons (Povlishock, 2000).

The most common locations to find DAI injuries are the lobar white matter due to the fact that the grey matter and the white matter meet in this junction; therefore because of different tissue density the white matter is prone to injuries (Figure 10), also the corpus callosum and the brainstem can be affected. DAI injuries could be accompanied by small hemorrhages due to the rupture of subependymal veins and can be accurately detected by the use of magnetic resonance instead of CT (Godoy, 2013).

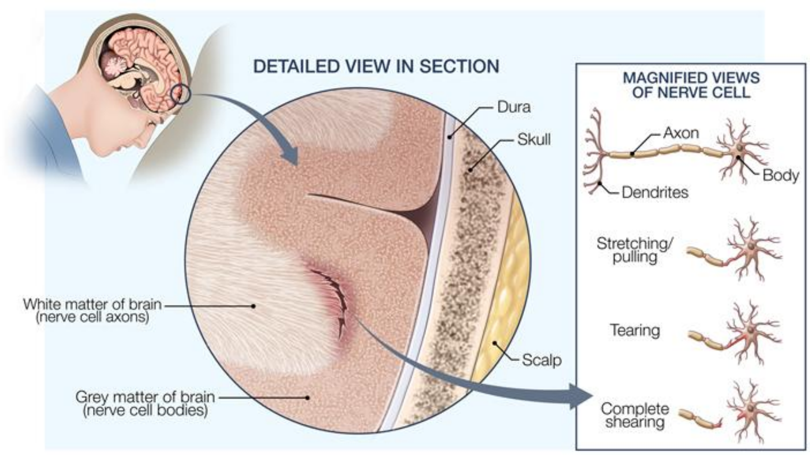


Figure 10 Diffuse Axonal Injury. (Kryski Biomedia, 2013)

1.3.2.5 Mild traumatic brain injury (mTBI) or Concussion

A concussion is the mildest form of a brain injury nonetheless it poses a threat to the health of the individual; a concussion is defined as a pathophysiological process affecting the brain induced by biomechanical forces (McCrory, et al., 2004); it can be the result of a blow to the head or the neck or anywhere else in the body where a force is lastly transmitted to the head, originating dizziness, headache, and may or may not present loss of consciousness (McCrory, et al., 2004).

A concussion is hard to obtain as a result of translational forces however when it comes to rotational accelerations the injury becomes more common therefore they are the main concerns of contact sports such as American Football or rugby (Cassidy, et al., 2004). Simulations performed on concussion injuries sustained in the National Football League (NFL) show the effect of rotational kinematics in the appearance of this type of injuries more so than the influence of translational motion (Kleiven, 2007)

1.4 Head injury criteria and thresholds for injuries

The necessity for experimental setups to compare the results with standardized values has given origin to different injuries criterions, each one considering alternative aspects of the impact in order to provide insight for every possible scenario.

1.4.1 Wayne State tolerance curve (WSTC)

The first known tolerance criterion was proposed by Lissner et al. (1960) and later modified by Patrick et al. (1965) by the addition of animal and volunteer information to the original corpse obtained data. With the studies a curve was developed (Figure 11) demonstrating the limits in acceleration on the Anterior-posterior direction that the head can withstand for short periods of time, any value above the curve is considered to be dangerous and could end up in lesions.

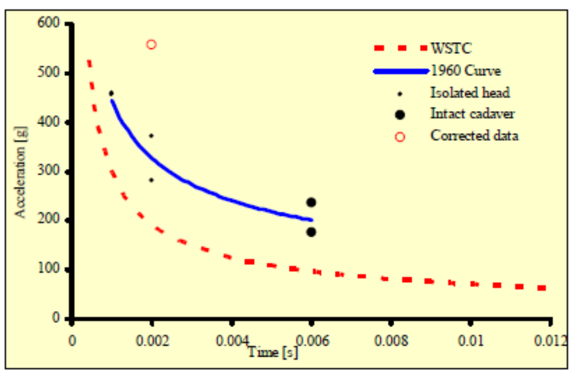


Figure 11 WSTC curve. (Yoganandan, et al.)

With the use of this curve Gadd developed the Severity index (SI) for head trauma (Hess, et al., 1981). This index was meant to catalogue the injuries depending on the life threatening possibility after the occurrence of the incident.

1.4.2 Head injury criterion (HIC)

The SI index was proven to be effective when evaluating short durations of impacts, but for longer time periods the system was not appropriate, it was for this reason that in 1971 Versace used the WSTC as a basis to developed a new injury criterion known today as the head injury criterion (HIC), he proposed weighting the acceleration time pulse by the total length of the effective pulse; this resulted in an equation later modified by the National Highway Traffic Safety Administration (NHTSA) (Winkelstein, 2012)

$$HIC = \max\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2-t_1)$$

Where t_1 and t_2 are two point in time during any interval of the impact that maximize HIC and a(t) is the head acceleration measured in g's (measured at the head center of gravity)

Although being criticized for not taking into consideration the rotational forces (Gennarelli, et al., 1982) (Kleiven, 2006) even when is considered that these forces are responsible for brain injuries like ASDH and DAI (Thibault & Gennarelli, 1985); and the lack of relation between the human head and the anthropomorphic test device acceleration response (Schmitt, et al., 2009); HIC is still the most used criterion for head impact evaluation. A HIC value over 1000 results in severe head injuries and in 8.5% probability of death; HIC=2000 31% death and 65% death at a HIC=4000 (Hopes & Chinn, 1990)

1.4.3 Generalized Acceleration Model for Brain Injury Threshold (GAMBIT)

In the year 1986 Newman tried to developed an assessment system for head injuries were not only the translational force was accounted for head simulation impacts but also the rotational acceleration; therefore the GAMBIT was proposed; the general equation for GAMBIT is as follows (Campen, et al., 1998)

$$G(t) = \frac{a_m}{a_c} + \frac{\ddot{\alpha}_m}{\ddot{\alpha}_c} \leq 1$$

With $a_c = 250\ g$ and $\ddot{\alpha}_c = 10.000\ \frac{rad}{s^2}$ which are the maximum allowable values for translational and rotational acceleration respectively; and a_m [g] and $\ddot{\alpha}_m$ [rad/s2] the mean values of linear and angular acceleration respectively.

Even though this criterion poses a serious advantage compared to its counterpart HIC since it accounts for the rotational acceleration it lacks validation and therefore is not included when evaluating helmet performance.

1.4.4 Head impact power (HIP)

In the year 2000 Newman et al. proposed a new injury assessment criterion that takes into consideration both sources of motion i.e. translational and rotational; the function also considers time duration. This model has been validated for concussions sustained in sports like football replicating the situation with the use of dummies. The basis of the newly developed formula estimates that the injury probability/severity depending on the rate of change kinetic energy of the head during the time of impact. The rate of change is also known as power therefore the name

HIP. The threshold reached under the shown equation estimates that if the power reaches a level of change of kinetic energy of 12.5 kW there is a 50 % chance of concussion and if the level reaches a value of 25 kW the concussion will almost certainly takes place (Lovell, et al., 2004)

The formula is as follows (Newman, et al., 2000)

$$HIP = Aa_x \int a_x dt + Ba_y \int a_y dt + Ca_z \int a_z dt + \eta\alpha_x \int \alpha_x dt + \beta\alpha_y \int \alpha_y dt + \chi\alpha_z \int \alpha_z dt$$

The formula then shows the six degrees of freedom for the head during an impact and evaluates both sources of energy; translational and rotational; where A, B, C, η , β and χ represent the injury sensitivity for each degree and a_x, a_y and a_z the translational acceleration for each respective degree of freedom and α_x , α_y and α_z the angular accelerations. Due to the absence of information regarding directional sensitivity, the coefficients in the above equation are expected to denote the mass and mass moments of inertia of a Hybrid III head-form.

The main drawback of this new assessment is that is validated for mild traumatic injuries only therefore a new set of experiments with current data for more severe traumatic injuries must be performed in order to adjust the equation so that it suit a broader field of injury scenarios where helmets are mostly used, i.e. motorcycle accidents. Nevertheless the use of HIP could be of great relevance in the design and improvement of helmet performance due to the fact that it considers both mechanisms of injury (translational and rotational) when an impact to the head takes place.

1.4.5 Summary of rotational acceleration injury thresholds

Due to the viscoelastic property of the brain, this segment is especially subjective to shear stress and strains caused by the rate of acceleration of the segment or changes in rotational velocity (Ommaya, et al., 1967) (Thibault & Gennarelli, 1985).

Unfortunately there has not yet been an agreement on the proper thresholds for rotational accelerations; the following table shows the variation of injury thresholds for these components found in the literature.

Lesion Type	Threshold	Measurement process	Reference
mTBI	5.900$\frac{rad}{s^{-2}}$ for 50% chance	Laboratory reconstruction	(Zhang, et al., 2004)
mTBI	300-4000$\frac{rad}{s^{-2}}$	Laboratory reconstruction	(Willinger & Baumgartner, 2003)
mTBI	8020$\frac{rad}{s^{-2}}$	Dynamic modelling	(Fréchéde & McIntosh, 2009)
No Lesion	2700$\frac{rad}{s^{-2}}$	Human volunteers	(Ewing, 1975)
No lesion	16.000$\frac{rad}{s^{-2}}$	Human boxers fighters	(Pincemaille, et al., 1989)
Subdural hematoma	4.500 $\frac{rad}{s^{-2}}$	Cadaver impacts	(Löwenhielm, 1974)

mTBI	$1800\frac{rad}{s^{-2}}$	Primate impacts	(Ommaya, et al., 1967)
DAI	$16.000\frac{rad}{s^{-2}}$	Primate, physical and numerical model impacts	(Ommaya, et al., 1967)
mTBI	$9267\frac{rad}{s^{-2}}$ for 95% chance	24 Cases of NFL impact situation	(Newman, et al., 1999)
mTBI	$9386\frac{rad}{s^{-2}}$ for 10%	64 studied cases of head impacts in the NFL where 4 presented concussions. Measured with Head Impact Telemetry (HIT)	(Funk, et al., 2007)
mTBI	$6383\frac{rad}{s^{-2}}$ for 50 % chance	57 concussion NFL study cases with the use of HIT	(Rowson, et al., 2012)
mTBI	$4500\frac{rad}{s^{-2}}$	27 concussion Simulations and 13 non concussive simulations reconstructions of rugby injuries	(Patton, et al., 2013)

Table 1 Rotational acceleration thresholds.

1.5 Shock absorption tests and review of helmet testing standards and regulations

To ensure the performance of helmets certain standards and procedures had to appear so that the production of newly devices complies with what is known to work. The first of these standards to emerge was the British Standard (BS) 1869: 1952 Crash Helmets for Racing Motor Cyclists (British Standards institution, 1960). The main concept of the testing required a shock loading of the helmet by a dropping of a hardwood block weighting in 4.5kg at a height of 2.7m; then the dynamic forces were measured by the use of a gauge located between the helmeted head-form and a stationary block; in order for the helmet to be approved the force must not exceed 2268 kN (Yoganandan, et al., 2001).

With the BS standards a tool for evaluating headgear existed and guidelines for developing new ones were already available.

In the United states the story is different, helmets were mainly developed for military purposes and it was not until the death of race car driver William Snell that a sense of criticality was given to civilian head gear protection; William Snell died in what was considered to be a survivable crash if the his headgear would not had failed at the time of the accident.

By the year 1959 the Snell organization had already produced the first standard denominated Snell General helmet standard, where the test consisted on impacting a 12 lb head form on the front, rear and the sides with a mass weighing 16.08 lbs; the impact surface will be spherical with a radius of 1.9 inch and the velocity of 20 ft per second. The Helmet should withstand a minimum of two blows under these conditions and avoid bottoming (bending of the material) and exceeding 400 G's. It must also be tested for chin strap hardness by supporting a weigh of 300 in tensile strength and for resistance to penetration by dropping a mass resulting in a deflection of the helmet in less than 3/8 of an inch (Snell Memorial Foundation, 1959).

On the other hand there is another major contributor to North American standards and regulations the FMVSS 218 commonly known as DOT (Department of transport) which shifts its focus to impact absorption instead of impact resistance like the Snell standard, in this sense it is considered the most accepted and popular standard by the North Americans (Silodrome gasoline culture).

In general all the updated versions of the helmet testing standards focus their rules under the shock absorption test which is the principal focus of this thesis. Although as the name of the test suggest the energy absorbed during impact is not measured rather than the linear acceleration of the impact; from these measurements injury parameters like HIC are to be utilized in order to estimate injuries.

The European Union follows several helmet regulations such as the ECE regulation 22.05 for motorcycle helmet testing (Figure 12). This regulation is the most widely used being utilized by more than 50 countries and accepted in worldwide Institutions such as The American Medical Association (AMA); motorcycle competition regulators like the WERA and the FIM and the racing committees of the Formula USA and the Moto GP (Silodrome gasoline culture).

The ECE regulation 22.05 is believed to be the most updated version comprehending the general basis of most of the standards and regulations; it utilizes the HIC criterion in order to determine whether the helmet has passed or fail the injury criteria and also determines that a maximum acceptable threshold should be of 275 G's on a linear impact onto an anvil with variation in its shape (Figure 13) depending on the desired test to be performed (United Nations Economic Commission for Europe, 2002).

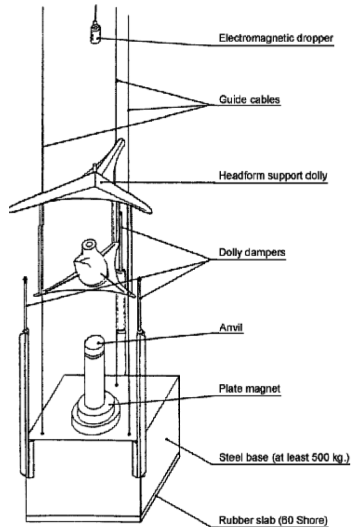


Figure 12 ECE 22.05 Head-form drop test. Source (United Nations Economic Commission for Europe, 2002)

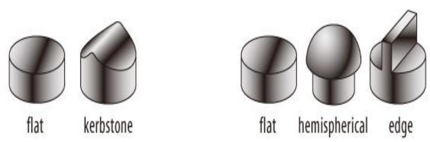


Figure 13 Different types of striking anvils for shock absorption drop tests. (Arai helmet Europe, 2014)

Other regulations such as the EN 1078 and EN 1080 also promote shock absorption tests much like the one stated in the ECE 22.05.

The EN 1078 known as the "*Helmets for pedal cyclists and for users of skateboards and roller skates"* was published in 1997 as a European Standard specifying the requirements helmets have to fulfill in order to comply with the European Personal Protective Equipment Directive. The drop test impact consists of a guided free fall impacting an anvil which can be of flat surface or kerbstone (Figure 14). The impact should never exceed 250g for an impact velocity of $5.42\frac{m}{s}$ on a flat anvil and $5{,}52\frac{m}{s}$ on a kerbstone anvil (European Standard EN 1078, 1997).

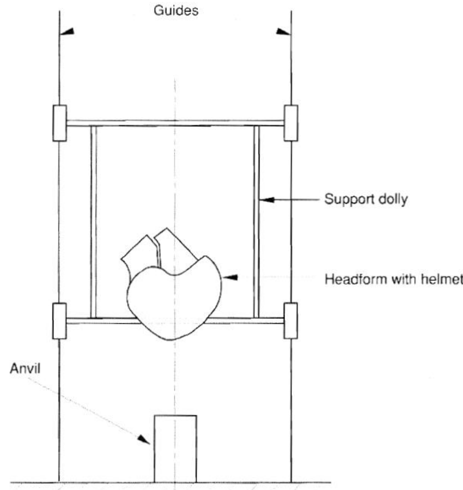


Figure 14 EN 1078 Shock absorption test. (European Standard EN 1078, 1997)

The EN 1080 known as the *"Impact protection helmets for young children"* is also a European approved helmet testing standard which intends to regulate the manufacturing of helmets produced for children; the helmet is meant to protect the forehead, rear, sides, temples and crown of the head. When tested on the shock absorption test (Figure 15) the threshold for linear acceleration should not exceed 250g for impacts with velocities corresponding to $5.42\frac{m}{s}$ on a flat anvil and $4.57\frac{m}{s}$ on a kerbstone anvil (European Standard EN 1080, 1997).

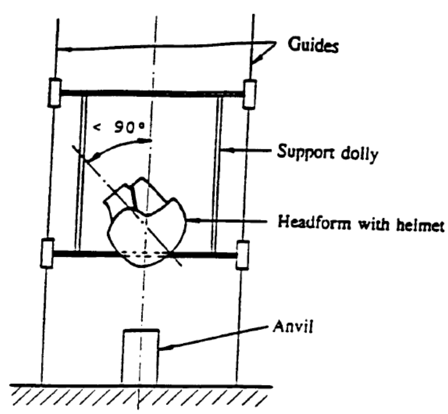


Figure 15 Shock Absorption test for EN 1080. Source (European Standard EN 1080, 1997)

Other standards and regulation that also base their tests similarly to the previously explained such as the EN 1077 designed for Skii Helmet evaluation and the EN 1384 directed for Equestrian activities helmet evaluations.

Another form of helmet testing is without the physical test itself but instead with the use of computational simulation scenarios that replicates the injury situation and offer conclusions about the test regarding possible lesions sustained to the head or brain. There are mainly two forms of testing helmets with numerical and computer analysis; the lump mass models and the finite element models.

1.5.1 Numerical and computational tools for drop test analysis

1.5.1.1 Lump mass models

The lump mass models are basically a group of rigid masses linked together by springs and dampers with no mass; not many representations of helmet head interactions have been represented by a lumped mass model but some literature can be found. Balandin, et. al., performs lumped mass model tests in order to study the performance of helmets to prevent head injuries under two scenarios, a fall from a bike or a motorcycle and when struck by a projectile like a ball during a baseball game (Figure 16), the result was expected to help broaden the knowledge on helmet design.

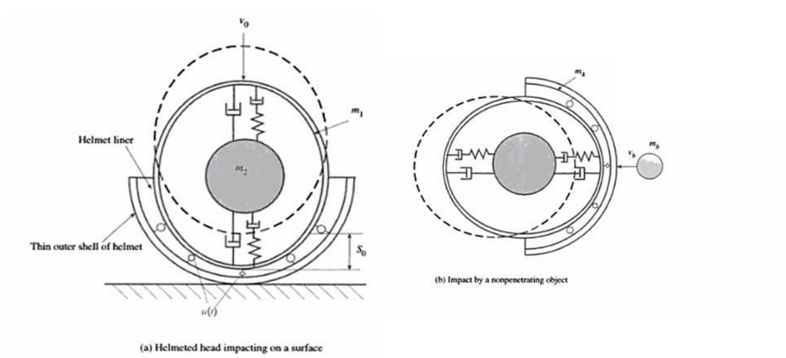


Figure 16 Graphical representation of the lumped mass model study. Source (Balandin, et al., 2001)

In short the test consisted of representing the model with two masses m_1 and m_2 connected by springs and dampers, where m_1 is the mass of the impacted skull bone and m_2 is the mass of the brain and the head bones which are not taken in consideration by m_1; the sum of both masses is the total mass of the head. The characteristics of the materials like mechanicals properties of the bones are assigned by the stiffness coefficient of the spring and one of the dampers and the other damper will represent the dissipative properties of the brain; the action of the helmet is modeled by a controlled force "u" applied to m_1, this force is expected to be generated after deforming the padding of the helmet, therefore improvements regarding padding contribution to injury prevention could be presented (Balandin, et al., 2001).

Other literature could be found regarding the use of the lumped mass models in drop tests specifically this was performed by Mills & Gilchrist, where they simulated the deformation of a helmet as a result of impacts sustained when striking a flat and hemispherical anvil. The main conclusion of their study was that the use of soft forms of padding inside the helmet will inevitably absorbed the energy from the impacts improving the crash capacities of the helmet (Mills & Gilchrist, 1988). Soon enough the same authors improved the model by adding an outer shell to their model simulating closer to reality, and just like previous studies they concluded that the force of the anvil could be reduced with a less stiff outer shell (more compliant) and a less stiff inner padding (Gilchrist & Mills, 1993).

1.5.1.2 Finite element models

The finite element models offer the advantage of being able to simulate different types of impacts and still produce adequate results, furthermore is usually a characteristic of the software to provide the option of changing the material properties of the objects being studied and therefore more accurate representations of reality and mechanical behavior of the helmet interaction for example can be obtained. But these results do not come as easy, to be able to perform a finite element analysis the model has to be created from scratch making the use of this software time consuming

Since finite element models offer a more complex dynamic; the interactions between head-helmet can be modeled, this proposes the opportunity of studying the rotational forces at the moment of an impact. When testing helmets values can be measured and evaluated, which offers an important advantage in estimating brain injury possibilities and provides the opportunity of comparing those results to field experimental work.

Several studies involving Finite Element analysis were found in literature, most of them to simulate and compare impact situations that represent reality; Brands et al. (1997) performed studies utilizing real experimental data from drop test experiments. Therefore the model that they constructed mimics the elements involved in that data in order to maintain a degree of reliability in the simulation; they concluded that the impact load is transmitted to the head via the crushing of the protective padding or via the vibrations of the outer shell. Lateral impacts were not possible due to the inexistence of contact points between the head and the padding of the helmet, this was improved in the study performed by Aare et al. where the contact definition between the FE model of the human head and the helmet, and the FE model of the Hybrid III dummy head and the helmet, was “surface-to-surface interference” (Aare, et al., 2004), which basically means that if the model of the head is larger than the one containing it (the helmet) there will be an intrinsic pressure on the contrary there will be no pressure since the head will be smaller than the helmet (Hallquist, 1998), this can obviously be improved by designing the head and the helmet of a size that fits perfectly.

1.6 Review of current oblique impact tests

There is some literature proposing new experimental testing methods that account for rotational components; Halldin, et al., developed a new helmet rotational force assessment by simulating a fall from a motorcycle on to the road surface or the windshield of a car. The main concept of the set-up is that an instrumented head-form falls vertically to impact a horizontally-moving surface, this moving surface (mostly rigid) comprised a moving steel plate covered with grinding paper; the movement of the plate is due to the action of a pneumatic piston (Figure 17).

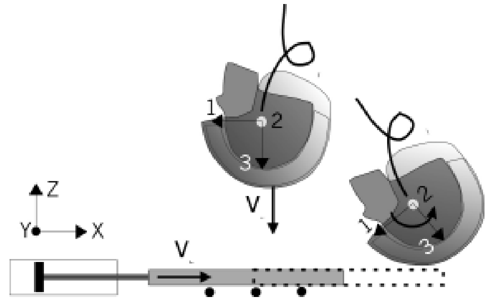


Figure 17 MPIT Oblique impact test. Obtained from (Halldin, et al., 2001). The V represent the horizontal velocity of the plate and the vertical velocity of the free falling helmet.

With the obtained results conclusions were drawn on the inner padding of the helmets developing a new system called MIPS able to reduce up to 50% the rotational effect of a fall compared to the conventional helmets by placing a low friction film between the outer shell and the protective padding liner (Halldin, et al., 2001).

On the other hand there are some established forms to measure the tangential forces for motorcycle helmets comprised in the ECE regulation N 22.05 Method A (Figure 18), however it comes with great deficiencies like the rotational forces are measured in the longitudinal axis of the anvil, this means that the force transducers are set inside the anvil instead of measuring onto the helmeted head-form itself. This arrangement increases the difficulty of the calculations and the test, besides of not having solid evidence of the correlation of the forces in the anvil and its relation with the forces and energy absorption experienced by the helmeted head-form (Mills, et al., 2009).

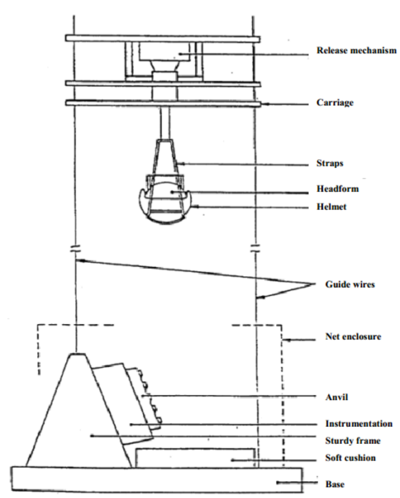
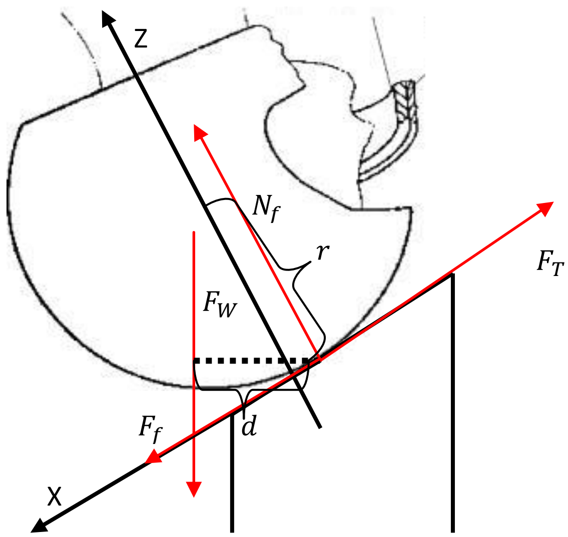


Figure 18 ECE regulation N 22 Method A; oblique impact testing. Obtained from (United Nations Economic Commission for Europe, 2002)

1.7 General hypothesis regarding method evaluation

It is expected that the results obtained with the MPIT differ from those obtained with AAIT; this is due to the fact that the impact configuration offers different contact scenarios. Thus the AAIT is likely to produce higher magnitudes of rotational accelerations; this can be observed by developing a basic free fall body diagram of the impact situation.

The following figures show how the moments (torque) affect the rotational acceleration at the point of contact



Where:

$$F_f = Friction\ force$$

$$N_f = Normal\ force$$

$$F_T = Tangential\ force$$

$$F_W = Weight\ of\ the\ center\ of\ mass$$

$$M_H = Moment\ produced\ by\ the\ head$$

$$M_T = Moment\ produced\ by\ the\ Tangential\ force$$

$$r = radius\ of\ the\ helmeted\ head - form$$

$$\ddot{\alpha}_Y = rotational\ acceleration\ around\ the\ \text{"Y"}\ axis$$

$$d\ and\ d' = distancefrom\ the\ point\ of\ impact\ to\ F_W$$

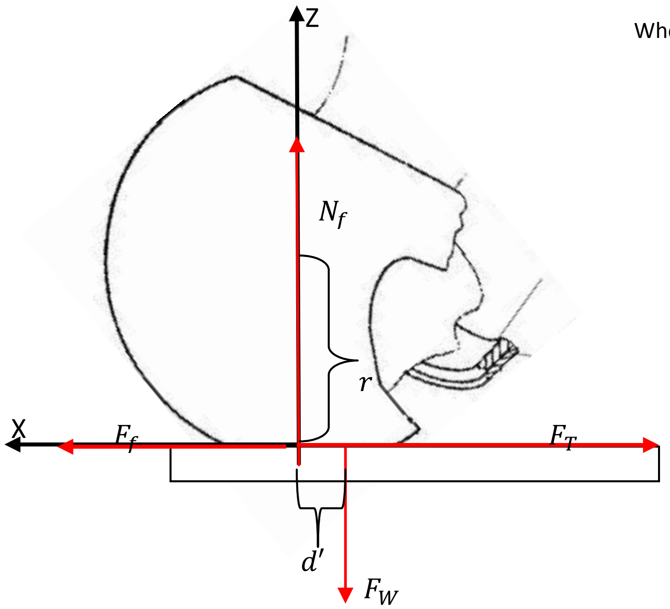
Then Moments (torque) around “Y” will be:

$$M_Y = M_H + M_T$$

$$M_Y = F_W \cdot d + F_T \cdot r$$

$$\ddot{\alpha}_Y = \frac{M_Y}{I_{yy}}$$

Figure 19 Free body diagram for AAIT test rig impact situation. Helmet head figure source (Chang, et al., 2000)



Where:

$$F_T = Force\ produced\ by\ the\ pneumatic\ piston$$

$$M_Y = M_H + M_T$$

$$M_Y = F_W \cdot (-d') + F_T \cdot r$$

$$\ddot{\alpha}_Y = \frac{M_Y}{I_{yy}}$$

Figure 20 Free body diagram for MPIT test rig impact situation. Helmet head figure source (Chang, et al., 2000)

In both figures it can be observed that the rotational acceleration around the "Y" axis depends on the values of the resultant moments (torque) around the same axis, in this sense the moments are dependent on the action of the force produced by the weight of the total mass of the helmet head configuration and the tangential force, none of which will be the same for both impact scenarios. The value of the distance "d" (dependent on the impact configuration) also varies; the radius of the head is the only value maintained constant. It is for this reason that tests will most likely require different impact velocities between the testing methods in order to obtain similar values for rotational accelerations.

2 Methods

2.1 Development of the test rig

The newly developed test rig will resemble a normal drop test rig such as those portrayed in the ECE 22.05, EN 1078, EN 1080, EN 1077 and EN 1384 with the difference that the impact will be carried out on an inclined anvil in order to induce the rotation of the head and therefore study the effects.

The main form of the device will consist of:

- Drop tower
- Basket for helmet support
- Concrete and aluminum base (including the anvil).

It was decided that for better support and stability the frame of the drop tower will consist of two steel columns with the sliding rail in the middle as follows (Figure 21 Pre-Design of the new test rig. Tool: Sketchup 2014.).

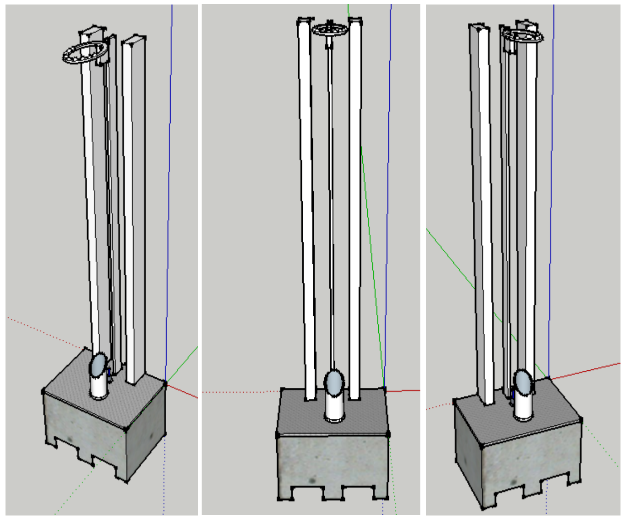


Figure 21 Pre-Design of the new test rig. Tool: Sketchup 2014.

2.2 Development questions

- What should be the inclination of the angled anvil?

According to literature the inclinations of the anvil should depend of the type of helmet desired to test; one has to take into consideration several factors that help the test to reproduce a reality simulation so that the experiments would carry an accepted level of external validity.

Table 2 represents a summary of impact angles and velocities found in literature dependent on the type of helmet that is desired to test.

Helmet	Speed of impact (m/s)	Angle (degrees)	Surface of impact	Source
Motorcycle helmets	12	< 30	Side of the car is the most frequent accident.	(Chinn, et al., 2001)
Bicycle helmets	4.8 (high probability of TBI); most crashes occur in a range of 2.2<6.8	Between 30<45	Impact against pavement at the moment of a fall	(Ching, et al., 1997) (Finan, et al., 2008) (Aare & Halldin, 2003)

	5.55 bicycle speed and 8.33 car speed	45	Impact against frontal of the car	(Mukherjee, et al., 2006)
	6.8 (average velocity)	33±20	Frontal of the car but lateral impact	(Bourdet, et al., 2013)
Equestrian	9	37	Grass, dirt, pavement	(Mellor & Chinn, 2007)

Table 2 Velocities and angles of the head at the moment of impact for different scenarios.

- Is it reasonable to build a test rig cost wise? Is it a better choice to buy a test rig from an external supplier or constructor?

As a reminder is important to stress the fact that the required oblique impact test rig is not available in the market since none of the current regulations for helmet testing and helmet approval require a rotational movement analysis.

- Will the external supplier be able to provide the characteristics desired by the experiment?

In this case the test rig has to be custom made, is it possible? There are few available helmet impact drop test suppliers; therefore the chances of supplier variability are scarce.

- Can a comparison be made between the new and old test rig?

In this sense it is important to establish the characteristics of both testing process since they will most likely be carried out under different conditions; is it possible to choose a testing process on top of the other? What makes one more valuable than the other?

2.3 Research strategy

The research strategy in this thesis will comprise of applying knowledge in procurement engineering, experimental and theoretical mechanical engineering and theoretical and experimental medical engineering.

Step I: Through research of the existing testing methods, the most appropriate test will be a free fall drop tower impacting an inclined anvil in order to obtain the rotational effects. Therefore a process of procurement engineering with the existing suppliers must be carried out to figure out the best price, location, and availability of parts. It is also necessary to carry out a cost-benefit study in order to determine whether is recommended to purchase a whole test rig from a supplier and order the alterations or in contrast develop an in-house test rig.

Goal: to develop a new test rig that is functional, cost effective and reliable.

Step II: Assemble the test rig in the easiest form possible in order to keep the procedure and the testing phase simple.

Goal: to be able to dismantle it and move it to a new location in a near future and also to simplify the testing method.

Step III: Compare the new obtained results for the rotational forces with the previous existing method (MPIT).

Goal: analyze the performance of both oblique testing methods and the management of the impact situations on both devices.

Step IV: Carry out tests on a finite element program in order to determine comparable scenarios for both testing methods.

Goal: it is expected that with the MPIT the results will differ from the AAIT. By utilizing a finite element program a correlation between both testing methods can be achieved.

Step V: Carry out experimental test derived by the FEA results.

Goal: to corroborate the correlation between methods experimentally by submitting them to the impact scenarios determined by the FEA.

2.4 Set-up and acquirement

2.4.1 Drop test set up

Following the current free fall shock absorption tests (ECE 22.05, EN1077, EN 1078, EN 1080 and EN 1384) the base is made out of a concrete with steel plates added, weighting a little more than 500 kgs, the agreed dimensions for the base are shown in Figure 22

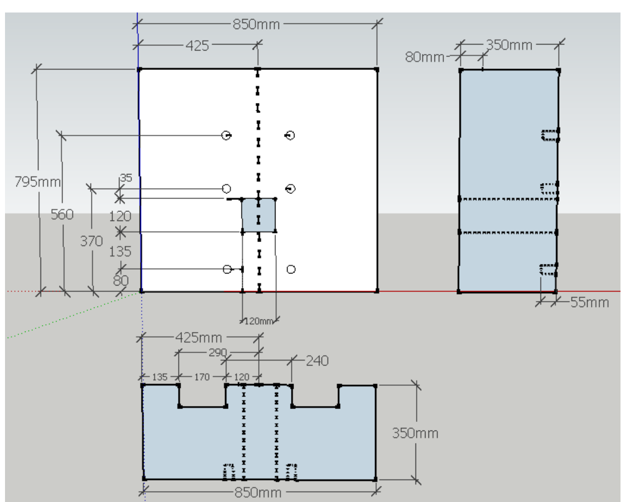


Figure 22 Dimensions of the base for the test rig. Tool: Sketchup 2014.

These dimensions were restricted to weight compliance with the standards and physical space restrictions; the volume of the item was determined according the following criteria

$$V_{base} = L \cdot H \cdot W$$

$$V_{base} = 0.795m \cdot 0.85m \cdot 0.35 = 0.237m^3$$

$$V_{holes} = V_{screws} + V_{cilinder}$$

$$V_{holes} = 6(\pi \cdot r^2 \cdot h) + (0.35m \cdot 0.120m \cdot 0.120) = 0.0054m^3$$

$$V_{total} = V_{base} - (V_{holes}) = 0.2316m^3$$

Density of normal concrete ranges from 2300 $\frac{kg}{m^3}$ to 2500 $\frac{kg}{m^3}$ (Newman & Seng Choo, 2003)

$$Weight = Volume \cdot Density = 0.2316m^3 \cdot 2400\frac{kg}{m^3} = 555.84kg$$

The end result should look something similar to the following figure 23 (also make reference to Chapter II, subtitle 2.1, Figure 21)

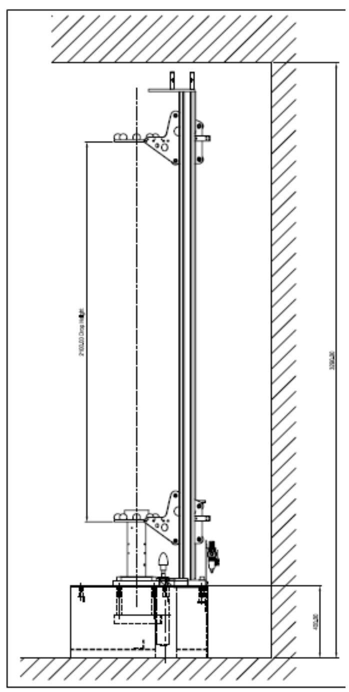
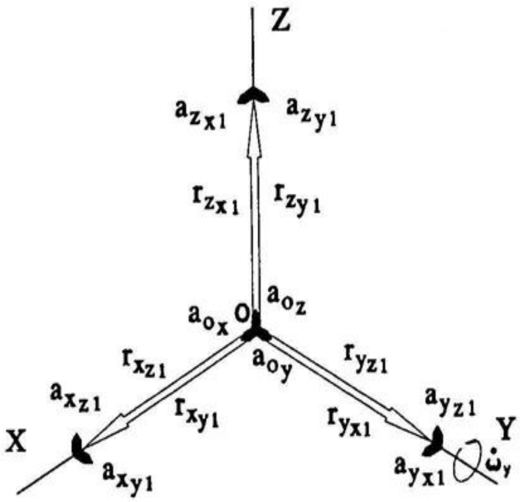


Figure 23 Helmet drop test design. Source: sketches from the company "AD engineering".

2.5 Data Acquisition in drop test experiments

In order to assess the results obtained by the newly constructed drop test rig, a setup with the use of nine accelerometers was utilized to measure translational accelerations, and rotational accelerations and velocities around the three axis. These accelerometers are located inside the head-form (Figure 25), with three accelerometers fixated in the center of the head-form and two extra ones located at the end of each axis.

Figure 24 shows a schematic overview of the functioning of the accelerometer setup, including the equations utilized to calculate the rotational accelerations; the translational accelerations can be measured directly from the accelerometers mounted in the center.



$$\dot{\omega}_x = \frac{1}{2}\left(\left(a_{y_{z1}} - a_{0_z}\right)\Big/ r_{y_{z1}} - \left(a_{z_{y1}} - a_{0_y}\right)\Big/ r_{z_{y1}}\right)$$

$$\dot{\omega}_y = \frac{1}{2}\left(\left(a_{z_{x1}} - a_{0_x}\right)\Big/ r_{z_{x1}} - \left(a_{x_{z1}} - a_{0_z}\right)\Big/ r_{x_{z1}}\right)$$

$$\dot{\omega}_x = \frac{1}{2}\left(\left(a_{x_{y1}} - a_{0_y}\right)\Big/ r_{x_{y1}} - \left(a_{y_{x1}} - a_{0_x}\right)\Big/ r_{y_{x1}}\right)$$

Figure 24 Schematic view of accelerometer action; rotational acceleration equations. Source: (Nahum & Melvin, 1993)

All the obtained data is then transferred to a computer that utilizes a software which determines the desired values with a range up to 500g for the translational accelerations; the software used is called Labview and the program code used was developed at the Royal Institute of Technology, Stockholm.

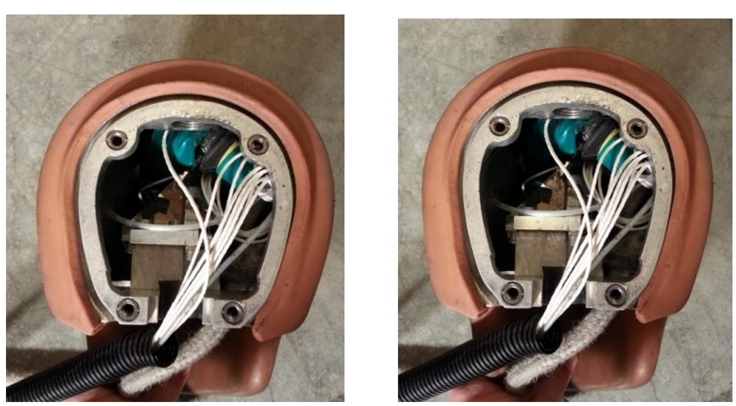


Figure 25 View of placement of the accelerometers inside the headform.

The helmets utilized for the testing of both oblique drop test rigs were the same; a Biltema helmet (Figure 26) size L; with a decided impact point of a frontal area, allocating the helmet in a completely horizontal scenario parallel to the surface of impact for the AAIT and with an inclination of 45° respect to the horizontal in the MPIT so that it relates with the same impact point.

Figure 26 View of the utilized Biltema helmet. Source: (Biltema, 2014)

2.6 Finite element analysis simulations parameters

The simulation is set to be performed by utilizing an already validated model for a helmet (brand: Scott); which even though it differs from the Biltema helmets utilized in the experimental tests it serves the purpose of demonstrating the interaction helmet-anvil impact.

Figure 27 Scott helmet model Groove utilized in the FEA simulations. Source: (Scott, 2014)

The validation of the performance of the simulation was developed by Svein Kleiven at the Royal institute of Technology in Stockholm.

2.6.1 Simulation configuration for AAIT situations

The simulation to take part consists of a hybrid III dummy head, a helmet and an inclined surface at 45˚ to serve the purpose of the anvil. Figure 28 shows a graphical representation of the configuration; the software utilized for the FEA (Finite Element Analysis) will be Ls Dyna Pre-Post.

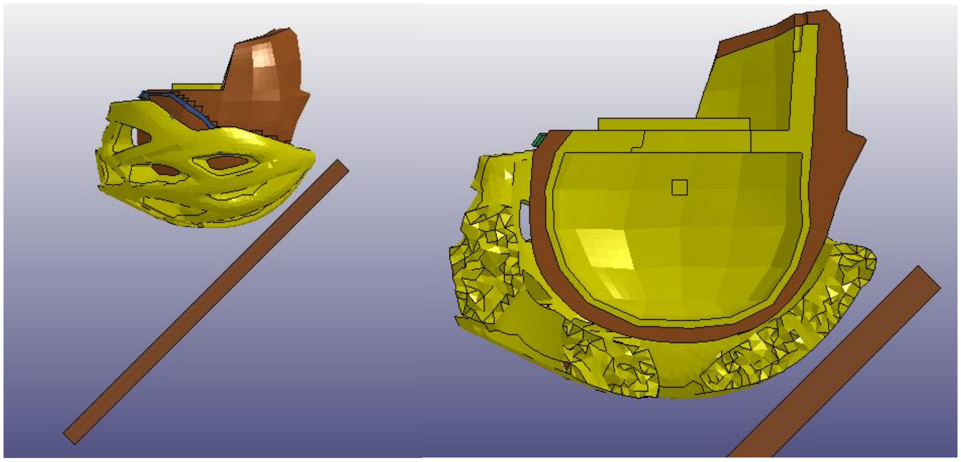


Figure 28 Impact configuration for the FEA simulation.

The head is set at a 0˚ angle in a vertical fall with translational velocities of $5\frac{m}{s}$ and $6\frac{m}{s}$ for two simulation scenarios.

The contact type between helmet-plate and head-helmet configuration was defined as “surface to surface” since is the recommended contact type for crash simulations; this contact type has a symmetric treatment, the definition of the slave surface and master surface is arbitrary since the results will be the same (Hallquist, 1998). The helmet-plate configuration is set for a static coefficient of friction of 0.5 and a dynamic coefficient of friction of 0.5, and the inner part of the helmet and the head a coefficient of friction of 0.4 for both static and dynamic, these are the parameters usually utilized for an FEA of the MPIT test rig.

Lastly the Head and the plate are defined as rigid entities that will not get any deformation, being the helmet the only entity were deformations can be observed.

2.6.2 Simulation configuration for MPIT situations

In this case the scenario changes to an impact where the head is drop vertically to a movable plate. The first simulation is set up with velocities of $4{,}24\frac{m}{s}$ both vertically and horizontally this will produce a resultant angle of 45° and $6\frac{m}{s}$*, the second simulation is set to the normal standards of utilization of the MPIT device with velocities of $3{,}9\frac{m}{s}$ vertically and $6{,}6\frac{m}{s}$ horizontally to produce a $7{,}6\frac{m}{s}$ resultant in an angle of 30°. Figure 29 shows the schematic configuration for these simulations it should be noted that the head is tilted forward around the “$-Y$” axis 45° in order to achieve a similar impact point as with the AAIT simulations.

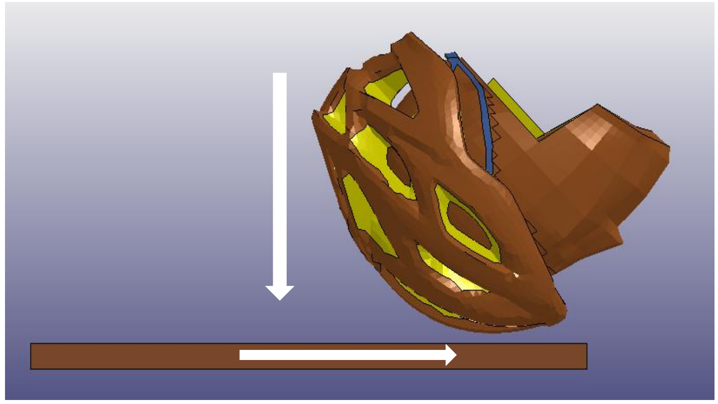


Figure 29 MPIT Finite element analysis scenarios.

* To adapt the MPIT method to the AAIT and therefore evaluate both methods under the same characteristics, there must be synchronization between the dropping element and the sliding plate resulting in a vector of $6\frac{m}{s}$ with an inclination of 45 degrees, by basic geometry it was determined that the velocity of both variables has to be set up to $4.24\frac{m}{s}$ this will be achieved by maintaining the dropping height as constant and altering the loading time of air to the piston in order to decrease the pressure of impulse which results in a lower velocity than what is originally set up.

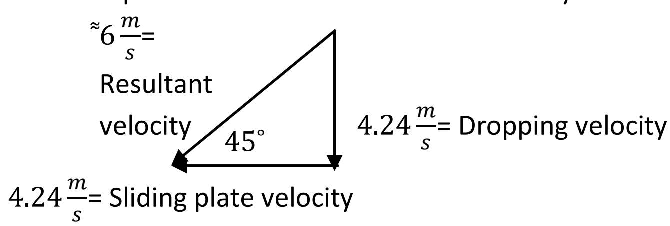


Figure 30 Schematic view for resultant velocity.

3 Results

3.1 Cost

3.1.1 Cost Analysis

The main purpose was to determine whether it is favorable for the project to purchase a whole drop test machine from an external supplier or to develop the machine in-house.

At the moment the market of drop test suppliers is handled mostly by two major competitors located in Canada and in Italy respectively; this and other factors must be taken in consideration when initiating the project and making the best decision possible price wise. In this sense the cause effect diagram illustrates the main factors that contribute in elevating the cost of acquisition or production of the machine (Figure 31). A cause effect diagram also known as an Ishikawa diagram or fishbone diagram is utilized to identify factors involved in a specific situation (Munro, 2002).

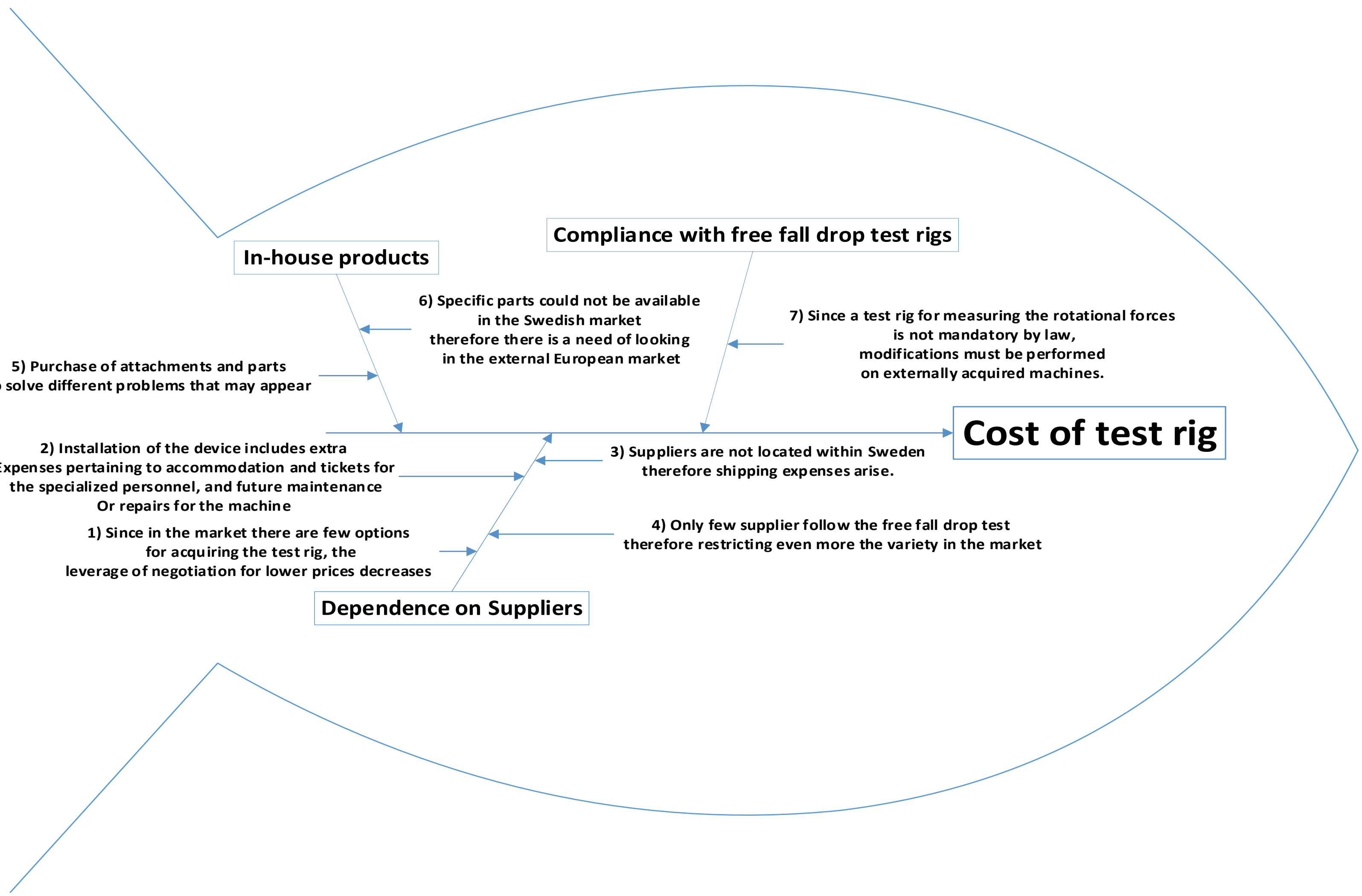


Figure 31 Cause Effect diagram on factors that contribute to cost increase.

3.1.2 Procurement process

In order to provide the project with the best option adapted to the budget a procurement process was carried out following a plan of 5 key steps (Figure 32)

Figure 32 Steps for procurement process. Source of information: (My Management Guide, 2011)

- During the specification phase the list of items to purchase was discussed; being a helmet drop tower the desired device. Also the budget was discussed in order to establish and appropriate range of feasibly available devices.
- The selection stage consists of determining the potential vendor for the necessary items discussed in the previous phase; the result was between a vendor in Canada and a vendor located in Italy; both vendors with professional backgrounds and experience in the market with several years of product allocations. The selection criteria was mainly based on whether those suppliers are able to comply with the standards and regulations appropriate with an oblique impact test, besides other criterions of great importance like, cost, service quality, and delivery estimates.
- The contracting stage is where the order is placed after the vendor is selected (Supplier located in Italy)*; terms like expected delivery dates and payment conditions were discussed, with several arrangements agreed with the supplier.
- The control phase is a managing phase where the due payments are kept in line, and a follow up on the delivery status of the pieces and items is carried out with the help of the supplier in this sense the accomplishment of the whole process is to be expected.
- Measurement is the final stage of the procurement process, and it was utilized to measure the success of the plan, and give answer to questions such as: were the items delivered correctly? Are there any defects on the purchased product? Was the delivery time carried out as accorded?; which in this particular case the answer to the first two questions is "yes" as in the delivery was successful, but the delivery time of the parts was affected on the suppliers side due to complications on acquiring some specific items which in turn delayed the project.

*The reason of selecting the vendor in Italy was due to better prices and location, in this sense if a need for new parts or consults it is easier to contact and work with a vendor closer geographically than one in Canada; another important reason is that the supplier in Canada develops devices following the American standards and regulations which means that the way of testing helmets differ from a free fall to a controlled fall with the help of an attachment disabling or restricting the rotational movement which is the main purpose of this study; in this sense a custom made machine had to be requested increasing the cost and on the other part since is not the daily work for this company, errors and defects may arise in this newly built machine from the supplier.

3.1.3 Cost of the project.

After conducting an analysis on the factors that influence the cost and developing a procurement process for the best supplier option, the decision made was to build the machine with parts acquired from an external vendor and complete the rest with In-house made attachments and parts supplied by vendors in the Swedish market avoiding extra expenses like shipping for example. In this sense economic tools can help determine that this was the best choice for the project (Table 3).

Cost benefit analysis is simply a way to compare the pros and cons of a project in this sense helping you compare and decide which of the available options is better suited to the case in hand. A decision is made simply by comparing costs and benefits; depending which outweighs the other a project would result beneficial or costly. Cost benefit analysis can be utilized in several situations ranging from social issues to economical evaluations. Then the CBA relates to decisions that consider the best use of its resources (Brent, 2007). In this case:

Cost benefit analysis CBA	
Cost	Benefit
Concrete base	Avoid cost of travel expenses from the technician
Acquired specific parts including delivery	Shipping cost decrease due to smaller package is necessary
Miscellaneous (steel bars, screws, rubber pads etc) that are not available in the workshop	Labor work has no cost since all the work is performed by the project team.
Less professional device more “rustic”	No extra cost for customization of the machine since it will be done In-house
	Miscellaneous (steel bars, screws, rubber pads etc) that are available in the workshop, decrease the need for spare parts
	Shipping for the concrete base is low due to the fact that is made in Sweden.
	Less complicated setup of the device
	Only the most important part of the device are built, creating a fully functional machine

Table 3 CBA analysis.

3.2 Helmet drop test results.

3.2.1 Construction result

After receiving the parts from the external supplier and also the required items from vendors inside the Swedish market Figure 33 shows the end result for the built device including all the customization work necessary to adapt the test rig to an oblique testing scenario.

Figure 33 View of the newly built drop test rig from different perspectives.

3.2.2 Impact tests

After conducting the first set of tests in both the AAIT and the MPIT, Table 4 shows the behavior of the impacts by demonstrating the rotational acceleration, translational acceleration and rotational velocity.

The test consisted of 5 helmet drops on AAIT and 5 helmet drops on the MPIT, impacting at a speed of $6\frac{m}{s}$ in the frontal area as shown in Figure 26 (also in Figure 28 and Figure 29).

In order to obtain the results a Matlab code is utilized; this code was developed by the MIPS group and is intended to compact all the obtained data from the accelerometers and represent it graphically in tables and plots

NAME	TRANS. ACC. [g]	ROT. ACC. [krad/s^2]	ROT. VEL. [rad/s]
MPIT_3	142,1	6,9	22,4
MPIT_4	143,5	8,2	23,9
MPIT_5	127,5	6,2	21,8
MPIT_6	135,1	6,7	25,8
MPIT_7	139,6	9,5	35,0
Mean	137,56	7,5	25,78
AAIT_1	155,6	9,9	34,1
AAIT_2	155,3	9,9	32,8
AAIT_8	139,6	9,5	35,0
AAIT_9	155,3	9,9	35,9
AAIT_10	140,4	9,0	31,6
Mean	149,24	9,64	33,88

Table 4 Results from drop tests.

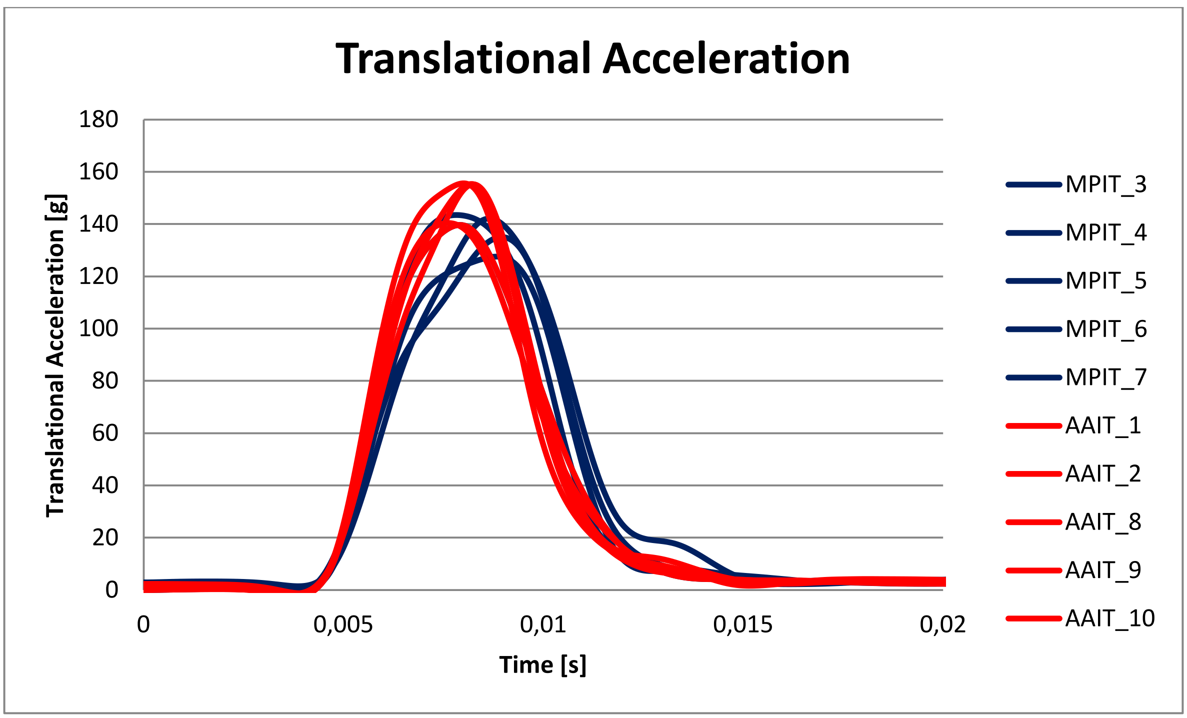


Figure 34 Translational acceleration.

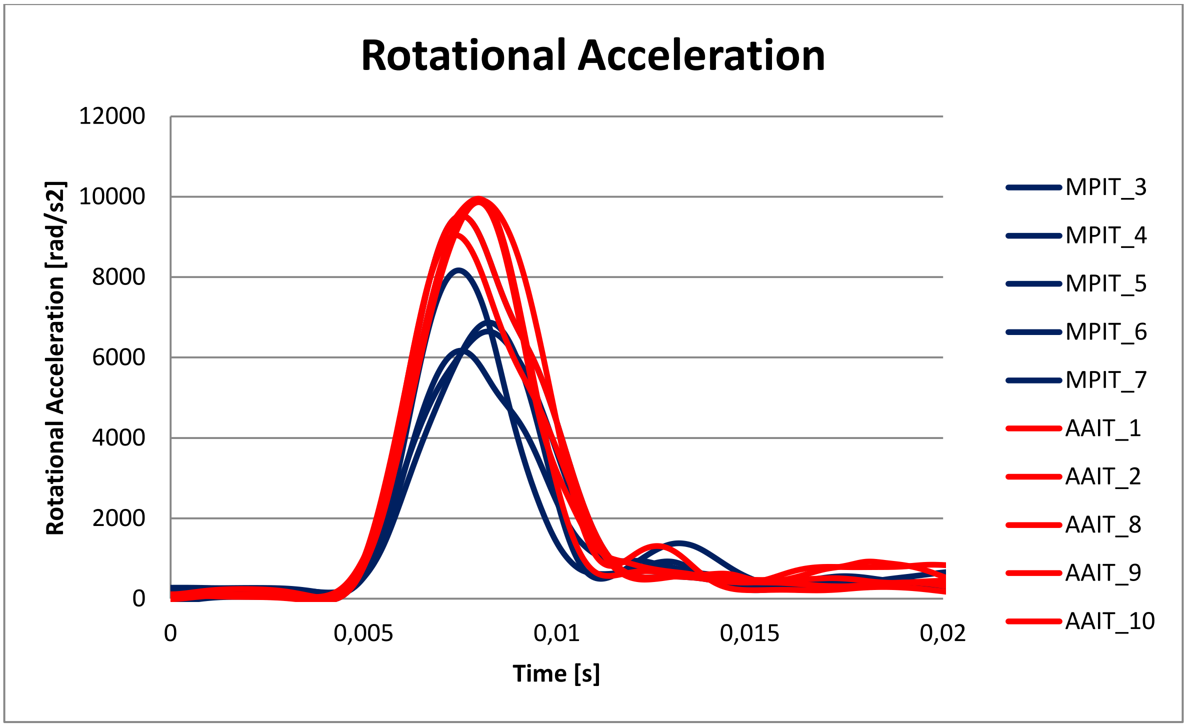


Figure 35 Rotational acceleration.

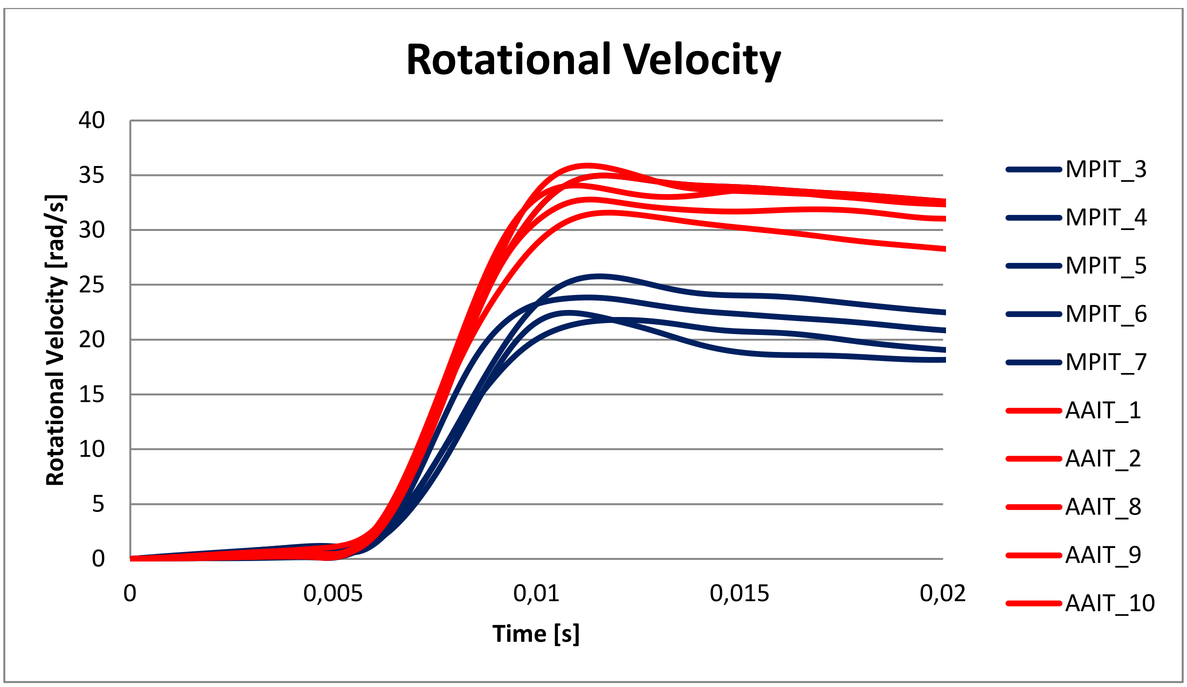


Figure 36 Rotational velocity.

With the obtained results it can be perceived how the supposed hypothesis occurs; the AAIT is characterized by showing higher values for all the measured velocities and accelerations. In this sense the question that rises is how to compare the impact scenarios so that they offer the same values and therefore establishing a relation between methods. Thus to try and give an answer to this situation a cost effective tool like performing a Finite element Analysis will provide the information necessary to reach the desired similarity between methods.

3.3 Finite Element Analysis

After performing the first set of simulations on the FEA at an impact velocity of $5\frac{m}{s}$ in the AAIT Figure 37 shows the stress sustained by the helmet can be assessed (represents stress levels approximately at 0.0139 seconds after impact and the fringe levels represented in red ranged from $3{,}01e^{+6}$ to $2{,}70e^{+6}$).

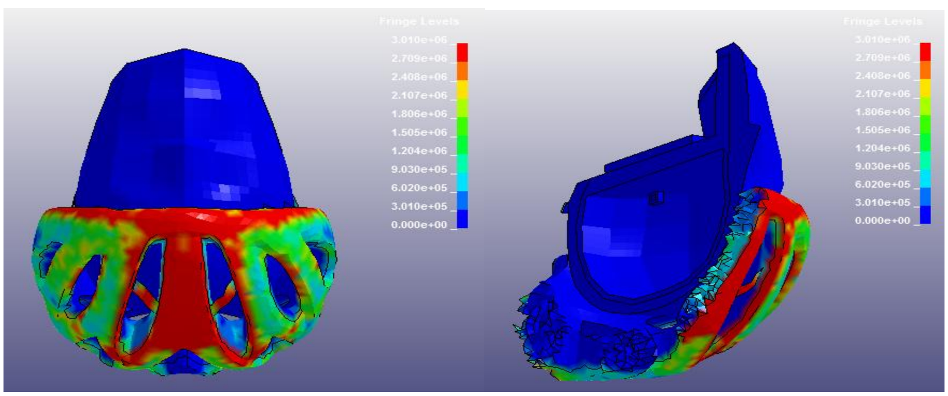


Figure 37 Von Misses stress for impact at 5mps (top: front view, Bottom: lateral view).

Following these simulations another set was performed under the same condition but altering the velocity at impact from $5\frac{m}{s}$ to $6\frac{m}{s}$; results are shown in table 5.

Figure 38 represents the Von Misses stress levels experienced by the helmet during the first set of simulations for the MPIT tests; these values are represented at similar time frame and fringe levels as the previously performed AAIT simulations and correspond to an impact velocity of $6\frac{m}{s}$. A second set of simulations at $7{,}6\frac{m}{s}$ was also performed and results are shown in table 5.

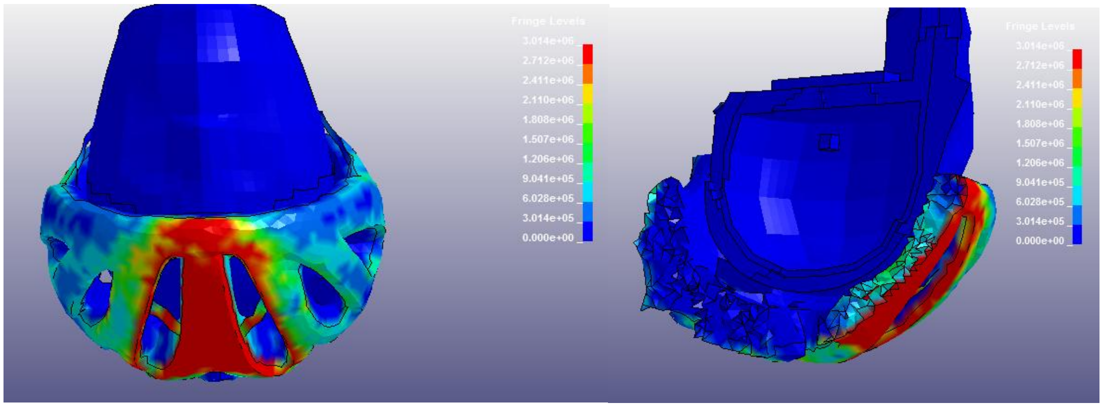


Figure 38 Von Misses stress levels for impacts on the MPIT device.

The following table shows the resultant values for the analyzed impact scenarios.

Type of simulation	Peak value resultant translational acceleration [g]	Peak value for resultant rotational velocity$[\frac{rad}{sec}]$	Peak value for resultant rotational acceleration $[\frac{rad}{sec^2}]$
$5\,\frac{m}{sec}$ 45° AAIT	102,06	18,89098	4589,820
$6\,\frac{m}{sec}$ 45° AAIT	128,70	24,04694	6249,907
$6\,\frac{m}{sec}$ 45° MPIT	141,34	18,29484	5620,625
$7{,}6\,\frac{m}{sec}$ 30° MPIT	123,84	25,73384	6609,294

Table 5 Results for Peak maximum values after conducting the FEA of the different scenarios.

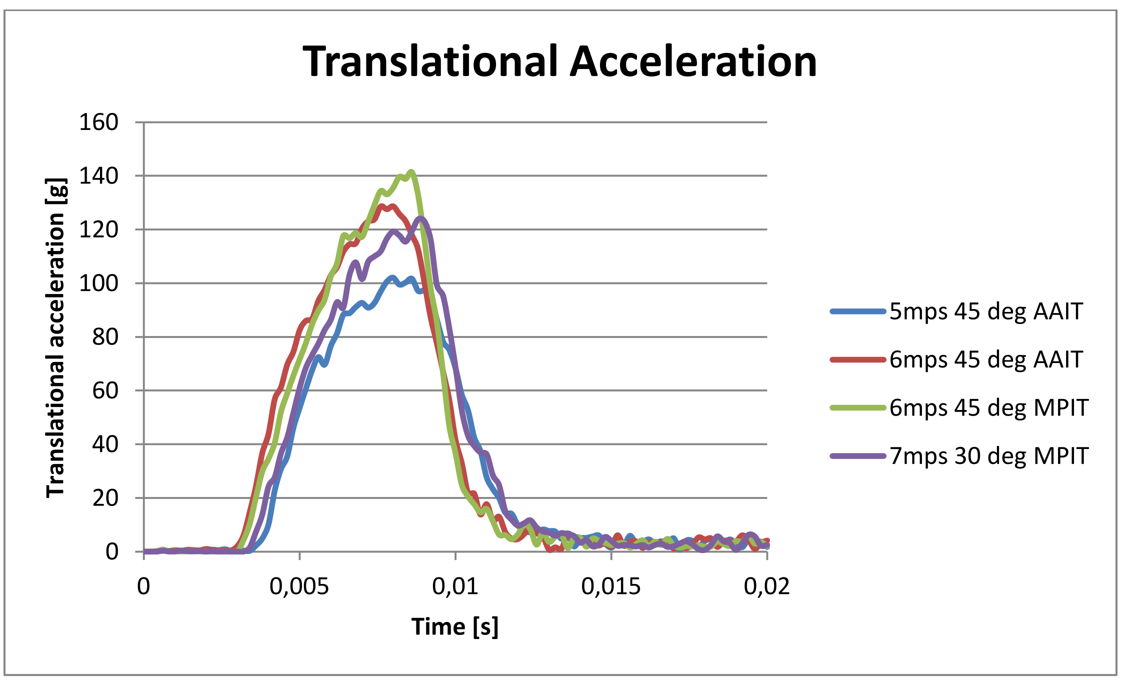


Figure 39 Translational acceleration obtained from the FEA simulations.

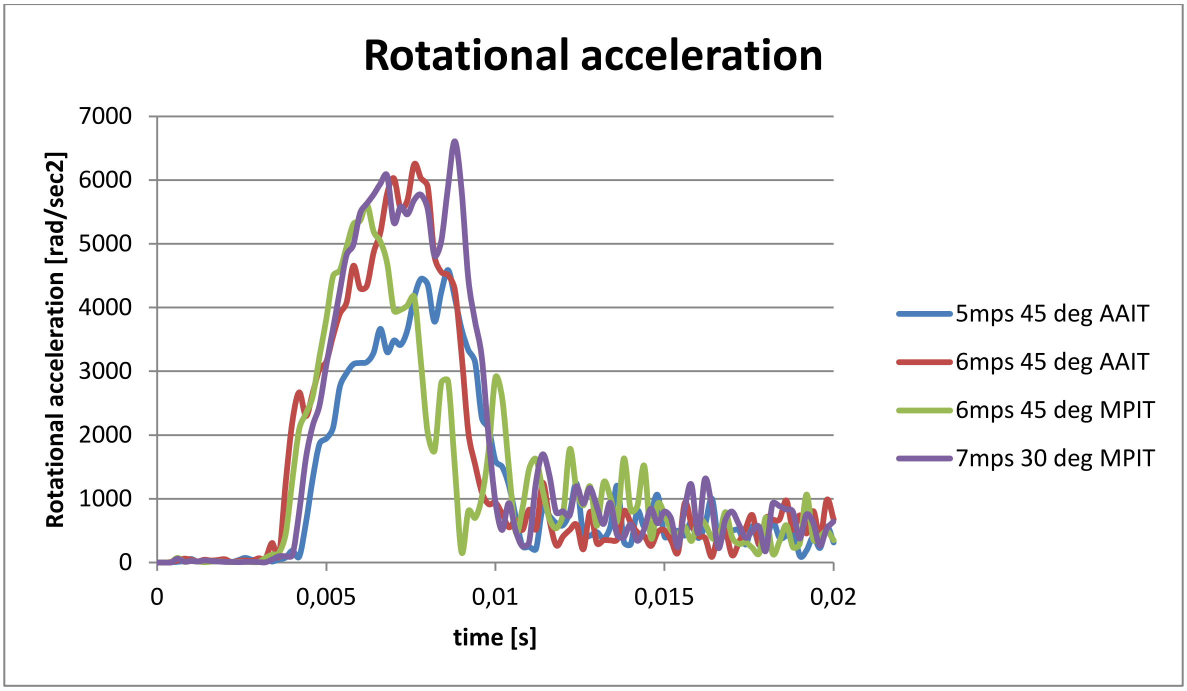


Figure 40 Rotational acceleration obtained from the FEA simulations

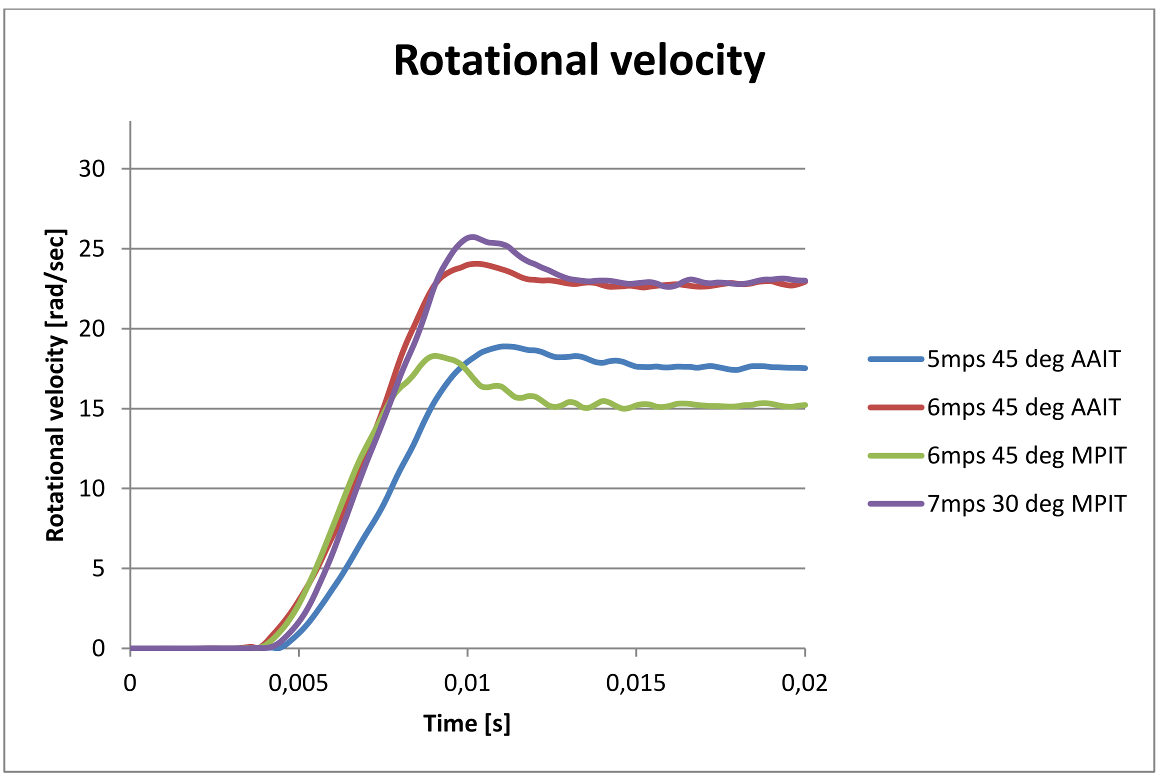


Figure 41 Rotational Velocity obtained from the FEA simulations.

As it can be seen in table 5 the best correlation between methods (least data dispersion) occurs when the AAIT is submitted to impact situations of $6\frac{m}{s}$ and 45° meanwhile the MPIT is conducted under a scenario of 7,6 $\frac{m}{s}$ and 30˚. The next step in then to try to asseverate this newly obtained information by performing experimental impact tests under the scenarios described by the FEA.

3.4 Experimental tests derived from FEA results

When the similarity between methods was obtained with the FEA, experimental tests carrying out these specific situations were conducted showing the following results:

NAME	TRANS. ACC. [g]	ROT. ACC. [krad/s^2]	ROT. VEL. [rad/s]
MPIT_19	134,2	10,7	29,9
MPIT_20	131,7	10,2	30,3
MPIT_21	123,3	9,9	31,8
MPIT_22	136,2	10,2	29,1
Mean	131,4	10,25	30,28
AAIT_1	155,6	9,9	34,1
AAIT_2	155,3	9,9	32,8
AAIT_8	139,6	9,5	35,0
AAIT_9	155,3	9,9	35,9
AAIT_10	140,4	9,0	31,6
Mean	149,24	9,64	33,8

Table 6 Experimental testing relating to values of FEA simulation.

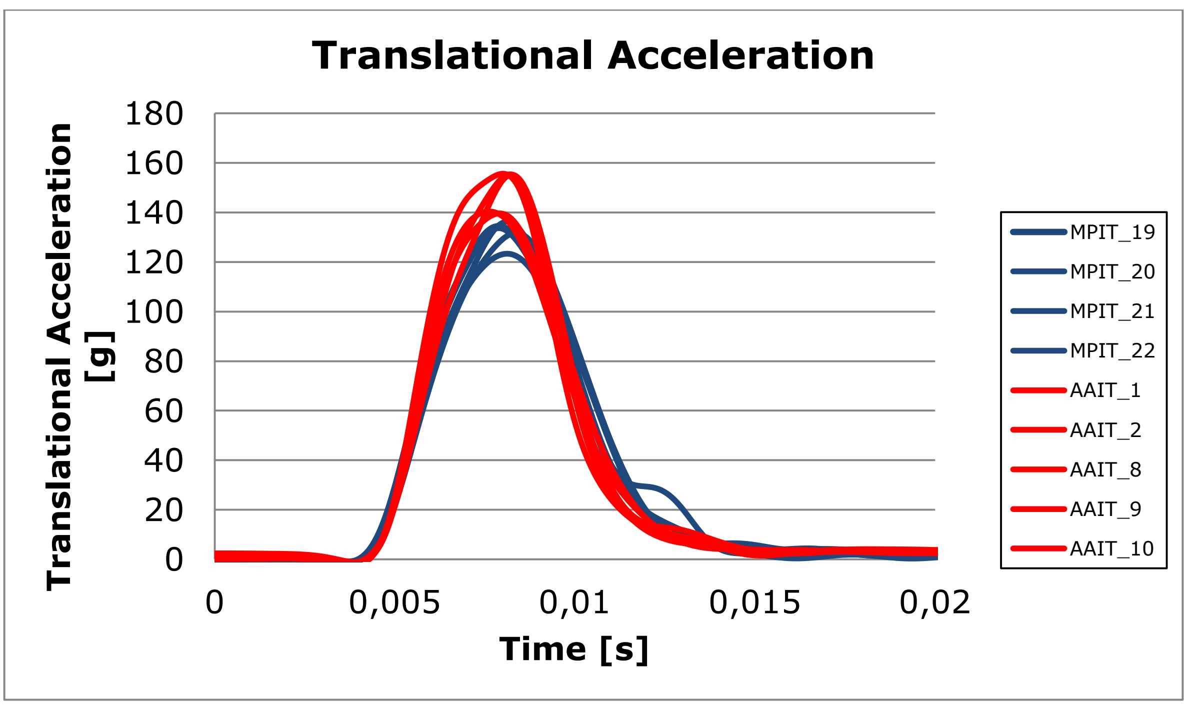


Figure 42 Translational acceleration related to FEA simulations.

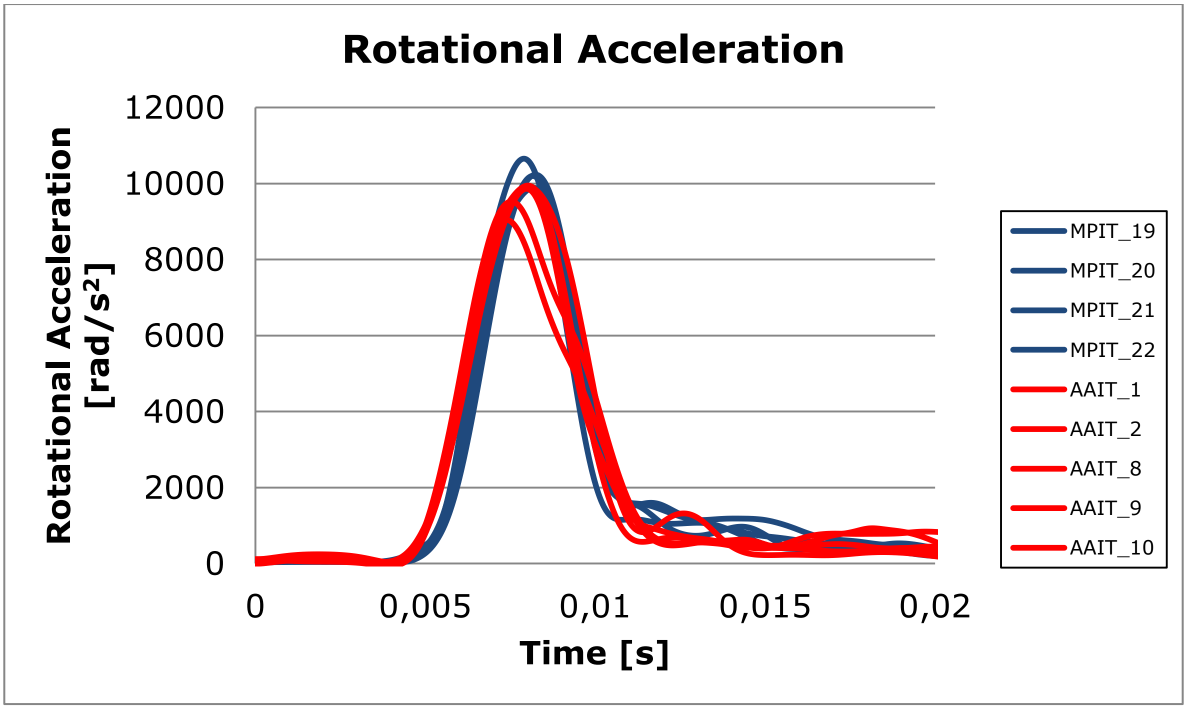


Figure 43 Rotational acceleration related to FEA simulations.

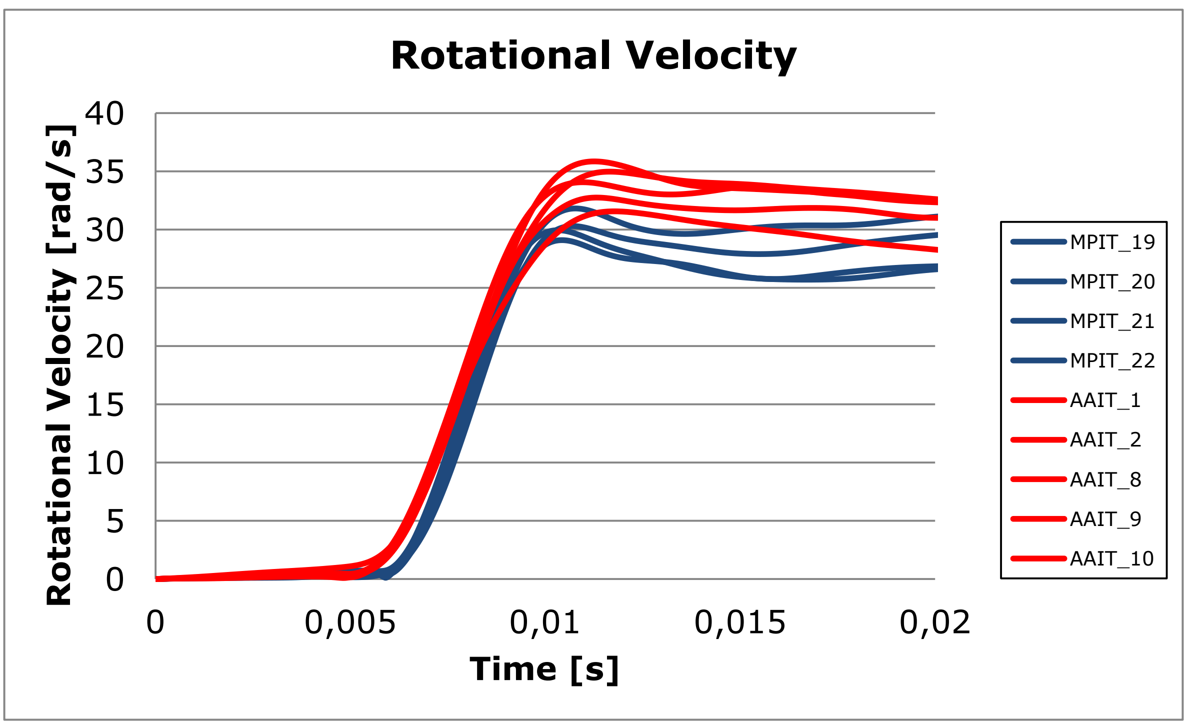


Figure 44 Translational Velocity related to FEA simulations.

With the experimental test performed it can be observed how the data is less dispersed than the previously performed impact test where both methods had a velocity of impact of $6\frac{m}{s}$ and 45˚.

However from the newly obtained plots it can still be appreciated a difference between the obtained data from both test methods; this suggest that changes can be made experimentally in order to adequate the impact scenario until a better fit can be achieved.

4 Discussion

The main purpose of this chapter is to analyze the results and provide an explanation on how those results were obtained commenting about them.

4.1 Discussion of standards and regulations

The current standards only evaluate the performance of helmets regarding translational energy neglecting the rotational component of the impact closely related to injuries like DAI, SDH and MTBI (McKhann, 2004), making the assessment of helmet protection and safety insufficient.

From a general comparison the ECE 22.05, EN1077, EN 1078, EN 1080 and EN 1384 are the ones not to adopt a ball-joint fixation system in order to carry out testing system (Ghajari, et al., 2008); therefore a guided free fall constitutes a valuable advantage for the development of a new test rig that can be used to measure rotational forces by impacting an inclined anvil and inducing rotation instead of utilizing the pre-described flat and kerbstone anvils.

Although most of the standards disregard the presence of the rotational components the British Standards and the ECE 22.05, present oblique impact tests however they are also considered insufficient by failing to acknowledge the effects of the neck and torso which will inevitably restrict the movement due to the anatomy of the segment and usually their presence decrease the loading impacts and rotational forces (Snell Memorial Foundation, 2005)

Therefore none of the standards comply to what reality predicts; ECE 22.05, EN 1077, EN1078, EN 1080 and EN 1384 assume a completely free fall head-form drop scenario simulating and over condition of the situation where the neck and body have no effect (no mass) and the Snell, DOT and British Standards simulate an infinite mass of the neck and torso assuming no movement other than translational or restricting the rotational effect like the British standard.

There are several other testing standards and regulations like the Australian Standard 1698-1988, 'Protective Helmets for Vehicle Users, BS 6658:1985 Specification for protective helmets for vehicle users, the New Zealand Standard NZ 5430, Protective helmets for vehicle users; the North American (USA) DOT FMVSS 218 and lastly the Japan Industrial Standard T8133, that even though share the basic principles of the other previously mentioned standards, adapt their testing methods to specific norms according to their countries policies and have the characteristic of containing different thresholds values for pass or fail criterions which means that some helmets may be approved by one standard but rejected by another. This gives space to important discussion elements like wondering which is better or which is more realistic.

An inexistent universally approved and validated standard accounting for all the deficiencies of the previously exposed regulations for helmet manufacturing constitute a sense of worry to a user who could asks himself what helmet to buy and according to what standard is approved leaving a valuable leeway for improvement.

4.2 Regarding cost

In title 3.1 some of the factors that influence the cost of the project were demonstrated with the use of an Ishikawa diagram; by proposing solutions to these issues the problem of high costs was dealt with. Table 7 shows the discussion after the analysis of the factors.

Cause	Solution
1) Since in the market there are few options for acquiring the test rig, the leverage of negotiation for lower prices decreases	Since it was decided to request for specific parts for the machine, more specific quotes were requested increasing the market of suppliers not only from the specialized helmet drop test companies but from other metal workers, this gives leverage in negotiating lower prices
2) Installation of the device includes extra Expenses pertaining to accommodation and travel tickets for the specialized personnel, and future maintenance Or repairs for the machine	There is no need for a specialized technician since the whole set up will not be necessary, therefore this cost disappears.
3) Suppliers are not located within Sweden therefore shipping expenses arise.	The plan is to request specific parts therefore the size of the package decreases and the same happens with the shipping expenses.
4) Only few suppliers follow the appropriate Drop test rig idea restricting even more the variety in the market	By purchasing specific parts and adapting the rest the oblique test rig was constructed and this issue is solved.
5) Purchase of attachments and parts to solve different problems that may appear	By utilizing the extra material in the workshop considered scrap or spare and adapting them to the test rig, this cost was dissipated.
6) Specific parts could not be available in the Swedish market therefore there is a need of looking in the external European market	This would increase the cost of the project but the solution for problem 5 was adequately applied in this case as well and no extra cost occurred.

7) Since a test rig for measuring the rotational forces is not mandatory by law, modifications must be performed on externally acquired machines.	This means basically the machine has to be custom made or custom adapted in this sense with the help of the mechanical workers of the workshop inventive solutions to fix the problems were explored.

Table 7 Proposed solutions to the cause effect diagram.

Also the choice of making a hybrid device was analyzed through a CBA or cost benefit analysis which shows that this decision was the most appropriate for undergoing the project (refer to Table 3).

There are some drawbacks of utilizing a tool like a Cost benefit analysis, such as:

- Is hard to identify all existing costs and benefits;
- Is problematic to give a monetary value to terms like "complicated or less complicated" making it hard to estimate the overall results;
- Is difficult to estimate future costs or benefits due to the fact that estimating future interest rates and possible scenarios is a troublesome task but nonetheless it can be based on estimates.

Nonetheless after deciding the strategy, if compared to purchasing of the whole device from the vendors either in Canada or Italy savings close to ≈ 442.749 SEK and ≈363.173 SEK respectively were achieved.

4.3 Regarding testing method

To comply with the main goal of this project tests were performed in both the MPIT and the AAIT. The first sets of tests were submitted to impacts with a velocity at impact of approximately $6\frac{m}{s}$. There are several reasons of why this specific speed; chiefly the height of the AAIT impedes the opportunity of achieving higher speeds, unless the height of the drop tower is increased in which case is not physically possible due to the ceiling limit. Another reason is due to the fact that this speed complies with a media velocity of impacts for bicycle helmet testing and equestrian helmet (even though they could be evaluated with a higher speed);

The testing method is then meant to be able to test all types of helmets; even motor bicycle helmets can also be tested and studied the behavior of the impact (although the speed of impact is significantly higher refer to Table 2).

The evaluation between the AAIT and the MPIT show results that differ greatly when tested at the same velocities before impact this is directly related to impact condition as it was shown in subtitle 1.7.

4.3.1 Comparison between testing methods

Several problems appeared at the moment of testing for example: keeping the velocity of the plate constant during the MPIT testing phase; which in turn means that when testing for a resultant vector of $6\frac{m}{s}$ the angle of impact differs from 45˚ disrupting the comparable scenario; this is caused by the fact that friction forces play a part in the sliding of the plate; the rubber wheels on which the plate slides may sometimes come off the axis element decreasing the speed of the plate.

Figure 19 and Figure 20 serve to asseverate what can intuitively be known with a little knowledge of physics; in the AAIT test rig due to the impact situation several forces contribute to the rotation of the head-form; the normal force, and the weight of the helmeted head-form induce the movement of rotation aided by the moment produced by the tangential force results in moments around the "+Y" axis which in turns translate into rotational movement; in contrast the MPIT device produces a positive moment in the "+Y" axis due to the tangential force but due to the location of force "weight of the center of mass" the moment of the head is produced in the negative "-Y" axis this decreases the capacity of intrinsic rotation of the head-form, so comparing the forces that promote the movement it was logical to expect lower values with the MPIT (Table 4).

In this sense in order to obtain similar results in both of the testing methods the specifications in which the impact situations take place must be different, therefore the options available are to simply increase the force in which the plate impacts the head-form; this is performed by increasing the speed of the sliding plate with the consequence of altering the angle of impact from 45˚ to a reduced resultant angle (refer to section 4.4).

Comparing the two methods seems complicated because they offer different alternatives and different impact situations, consequently deciding on which method is better is a hard task to take; they both have advantages and drawbacks seen on Table 8.

AAIT test rig vs MPIT test rig	
Advantages	Drawbacks
-The AAIT rig is more ergonomical than MPIT test rig (refer to 4.5)	- In the AAIT the angles of impact cannot be altered unless new impact anvils are designed, whereas in the MPIT test rig they can be custom to the situation just by shifting the velocity of the sliding plate
-The impact situation for the AAIT rig is more simple to evaluate than that of the MPIT test rig; less variables take place	- The velocity of impact in the AAIT test rig is subjected to a maximum of $6\frac{m}{s}$ due to height restrictions, the restrictions of the velocity for MPIT test rig depends on the capacity of the pneumatic piston

-The AAIT test rig can be easily handled by one person whereas the MPIY test rig is harder to maneuver by one person.	- The MPIT test rig is better suited to represent crashing against cars simulation where not only the head-helmet is moving but the other entity to which is crashing is moving as well.
-The AAIT rig possesses a catching systems for after the impact, the MPIT test rig has to be seized by the user	- The MPIT is more realistic in simulating falls to the ground (like a single bike accident) due to the fact that the normal force is perpendicular to the impact whereas in the AAIT this is not the case.

Table 8 Comparison between oblique testing methods.

In essence the testing devices and testing methods are meant to give estimations of the severity impact situations and the chances of those situations producing a traumatic brain injury. According to Table 1 an estimate of a brain injury can be addressed to the utilized helmet where the peak value recorded for the MPIT was ranging around 8.2 $\frac{krad}{s^{-2}}$-9.5 $\frac{krad}{s^{-2}}$ meaning there is a chance of the ocurrance for a concussion; the same can be said regarding the AAIT test rig where the peak resultant rotational acceleration was of 9.9$\frac{krad}{s^{-2}}$ where a mild traumatic brain injury could be sustained by the user.

4.4 Comparison with finite element method

The experiments conducted with the finite element analysis showed that the best correlation between methods for this specific impact point is performing tests on the AAIT test rig at 6 $\frac{m}{s}$ and angle of 45 degrees versus a resultant vector of 7,6 $\frac{m}{s}$ at a 30 degree angle on the MPIT. This correlation is only acceptable for the current impact simulation if on the other hand the impact point is change the forces acting in the helmet-headform-anvil/sliding plate, will change and produce different values since the moments around the "Y" axis will undoubtedly vary.

By performing these tests experimentally on both of the test rigs the results shown in table 6 are obtained.

In Figure 42 Figure 43 Figure 44, it can be noticed how the data adapts better than when the testing was performed on the similar conditions dictated by the AAIT test rig (6 $\frac{m}{s}$ and 45 degrees); the data suggest that the rotational acceleration correlates adequately but the translational acceleration is still lower when compared to the AAIT free fall drop tests and does not correlate perfectly, this could be due to several reasons for example the fact that the sliding plate was not able to maintain a horizontal speed of 6,6 $\frac{m}{s}$ because of reasons like the rolling wheels coming out the rolling axis and the pneumatic piston oscillating its performance, but more importantly than the horizontal velocity, the vertical velocity also varied affecting the resultant vector which will not meet the ideal $7{,}6\frac{m}{s}$ which in turns decreases the resultant translational acceleration. It is complicated to maintain specific horizontal and vertical speeds on the MPIT device and small variances are always expected.

On the other hand the rotational velocity shows a good correlation but not a perfect one, this could be due to fact that since the horizontal and vertical speed oscillated the resultant angle of impact differ from the expected 30 degrees stipulated by the simulation and the impact point could have shifted affecting the resultant values; nonetheless the data fits with an standard deviation(σ) of σ=0,45 for the rotational acceleration and σ=2,33 for the rotational velocity improving the previous σ=1,48 for rotational acceleration and σ=5,67 for the rotational velocity when compared at $6\frac{m}{s}$ and 45 degrees. The previous issues could be solved by increasing the dropping height of the MPIT in which case the translational acceleration would increase adjusting to values more similar to the ones obtained in the AAIT test rig. And is also important to reiterate that the this correlation of results is dependent on the impact point; if the impact point changes then the impact scenario changes and this situation defined by the FEA might not be adequate.

4.5 Ergonomic assessment

In order to complement the analysis between these two helmet testing methods an extra point of study is to demonstrate the ergonomical benefits that the new test rig offers. Ergonomic assessments are performed with the intention to study workplace environment and attempt to reduce musculoskeletal diseases that could be contracted during day to day work situations.

For this task two very simple yet worldwide practiced ergonomic tools were utilized; known as the Rapid Entire Body Assessment (REBA) this tool was specifically designed to be sensitive to unpredictable working postures in the area of Healthcare and other business; it is aimed to (Hignett & McAtamney, 2000):

- Analyze postures sensitive to musculoskeletal risks during the performance of the task
- Provide a scoring system for muscle activity caused by static, dynamic, rapid changing or unstable postures.
- Study the effect of the handling of loads.
- Give an indicatory of urgency of changing the working environment
- Require minimal equipment just a form on which to base the study.
- The study of Hignett and McAtamney reported a validity for the tool ranging from 62%-85% for 14 studied users

The Second ergonomic tool is very similar to REBA and it has by name Rapid Upper Limb Assessment (RULA) developed to investigate workplaces where work related upper limb disorders are reported; its aims are to (McAtamney & Corlett, 1993):

- Provide quick assessment of postures for upper limbs, neck and trunk.
- Study the effect of muscle function and external loading experience by the body
- It utilizes a scoring system that generates an action list depending on the risk of injury for the operator
- No professional tools are requires just the RULA assessment form.
- It was validated in a statistical analysis conducted by McAtamney and Corlett.

The ergonomic assessment was carried out on a working scenario of setting the helmet in the dropping carriage and taking the measurements of the impact points on both test rigs Annex A1 shows the working task analyzed and the analysis performed on the REBA and RULA worksheet.

The MPIT test rig scored a 10 in the REBA analysis and a 7 in the RULA which means that the posture is correlated with a “high” risk for musculoskeletal diseases and there must be an investigation of the process so that to implement changes; by elevating the helmet dropping basket on each test a better posture can be achieve and avoid straining the knees however it could make the process tedious and time consuming. On the other hand the new AAIT test rig scored a 3 in the REBA and a 5 in the RULA which correlates to “low” risk for contracting musculoskeletal injuries but nonetheless changes to posture could be necessary in the future.

5 Conclusions

- On the subject of cost of the project the implemented strategy for reducing costs was successful. By utilizing valuable tools like a system of procurement engineering, an Ishikawa diagram to analyze the main contributors to higher costs and a cost benefit analysis the option of building the new test rig based on a hybrid of parts supplied from an external vendor, parts and attachments developed in the workshop and acquiring parts in the Swedish markets demonstrated to be the accurate path for completing the assignment.
- Regarding the evaluation between methods it can be said that they both serve purposes of measuring the rotational effects on the head during an impact, making an assessment on which one is better is a hard task since it was proven how they both manage the impact situation with different characteristics, however it can be said that the newly constructed device is easier to manage by one user and easier to control since less variables are involved, plus is also a more ergonomical solution.
- Regarding the utilization of a finite element analysis simulation it was determined that the best correlation between tests methods for the specific analyzed scenario, is that of an impact situation of $6\frac{m}{s}$ and angle of 45 degrees on the AAIT test rig versus a resultant vector of $7{,}6\frac{m}{s}$ at a 30 degree angle on the MPIT, this was corroborated by performing experimental tests in which the results concur with the FEA but show that it could be possible to achieve a better fit by increasing the dropping height in which case the translational acceleration will increase adjusting to the values obtained in the AAIT test rig, this action will undoubtedly increase the resultant velocity vector affecting the resultant angle of impact.
- On a general conclusion a different testing method has been evaluated demonstrating is a simple, robust and cost effective method, where the interchangeability aspect of the angle of the anvils makes the test rig adjustable to several helmet segment testing situations (Ski, bicycle, skateboard, roller skating, motorcycling, equestrian etc) complying with the different accident data reconstruction pertaining to each case.

6 Recommendations for future studies

- The inclusion of the neck is still a variable to take into consideration, studies regarding the utilization of this segment must be performed to analyze its impact on the drop test; the neck gives an opportunity for an easier fixation at the moment of dropping the head during a free fall helmet test (Halldin & Kleiven, 2013). This results in necessary modifications to the current AAIT to accommodate the neck fixation.

- A study utilizing a FEA with the Biltema helmets would provide a good source of analysis against the experimentally performed tests, in order for that to be achieved a modeling of the helmet must be executed
- Encouragement for others to perform tests utilizing the same concept as the newly built AAIT test rig is recommended so that results can be compared and performance reliability can be measured, this also provides more foundation on including the measurement of rotational forces at the moment of impact in the current standards and regulation.
- A study regarding a threshold on injury parameters must be carried out and validated, a consensus on a specific limit/pass fail criteria for rotational acceleration values would provide a better source of analysis and conduce to an improve helmet manufacturing process.
- Another possible future study could be based on the disregarded issue of not considering the presence of the hair which could decrease the friction between the helmet and head therefore making the helmet absorb more of the rotational forces decreasing the magnitudes currently obtained.
- A further improvement and analysis to both testing methods is regarding the area of helmeted head-form/dropping basket fixation at the moment of impact especially concerning the AAIT. In this sense a fixation device can be implemented so that the variety of impact locations is determined by the user and not by the limitations of the machine. By performing this study a wider knowledge on the effect of impact location can be obtained and an upgrading to helmet development can be reached by creating specialized devices capable to protect those areas that are the most affected.

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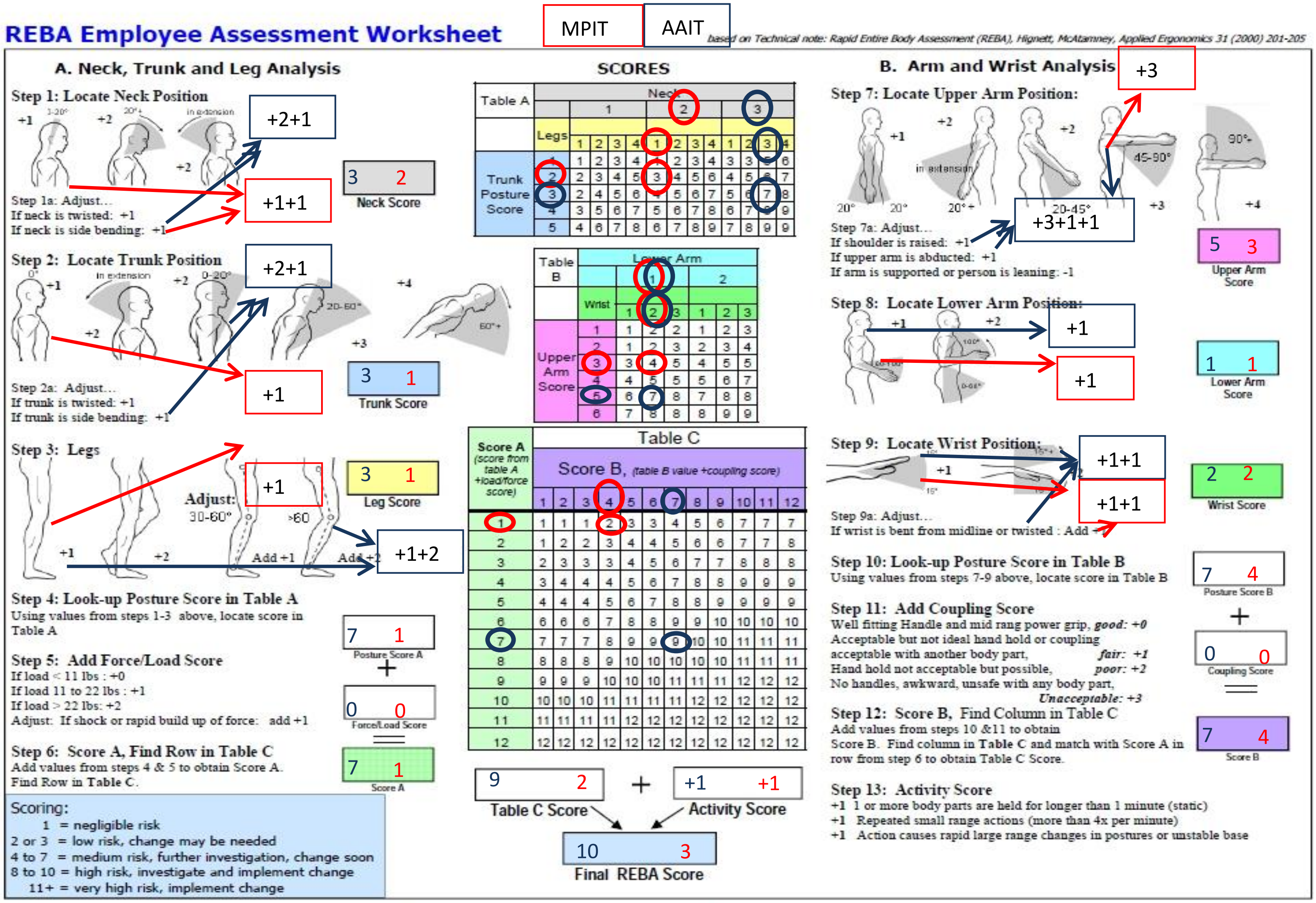
8 Appendix

Appendix A An ergonomical assessment of the helmet allocation

Appendix 1 Helmet allocation in both test rig, upper figures relates to MPIT device, bottom figure AAIT test rig.



REBA Employee Assessment Worksheet

MPIT | AAIT

based on Technical note: Rapid Entire Body Assessment (REBA), Hignett, McAtamney, Applied Ergonomics 31 (2000) 201-205

A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 10-20° +2 20°+ +2 in extension

+2+1

Step 1a: Adjust…
If neck is twisted: +1
If neck is side bending: +1

+1+1

3 2 Neck Score

Step 2: Locate Trunk Position

0° +1 in extension +2 0-20° +2 20-60° +3 60°+ +4

+2+1

Step 2a: Adjust…
If trunk is twisted: +1
If trunk is side bending: +1

+1

3 1 Trunk Score

Step 3: Legs

+1 +2 Adjust: 30-60° Add +1 >60 Add +2

+1

+1+2

3 1 Leg Score

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above, locate score in Table A

7 1 Posture Score A

+

Step 5: Add Force/Load Score
If load < 11 lbs : +0
If load 11 to 22 lbs : +1
If load > 22 lbs: +2
Adjust: If shock or rapid build up of force: add +1

0 0 Force/Load Score

=

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in Table C.

7 1 Score A

Scoring:
1 = negligible risk
2 or 3 = low risk, change may be needed
4 to 7 = medium risk, further investigation, change soon
8 to 10 = high risk, investigate and implement change
11+ = very high risk, implement change

SCORES

Table A

Table A	Neck	1				2				3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

Table B

Table B	Lower Arm	1			2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Table C

Score A (score from table A +load/force score)	Score B, (table B value +coupling score) 1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

9 2 Table C Score + +1 +1 Activity Score

10 3 Final REBA Score

B. Arm and Wrist Analysis

+3

Step 7: Locate Upper Arm Position:

+1 20° 20° in extension +2 20°+ +2 20-45° +3 45-90° +4 90°+

Step 7a: Adjust…
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

+3+1+1

5 3 Upper Arm Score

Step 8: Locate Lower Arm Position:

+1 60-100° +2 100°+ 0-60°

+1

+1

1 1 Lower Arm Score

Step 9: Locate Wrist Position:

+1 15° 15°+ +2

+1+1

Step 9a: Adjust…
If wrist is bent from midline or twisted : Add +1

+1+1

2 2 Wrist Score

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

7 4 Posture Score B

+

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, *good: +0*
Acceptable but not ideal hand hold or coupling acceptable with another body part, *fair: +1*
Hand hold not acceptable but possible, *poor: +2*
No handles, awkward, unsafe with any body part, *Unacceptable: +3*

0 0 Coupling Score

=

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in Table C and match with Score A in row from step 6 to obtain Table C Score.

7 4 Score B

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Task name: Review of helmet positioning Reviewer: Christian Carnevale Date: 17 / 8 / 2014

provided by Practical Ergonomics
rbarker@ergosmart.com (816) 444-1667

This tool is provided without warranty. The author has provided this tool as a simple means for applying the concepts provided in REBA.

Appendix 2 REBA assessment for helmet allocation.

RULA Employee Assessment Worksheet

based on RULA: a survey method for the investigation of work-related upper limb disorders, McAtamney & Corlett, Applied Ergonomics 1993, 24(2), 91-99

MPIT AAIT

A. Arm and Wrist Analysis

Step 1: Locate Upper Arm Position: +3

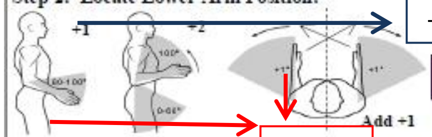
Step 1a: Adjust…
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

+3+1+1

5 3
Upper Arm Score

Step 2: Locate Lower Arm Position:

+1



Add +1

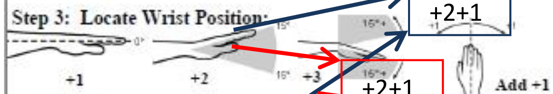
1 2
Lower Arm Score

Step 2a: Adjust…
If either arm is working across midline or out to side of body: Add +1

+1+1

Step 3: Locate Wrist Position:

+2+1



+2+1

Step 3a: Adjust…
If wrist is bent from midline: Add +1

3 3
Wrist Score

Step 4: Wrist Twist:
If wrist is twisted in mid-range: +1
If wrist is at or near end of range: +2

+1 +1
Wrist Twist Score

Step 5: Look-up Posture Score in Table A:
Using values from steps 1-4 above, locate score in Table A

5 4
Posture Score A

+

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

+1 +1
Muscle Use Score

+

Step 7: Add Force/Load Score
If load < 4.4 lbs (intermittent): +0
If load 4.4 to 22 lbs (intermittent): +1
If load 4.4 to 22 lbs (static or repeated): +2
If more than 22 lbs or repeated or shocks: +3

0 0
Force/Load Score

=

Step 8: Find Row in Table C
Add values from steps 5-7 to obtain
Wrist and Arm Score. Find row in Table C.

6 5
Wrist & Arm Score

SCORES

Table A: Wrist Posture Score

Upper Arm	Lower Arm	1 Wrist Twist 1	1 Wrist Twist 2	2 Wrist Twist 1	2 Wrist Twist 2	3 Wrist Twist 1	3 Wrist Twist 2	4 Wrist Twist 1	4 Wrist Twist 2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Table C: Neck, trunk and leg score

Wrist and Arm Score	1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

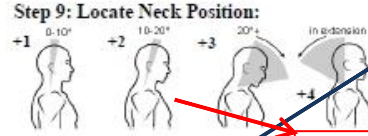
Scoring: (final score from Table C)
1 or 2 = acceptable posture
3 or 4 = further investigation, change may be needed
5 or 6 = further investigation, change soon
7 = investigate and implement change

7 5
Final Score

B. Neck, Trunk and Leg Analysis

+4+1

Step 9: Locate Neck Position:



5 3
Neck Score

Step 9a: Adjust…
If neck is twisted: +1
If neck is side bending: +1

+2+1

Step 10: Locate Trunk Position:

+2+1

3 1
Trunk Score

Step 10a: Adjust…
If trunk is twisted: +1
If trunk is side bending: +1

+1

Step 11: Legs:
If legs and feet are supported: +1
If not: +2

1 1
Leg Score

Table B: Trunk Posture Score

Neck Posture Score	1 Legs 1	1 Legs 2	2 Legs 1	2 Legs 2	3 Legs 1	3 Legs 2	4 Legs 1	4 Legs 2	5 Legs 1	5 Legs 2	6 Legs 1	6 Legs 2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B:
Using values from steps 9-11 above,
locate score in Table B

7 3
Posture Score B

+

Step 13: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

1 1
Muscle Use Score

+

Step 14: Add Force/Load Score
If load < 4.4 lbs (intermittent): +0
If load 4.4 to 22 lbs (intermittent): +1
If load 4.4 to 22 lbs (static or repeated): +2
If more than 22 lbs or repeated or shocks: +3

0 0
Force/Load Score

=

Step 15: Find Column in Table C
Add values from steps 12-14 to obtain
Neck, Trunk and Leg Score. Find Column in Table C.

8 4
Neck, Trunk & Leg Score

Task name: Review of helmet positioning Reviewer: Christian Carnevale Date: 17 / 8 / 2014

provided by Practical Ergonomics

Appendix 3 RULA assessment for helmet allocation