# Predicting Mild Traumatic Brain Injury with Injury Risk Functions

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## ABSTRACT

To assess the safety of various products, equipment, and vehicles during traumatic events injury risk curves have been developed correlate measurable parameters with risk of injury. The first risk curves to predict head injuries focused on severe head injuries such as skull fractures. These curves were generated by impacting cadaver heads. To understand the biomechanics of mild traumatic brain injuries, cadaver heads have also been used to monitor pressure and strain in the brain during impacts. Live animal models have been used to understand the physiological response of the brain to impact to create thresholds for mild traumatic brain injuries such as concussions. These results have been scaled to humans. To generate injury risk curves from live human models, impacts from games in the NFL have been reconstructed in the laboratory. Helmets of NCAA football players have also be instrumented with accelerometers to collect all impacts during a season resulting in the development of injury risk curves that predict concussion as a function of both linear and rotational acceleration. These risk curves provide researchers with a better understanding of the efficacy of various safety systems and give insight as to how safety systems can be improved.

Key Words: Injury risk, head injury, skull fracture, concussion, football impact

## INTRODUCTION

Injury risk curves are used to predict the likelihood of injuries caused by traumatic events. To generate curves that predict the risk of injury, injuries have been induced in cadavers, animal models, and volunteers. Various parameters such as linear acceleration, rotational acceleration, pressure, and strain have been measured to generate a curve that predicts the risk for injury as a function of these measurable parameters. The following is a summary of various injury risk curves that have been developed to predict injuries during traumatic events with a focus on head injuries.

In addition to the head, risk functions have been developed for various body regions including the eye, thorax, abdomen and extremities. The risk for ocular injuries such as hyphema, lens damage, retinal damage, and globe ruptures caused by projectile impacts or blast waves have been determined by impacting human cadaver eyes with projectiles and blast waves while measuring intraocular pressure.[1-3] Injury risk curves for the neck and thorax have been developed to predict injuries by measuring levels of neck bending and chest compression caused by blunt impact and quantifying the mechanical properties of rib bones.[4-6] Injury risk curves for abdominal and maternal tissues have been developed to predict the likelihood of injury to soft tissues in the abdominal cavity caused by traumatic loading by measuring the dynamic material properties of the tissues.[7,8] Mechanical properties of the bones in extremities have been quantified to predict injuries resulting from bending and compressive loading experienced during traumatic events.[9] All of these injury risk functions are used by researchers to evaluate the safety of products and vehicles by understanding the likelihood of injury during a traumatic event.

## HEAD INJURY RISK FUNCTIONS

Early research predicting traumatic brain injuries primarily focused on quantifying risk for severe head injuries such as skull fractures. Cadaver heads have been used to study tolerance and injury risk to traumatic impacts. Impacts of various magnitudes have been studied while measuring parameters such as linear acceleration, rotational acceleration, and intracranial pressure in order to produce injury risk curves. In 1997, Mertz developed an injury risk curve based on the Head Injury Criterion (HIC) which has been shown to accurately predict severe head injuries such as skull fractures.[10] The HIC value is defined as:

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

In order to more accurately predict injury, a 15 ms timespan is used for the HIC15 to ensure the most severe acceleration interval is used. Mertz et al published risk of AIS >= 4 and skull fracture injuries based on HIC15 (**Figure 1**). The HIC15 is the only commonly accepted head injury criterion in industry.

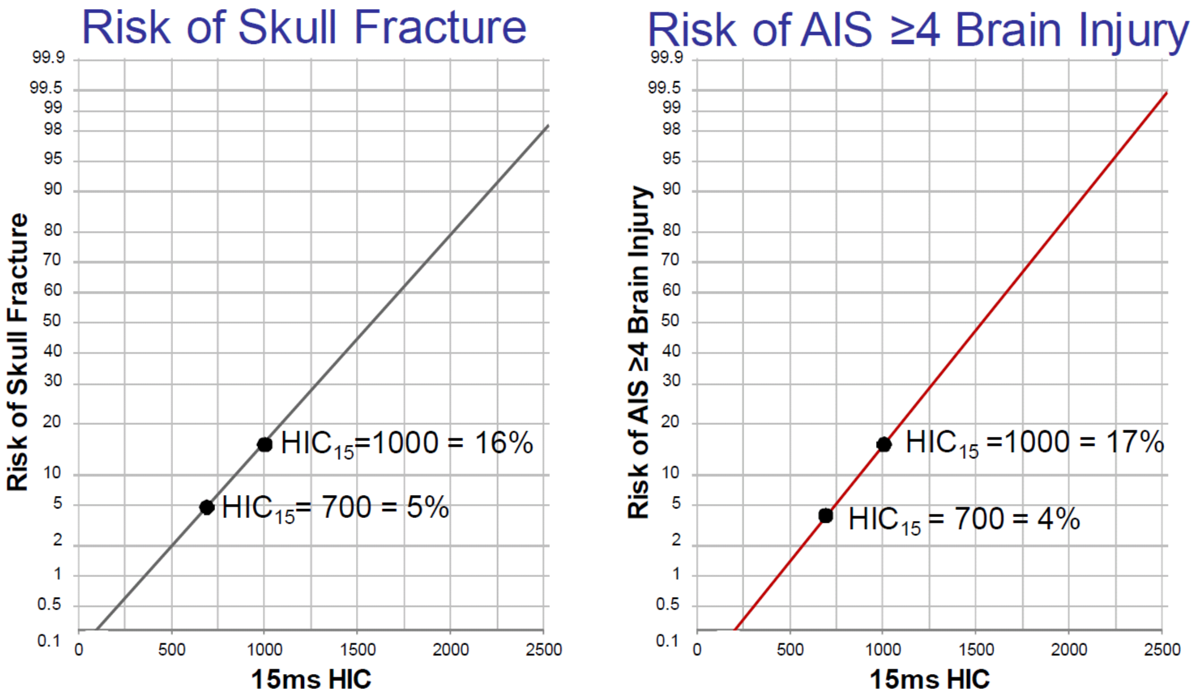

Figure 1. Metz et al. developed injury risk curves to predict skull fracture and AIS ≥4 brain injuries based on HIC15.

While the HIC15 has proven to be useful in mitigating severe head injuries, mild traumatic brain injuries, such as concussions, are not addressed. More recently, the biomechanics of mild traumatic brain injuries have been studied by analyzing the effects of linear and rotational acceleration on human brains. In 2007, Hardy et al. conducted a study to determine the brain displacement and deformation during impacts caused by various degrees of linear and rotational accelerations.[11] In this study, intracranial pressure transducers and neutral density targets were implanted into the brains of eight cadavers to monitor pressure, displacement, and deformation using biplane x-ray during thirty five impacts. It was determined that the maximum principal strain and peak coup pressure in the brain increases with linear acceleration in the direction of impact. However, no significant correlation was determined between pressure or strain parameters and rotational acceleration. This study has applications towards understanding the causes of mild traumatic brain injuries by quantifying the kinematic response of the human brain to traumatic loading.

While cadaver studies are a valuable tool to understand the kinematics and mechanics of the brain during a traumatic event, a large aspect of mild traumatic brain injuries includes the physiological response of the brain post injury. Currently, concussions are diagnosed by reported and observed symptoms exhibited by patients who have undergone head trauma. Thus, live brains are vital to studying mild traumatic brain injuries. To determine the threshold for concussion caused by rotational whiplash forces, Ommaya et al. conducted 200 primate impact tests were conducted at a variety of angular velocities, accelerations, and pulse durations.[12-15] In these studies, torso acceleration tests were performed to quantify the threshold of concussive injury in different primate species. These results were then scaled to humans using a brain mass scaling relation (**Figure 2**).

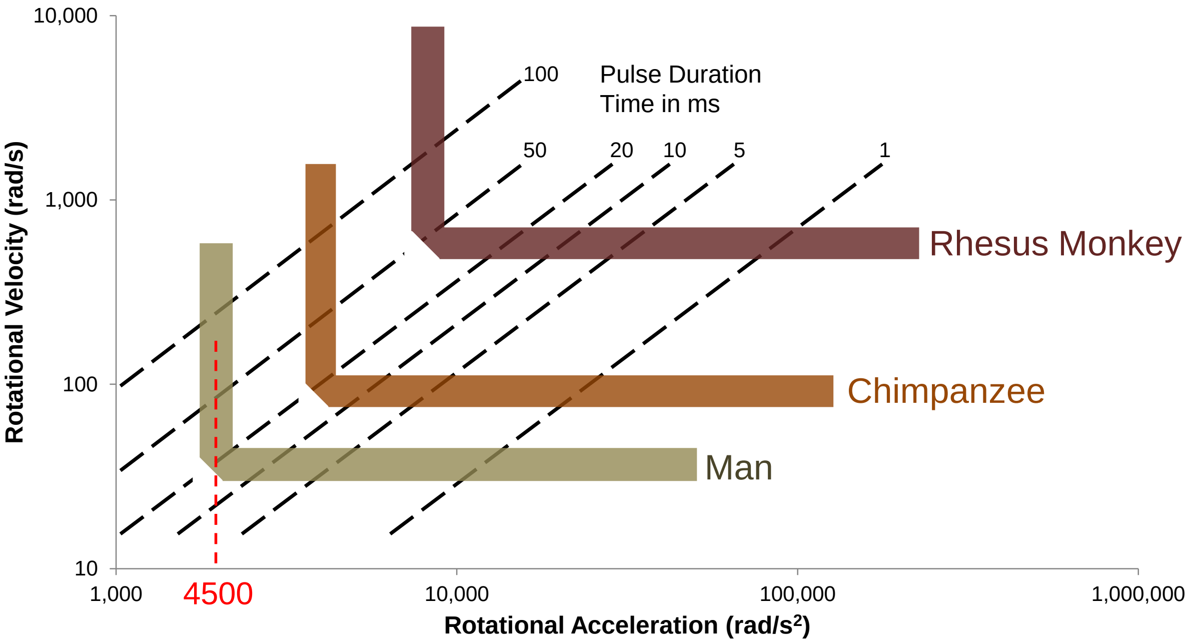

Figure 2. Ommaya et al. conducted noncontact rotational head impacts to develop injury tolerances for various primate species. These results were then scaled to man using a brain mass scaling relation.

Quantification of injury risk and injury thresholds in primate models provides the opportunity to study mild traumatic brain injuries because physiological responses are produced. However, In order to scale the results of such studies to humans, scaling techniques must be utilized which inherently reduces the accuracy of the results. Football players provide a unique opportunity to study the effects of concussive and subconcussive impacts on the human brain directly in an ethical manner. Between the years of 1996 and 2001, Pellman et al. collected game video in the NFL. Impacts causing diagnosed concussions were located in the video data. Through video analysis of the concussive impacts, the impact speed and location were determined. From this analysis, 31 impacts, including 25 concussive impacts and 6 noninjurious impacts, were reconstructed in the lab. To reconstruct the impacts, Hybrid III testing devices were equipped with football helmets and were impacted with initial energy equivalent to that determined from the video analysis. Accelerometers instrumented in the Hybrid III head were used to measure linear acceleration at the center of gravity of the head. From this study, a risk curve was developed to predict the likelihood of injury based on linear acceleration (**Figure 3**).[16]

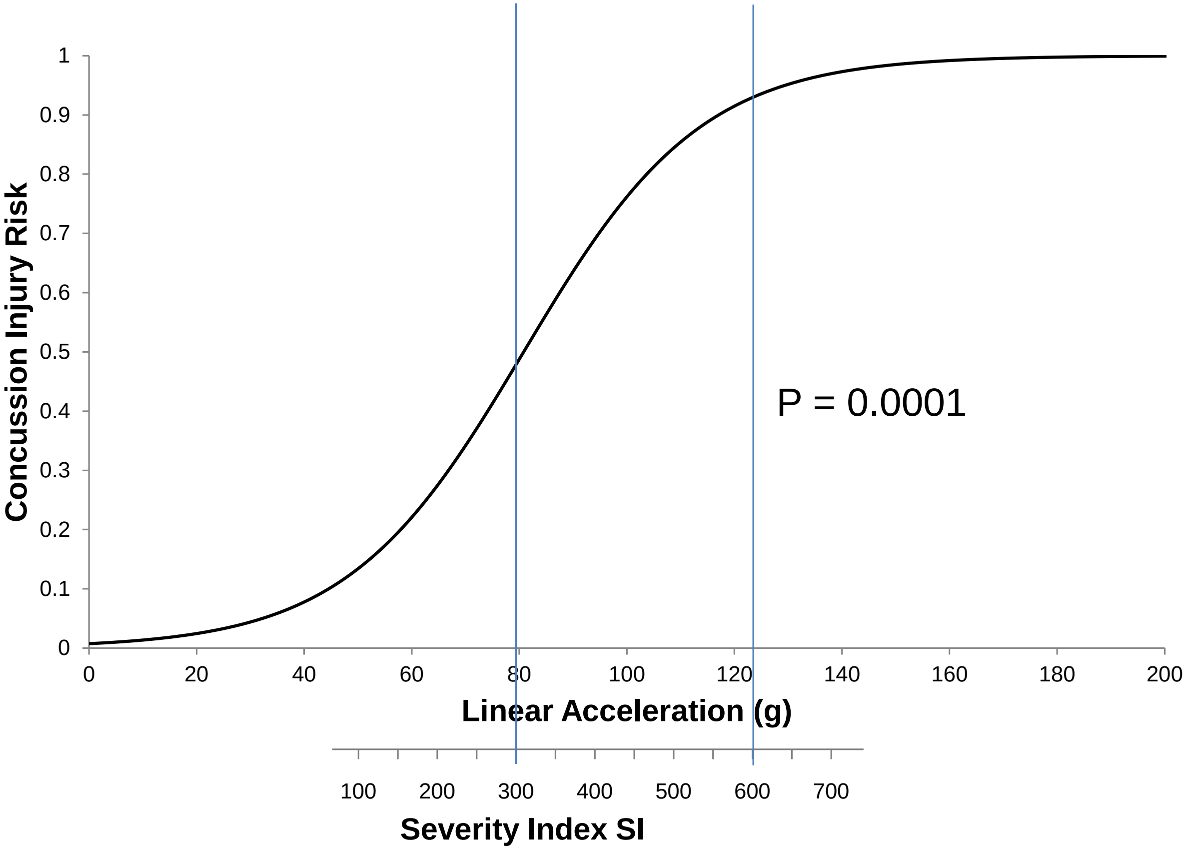

Figure 3. Pellmen et al. developed an injury risk curve to predict concussion as a function of linear acceleration using laboratory reconstructed NFL impacts.

The injury risk curve developed by Pellman et al. used a small number of concussive and subconcussive impacts. In order to more accurately predict the risk for injury, a larger set of both concussive and subconcussive impacts should be analyzed. To collect data describing all impacts experienced by players in a given season, accelerometers can be instrumented into the helmets of players (**Figure 4**). These accelerometers collect impact data and transmit them to a sideline computer. Linear acceleration, angular acceleration, and location of impact are transmitted to allow for impact exposure to be quantified for each player. In 2003, Virginia Tech began instrumenting the helmets of their football players. Over the last ten years, other universities have begun to instrument their players resulting in over 2,000,000 head impacts collected from NCAA football players.[17-43]

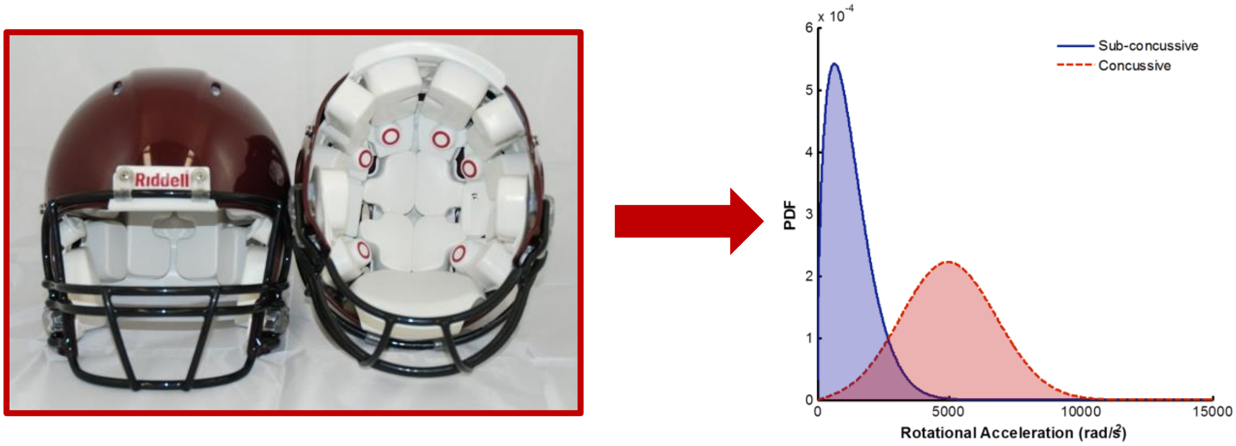

Figure 4. Head impacts have been collected from NCAA football players over the last decade using helmet mounted accelerometers. Subconcussive impacts are right skewed due to the high number of low magnitude impacts and concussive impacts are normally distributed.

The distribution of linear and rotational acceleration of subconcussive impacts is right skewed due to the high number of low magnitude impacts. Concussive impacts, however, are normally distributed (**Figure 4**). From this data, Rowson et al. created a risk function to predict concussion as a function of linear acceleration.[35]

In addition to linear acceleration, angular acceleration has been proposed to play a significant role in concussions. In order to accurately predict the risk of concussion, both linear and rotational acceleration should be accounted for to determine the combined risk. In 2012, Rowson et al. created a combined probability risk curve to determine the risk of concussion as a result of linear and angular acceleration (**Figure 5**).[37]

$$Risk = \frac{1}{1 + e^{-(-10.2 + \underbrace{0.0433a}_{\text{Linear Acceleration}} + \underbrace{0.000873\propto}_{\text{Rotational Acceleration}} - \underbrace{0.00000092a\propto}_{\text{Interaction}})}}$$

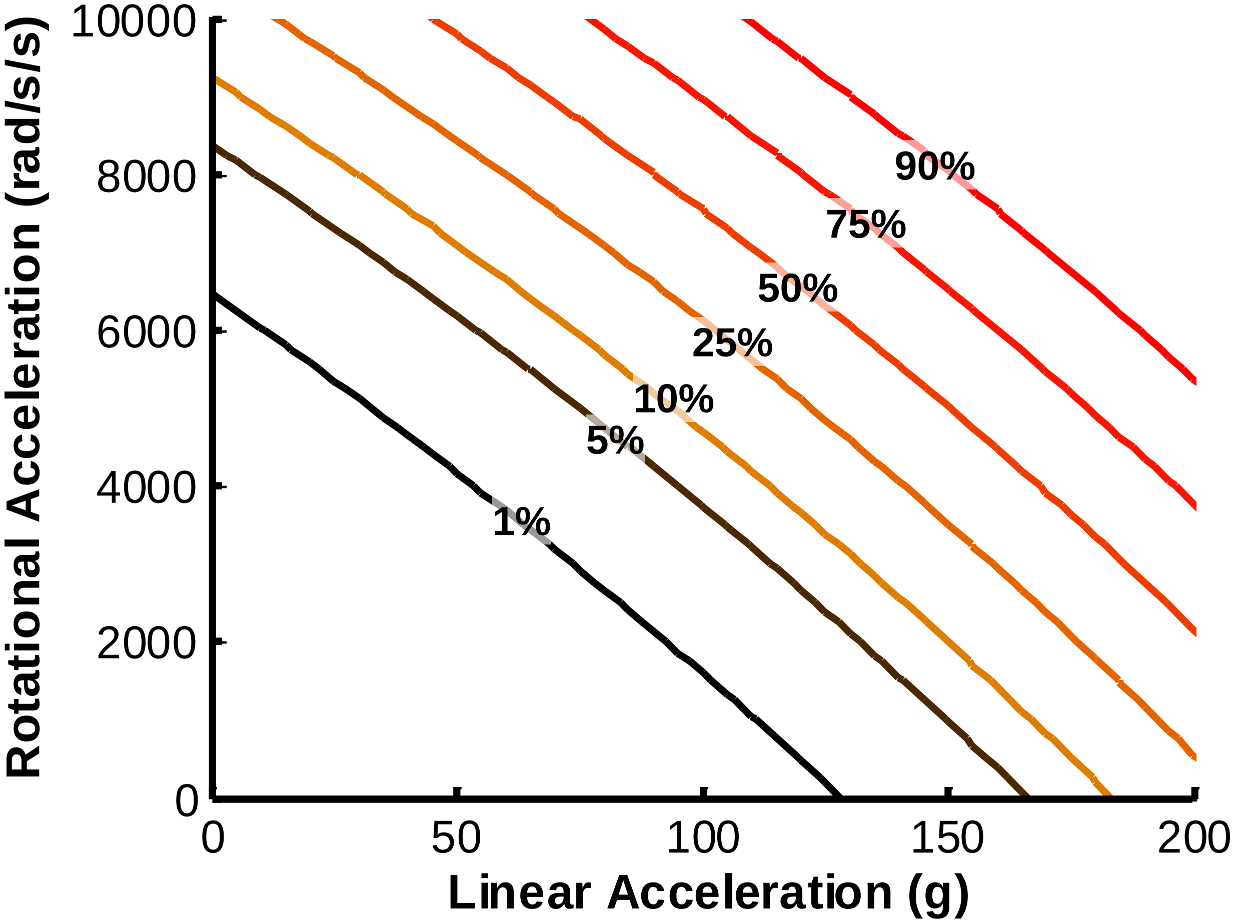

Figure 5. Rowson et al. created a concussion risk curve as a function of both linear and angular acceleration.

## CONCLUSION

Over the last 50 years, head injury risk curves have been developed to predict severe and mild traumatic brain injuries. Cadavers served as the model to predict severe brain injuries, such as skull fractures, and have resulted in the only currently accepted injury risk curve accepted by industry today. Animal models, NFL data analysis, and NCAA volunteer data have resulted in injury risk curves that can predict mild traumatic brain injuries based on both linear and angular acceleration. These risk curves are a valuable tool that can aid researchers in designing safer vehicles, protective equipment, and products that can minimize the amount injuries that occur during traumatic events.

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