White Paper: Research and Development Efforts towards the Development of the Leatt® Turbine System

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Declaration

We, the undersigned, hereby declare that the scientific work described in this white paper is our own original work.

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Date: ***February 2018***

Abstract

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Head injuries and more specifically those leading to concussion have become a hotly debated topic over the last few years. Most noticeably in high velocity, high impact sport disciplines where helmets are already being used, such as motorcycle riding and American football. The brain is a very complex organ and injury mechanisms related to concussion are only now being better understood, albeit a lot remains unclear. It is believed that repeated low speed impacts and rotational effects during head impacts are the largest contributors as mechanism to concussive injury and possible MTBI.

This White Paper summarizes research, development, and performance verification activities conducted by Leatt Corporation towards the development of a system to reduce the severity of impacts associated with low speed and rotational mechanisms. This system called the Turbine System was designed to reduce concussion and possible MTBI related to abovementioned injury mechanisms. Individuals involved in the work include Dr. Chris Leatt, biomedical engineers Cornel de Jongh and Pieter Keevy.

Background research provided information on head trauma, brain dynamics and the coupled forces and accelerations involved in dynamic events. This resulted in an understanding of injury mechanisms and injury tolerance levels associated with head injury in contact sports. Tests were conducted with the proposed device across

a range of velocities (representing injury producing loads) evaluating linear and rotational acceleration responses in a test environment.

This document is intended to answer common questions asked by users, institutions and the public. Encouraging by our testing is the fact that the Leatt ® Turbine lowers the incidence and severity of concussion-level linear and rotational accelerations.

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Nomenclature

Variables

N	newton
Nm	newton-meter
MPa	Megapascal
g	units of acceleration ($9.81 m/s^2$)

Abbreviations

EPS	Expanded Polystyrene
MTBI	Mild Traumatic Brain Injury
DAI	Diffuse axonal injuries
SDH	Subdural Hematoma
HIC	Head Injury Criteria

Chapter 1

Introduction

1.1 Background

Traditionally, the key element in helmet energy absorption was the EPS layer and apart from alterations to the density of EPS and use of other energy absorbing foams, sports helmet technology has not really advanced in the last 30 years. In addition, the trend for smaller and slimmer helmets has only increased the density and stiffness of these foams to pass test standards at high speeds, leading to helmets which do not necessarily perform well in low speed impacts. The frequency of sub-concussive impacts has been associated with mild traumatic brain injury (MTBI) with long-term effects. Albeit that no definitive concussion threshold has been established, it is clear that low speed impact (especially repeated incidents thereof) has a correlation with concussion and possible future MTBI. This is a key concern at present in contact sports and a growing concern in relation to head protection systems.

In addition to linear acceleration, a component of rotational acceleration is imparted to the head in most instances of trauma. Impacts to the head often occur at an angle and therefore the rotational component of acceleration can be significant. The recent focus of research into rotational acceleration of the brain is capturing the attention of helmet manufacturers who are now endeavouring to improve protection against it.

The design rational of the Leatt® Turbine System includes consideration of methods to absorb centripetal or radial forces associated with low speed impact (linear accelerations) and mitigate against tangentially orientated shear forces derived from rotational effects on the helmet. These effects were evaluated through testing of the system and comparison to existing MTBI probability risk curves.

The Leatt® Turbine System has been designed by a team of specialized professionals to optimize its performance for brain protection in extreme helmeted sports. This, in conjunction with testing and constant reference to human reactions and tolerance to various head impact scenarios, ensured that the device design was optimized through multiple design iterations.

1.2 Motivation

Head injuries are one of the most severe and potentially life-altering injury types in extreme sports such as off-road motorcycling. Repeated concussion or even high-frequency sub-concussive impacts can cause serious repercussions for athletes in later life, and it was for these reasons that a device was designed to help protect against mechanisms related to this type of trauma.

1.3 Objectives

The research, design, and testing underlying the Leatt® Turbine System focused on overall efficacy in creating an effective and reliable product. The Leatt® Turbine System Research and Development (R&D) rationale is presented in this paper, and the objective is to elaborate on the testing conducted during the development thereof.

Chapter 2

Literature Review

2.1 Injuries as a Result of Linear Acceleration

Linear brain injuries can be divided into two categories dependent on the injury mechanism; diffuse and focal injuries**Error! Reference source not found.**. Diffuse (distributed) brain injuries are normally associated with impacts to rigid surfaces, abrupt head deceleration or a combination of the two. This type of impact causes high brain accelerations, resulting in injuries that can range from mild concussion to a fatality. Focal (localized) brain injuries occur due to a direct impact on a specific area of the brain. This results in injuries ranging from bruising to direct brain penetration. Brain damage is caused by reduced blood flow to the brain or internal brain rupturing, tearing of tracts or haemorrhaging (bleeding), which is a direct result of these two types of brain injuries. Depending on its extent and severity, brain damage can be permanent.

The relationship between acceleration of the brain and the duration of the pulse is of crucial importance. The brain can withstand higher peak acceleration if the duration of the pulse is short. The longer the pulse, the lower the tolerance for high acceleration becomes. This phenomenon was parameterized through the establishment of the well-known Wayne State Tolerance Curve (Figure 2-1). Brain injuries can be sustained at brain accelerations as low as 60 G, which is related to a helmeted impact velocity of only 2 ms^{-1} using a standard Snell/DOT or ECE helmet with only EPS protection. Conventional helmets do not necessarily reduce resultant brain accelerations related to low speed impact.

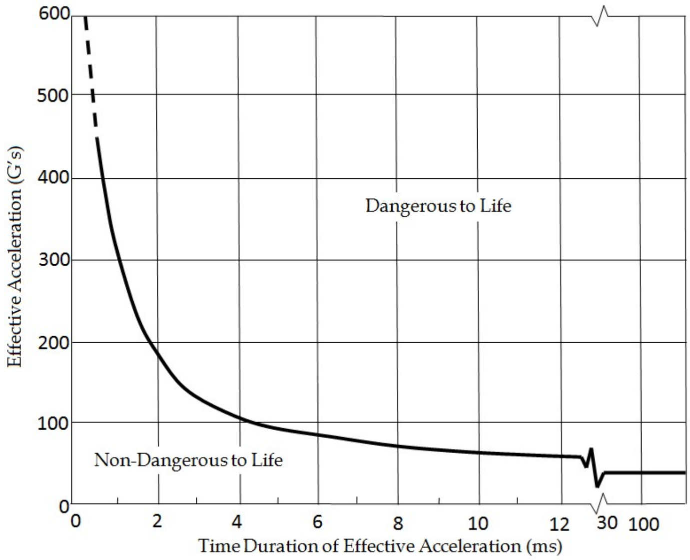

Figure 2-1: Wayne State Tolerance Curve [1]

2.2 Injuries as a Result of Rotational Acceleration

The brain is even more vulnerable to rotational acceleration imparted to it. This has been well documented with injury thresholds being commonly used to define the limits of brain rotation during impacts.

Two curves, not unlike the Wayne State Tolerance Curve, indicating the acceleration/velocity/time injury criterion interactions, are presented in Figure 2-2 and Figure 2-3 below. Rotational injuries may include shearing (tearing) of the bridging veins between the skull and brain because of excessive tissue strain (Figure 2-4 and Figure 2-5), leading to subdural hematoma (SDH) (x in Figure 2-2). Diffuse axonal injuries (DAI) may also occur (Figure 2-3). SDH refers to bleeding within the inner meningeal layer of the dura (the outer protective covering of the brain), whilst DAI causes extensive, widespread lesions in white matter tracts because of shearing in this area. It was postulated by Kleiven [2] that bridging vein rupture may occur when the peak angular acceleration and peak change in velocity exceed 4 500 rad/s^2

and 50 rad/s respectively. This relates to an impact velocity of only about 4 ms^{-1} with a conventional helmet (Snell/DOT or ECE).

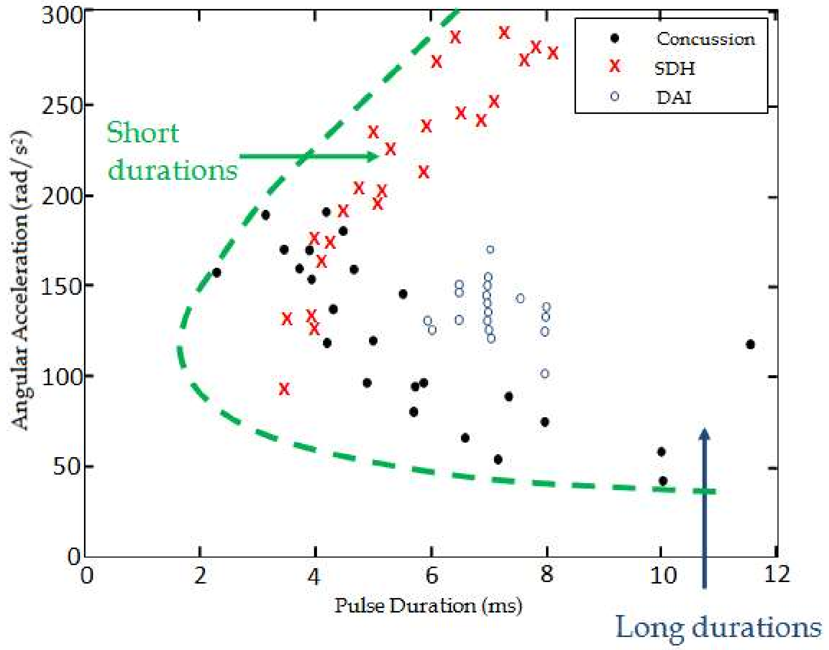

Figure 2-2: Acceleration vs. time injury tolerance curve [2]

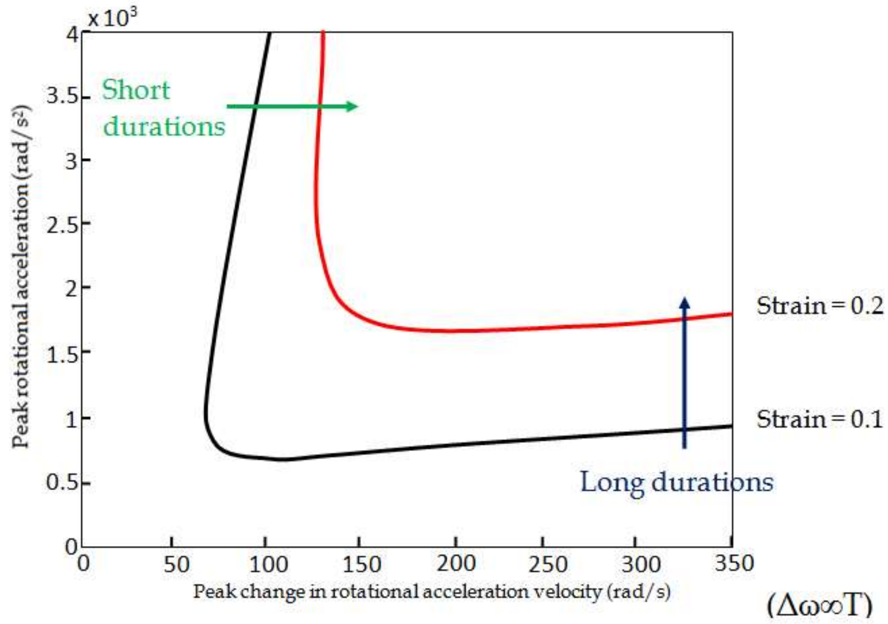

Figure 2-3: Acceleration vs. time injury tolerance curve [2]

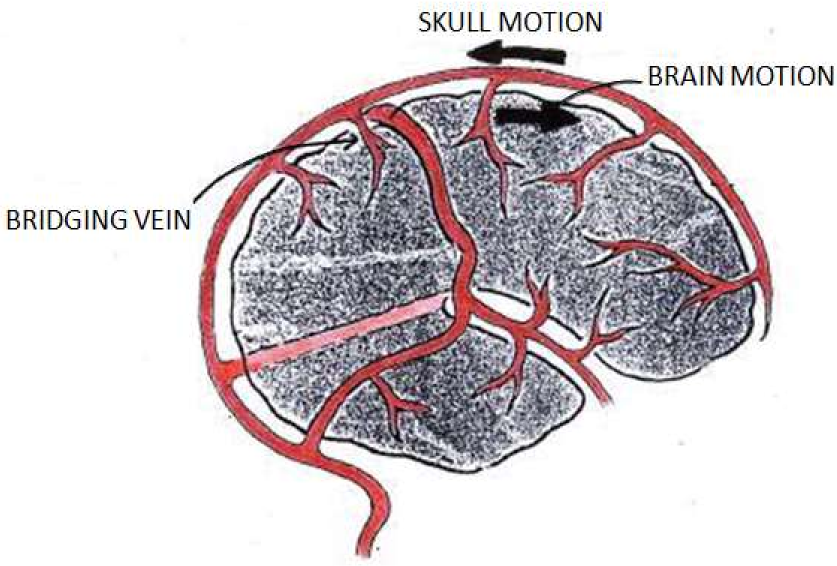

Figure 2-4: Bridging vein shear with relative brain/skull motion [2]

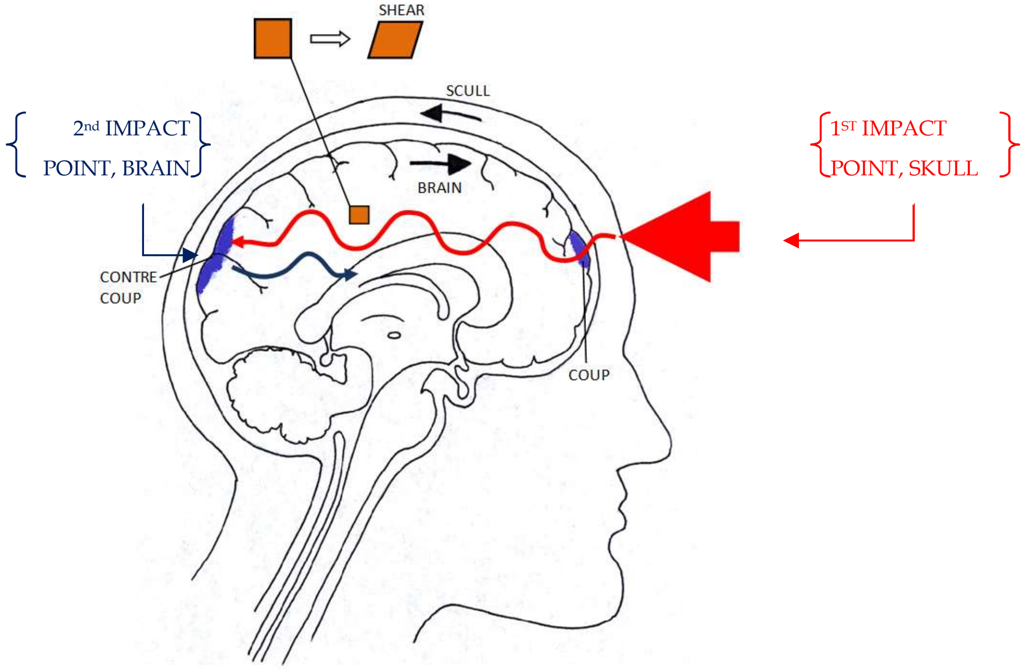

Figure 2-5: DAI biomechanics [2]

It should be considered that a helmet can play a significant role in the absorption and deceleration of the skull upon impact. This is relevant for *linear* as well as *rotational* acceleration. It therefore is important that a good understanding of the abovementioned factors be obtained to assess brain dynamics and the subsequent injury potential of the brain with and without the use of a helmet, especially as it relates to low energy impacts.

Brain Injury thresholds

Thresholds for MTBI are represented in the form of an injury probability risk curves. This curve depicts thresholds for transmitted linear acceleration as well as rotational acceleration in the brain. Some risk curves are also depicted in terms of Head Injury Criterion (HIC). These can be used to gauge the efficacy of energy management devices such as the Turbine System.

The following preliminary nominal injury assessment reference values associated with risk of MTBI were proposed by Zhang et. all in the figure below [3]. These values have gained traction in the scientific community and the values for 50% probability of MTBI are now typically used [4],[5].

Probability of Sustaining MTBI	Linear Acceleration	Rotational Acceleration
25%	66 G	4600 rad/s^2
50%	82 G	5900 rad/s^2
80%	106 G	7900 rad/s^2

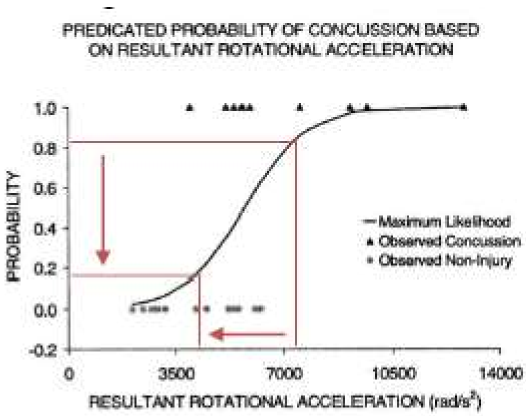

Figure 2-6: MTBI probability risk curve

The tests conducted on the Leatt® Turbine System to evaluate these parameters are discussed below.

Chapter 3

The Leatt® Turbine System

3.1 Introduction

The Leatt® Turbine technology was developed to maximize low energy linear impact absorption, as well as low to high velocity rotational impact absorption.

Figure 3-1: Leatt® Turbine System

The Turbines were designed as collapsible structures which deform when linear and shear force due to low speed linear and rotational acceleration is imparted to the turbines, allowing the shell and inner liner to move relative to each other in a controlled fashion (Figure 3-2). This movement offsets the relative rotation between the brain and the skull and subsequently reduces peak rotational acceleration imparted to the brain.

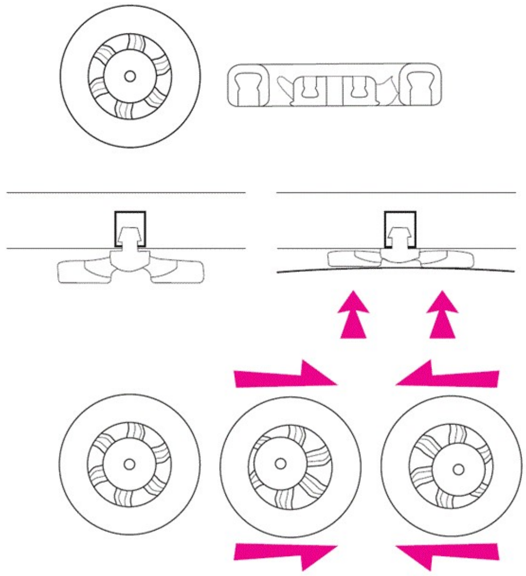

Figure 3-2: Turbine Force Representation

The design rationale was born from the need to develop a system that will reduce the likelihood of concussion or MTBI occurring during low speed impacts and/or rotational acceleration imparted to the head.

The typical arrangement of turbines in a helmet liner and on the EPS is shown in Figure 3-3 below.

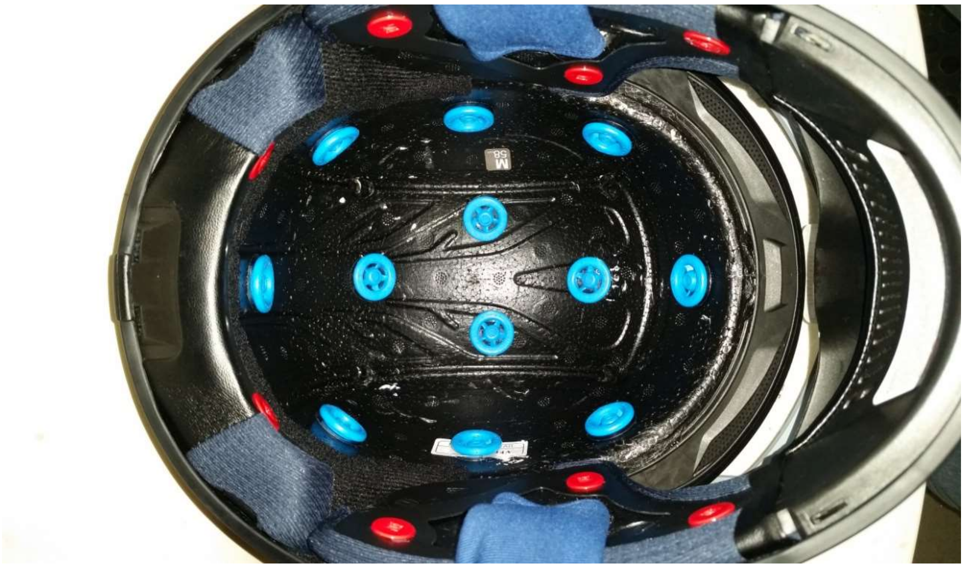

Figure 3-3: Tubines in place within the EPS structure

Chapter 4

Testing of the Leatt® Turbine System

4.1 Quassi-Static Testing

4.1.1 Introduction

The primary function of the Leatt® Turbine technology system is to reduce or prevent the likelihood of the following injuries:

- Concussion related to low speed impact and rotational acceleration
- MTBI related to multiple sub-concussive impacts and/or high frequency concussion level impacts.

4.1.2 Test Procedure

Oblique impact tests

An oblique impact helmet test rig was used for analysis of *rotational* impacts. The ability of the equipment to measure the linear component of these higher velocity impacts was utilised. It consists of a free-falling wedge striker with 80 grit sand paper attached to the impact surface, a 50th percentile Hybrid III headform (3-2-2-2 accelerometer array), upper neck load cell (Fx, Fy, Fz, Mx, My, Mz) and a simply supported swing arm to mimic the inertia of the body.

The test rig uses a 16-channel data logger at 50 kHz sampling rate to capture *linear and rotational accelerations* in the head, loads on the wedge striker plate and loads and moments in the Hybrid III neck. Accelerometer and load cell signals are filtered with a 4th order Butterworth filter at 800 Hz (according to SAE J211 protocol) to remove noise. In addition, a Phantom Miro310 high speed camera was used to record a number of tests at 5,000 frames per second for reference and post-processing analysis including tracking.

Impact tests were carried out using a 30-degree impact striker for maximum rotational effect. Frontal oblique impacts were conducted at 2 velocities, namely 4.3 m/s and 6.1 m/s and rear oblique impacts at 6.1 m/s.

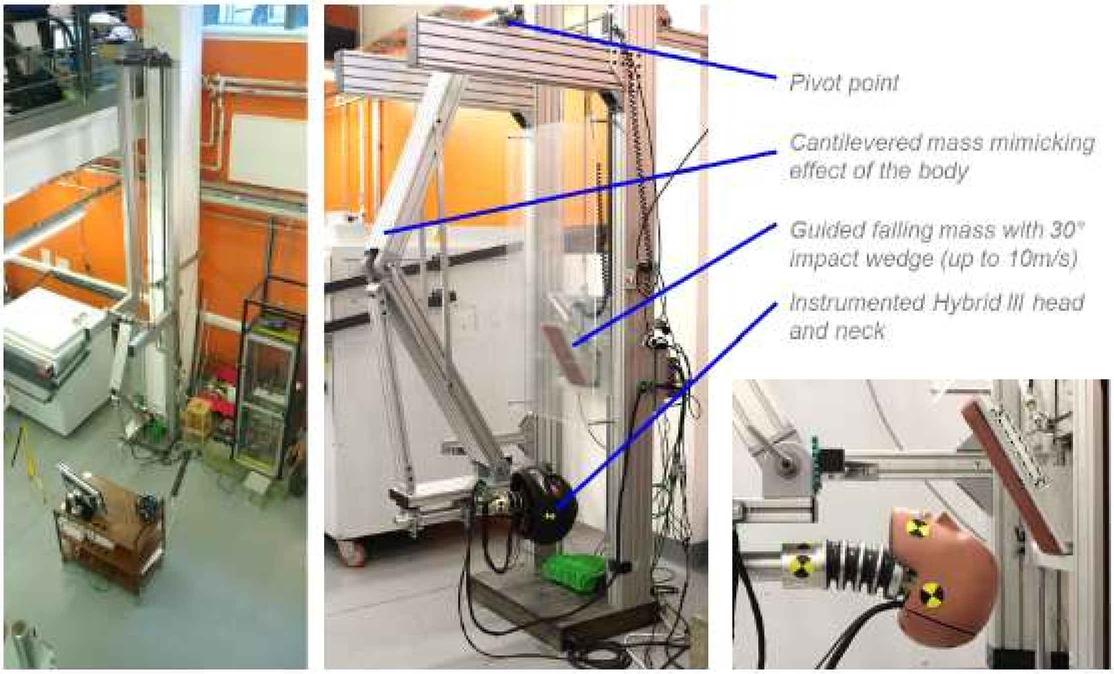

Figure 4-1: Oblique impact helmet test rig

Samples of Leatt® GPX and DBX helmets (n=20) were used for testing.

Low speed linear impact tests

For *low speed linear impact* analysis, an ECE 22.05 test rig with flat anvil was utilised. Standard ambient (room) temperature conditions were used for the test. A suspended instrumented 50th percentile Hybrid III headform (3-2-2-2 accelerometer array) was dropped onto a flat anvil at impacts speeds of 1 m/s, 2 m/s and 3 m/s (Figure 4-3).

Figure 4-2: ECE 22.05 test rig

Samples of Leatt® GPX and DBX helmets (n=20) were used for testing.

4.1.3 Results

Oblique impact tests

The results below are tabulated and expresses the data for the linear and rotational acceleration component achieved with and without the Leatt® Turbines in place for the various impact velocities and head impact locations using the oblique impact test rig.

No side impact test results are reported for the 6.1 m/s impact due the complexity of the outside surface geometry around the vents. This resulted in poor repeatability due to inconsistencies in impact location.

TABLE 4-1: 4.3 M/S TESTS – FRONTAL IMPACT (SAGITTAL PLANE) / SIDE IMPACT (CORONAL PLANE) / REAR IMPACT (SAGITTAL PLANE)

Velocity	Sample	Sample Name	Peak Linear Acceleration (g)	Mean (g) (%reduction)	Peak Rotational Acceleration (rad/s²)	Mean (rad/s²) (%reduction)
4.3 m/s Tests – Frontal Impact (Sagittal Plane)	Turbines Removed	DBX Enduro Ref 1 (no turbines)	55.63	57.58 –	6329.56	6649.12 –
		DBX Enduro Ref 2 (no turbines)	61.2		6975.64	
		DBX Enduro Ref 3 (no turbines)	55.9		6642.16	
	With Turbines	DBX Enduro T1 (with turbines)	46.67	53.10 (8%)	5189.26	5827.69 (12%)
		DBX Enduro T2 (with turbines)	56.01		6070.4	
		DBX Enduro T3 (with turbines)	56.61		6223.42	
4.3 m/s Tests – Side Impact (Coronal Plane)	Turbines Removed	DBX Enduro Ref 1 (no turbines)	54.58	47.78 –	9007.01	6784.17 –
		DBX Enduro Ref 2 (no turbines)	44.51		4962.22	
		DBX Enduro Ref 3 (no turbines)	44.26		6383.27	
	With Turbines	DBX Enduro T1 (with turbines)	32.47	41.11 (14%)	4210.17	5071.62 (25%)
		DBX Enduro T2 (with turbines)	45.7		5199.15	
		DBX Enduro T3 (with turbines)	45.17		5805.54	
4.3 m/s Tests – Rear Impact (Sagittal Plane)	Turbines Removed	DBX Enduro Ref 1 (no turbines)	44.63	44.23 –	6775.83	6579.74 –
		DBX Enduro Ref 2 (no turbines)	41.2		7229.83	
		DBX Enduro Ref 3 (no turbines)	46.87		5733.57	
	With Turbines	DBX Enduro T1 (with turbines)	42.74	40.69 (8%)	4913.73	4757.77 (28%)
		DBX Enduro T2 (with turbines)	44.36		4759.28	
		DBX Enduro T3 (with turbines)	34.97		4600.29	

TABLE 4-2: 6.1 M/S TESTS – FRONTAL IMPACT (SAGITTAL PLANE)

Sample	Sample Name	Linear Acceleration (g)	Mean (g) (%reduction)	Rotational Acceleration (rad/s²)	Mean (rad/s²) (%reduction)
Turbines Removed	Leatt GPX 5.5 No Turbines Size L Helmet 6	44.11	44.72	5127.53	5420.19
	Leatt GPX 5.5 No Turbines Size L Helmet 9	34.78		4859.77	
	Leatt GPX 5.5 no Turbines Size L Helmet 11	55.26		6273.27	
With Turbines	Leatt GPX 5.5 With Turbines Size L Helmet 5	44.36	42.96 (4%)	5414.3	4844.24 (11%)
	Leatt GPX 5.5 With Turbines Size L Helmet 8	36.88		3839.18	
	Leatt GPX 5.5 with Turbines Size L Helmet 10	38.29		4484.23	
	Leatt GPX 5.5 with Turbines Size L Helmet 12	52.3		5639.25	

TABLE 4-3: 6.1 M/S TESTS – REAR IMPACT (SAGITTAL PLANE)

Sample	Sample Name	Linear Acceleration (g)	Mean (g) (%reduction)	Rotational Acceleration (rad/s²)	Mean (rad/s²) (%reduction)
Turbines Removed	Leatt GPS 5.5 v0.5 No Turbines Size L Helmet 2	38.71	38.21	6753.26	6370.79
	Leatt GPS 5.5 v0.5 No Turbines Size L Helmet 4	40.97		6678.32	
	Leatt GPS 5.5 v0.5 No Turbines Size L Helmet 6	34.96		5680.8	
With Turbines	Leatt GPS 5.5 v0.5 with Turbines Size L Helmet 1	41.57	44.28 (-16%)	4066.51	3971.59 (38%)
	Leatt GPS 5.5 v0.5 with Turbines Size L Helmet 3	44.02		3582.33	
	Leatt GPS 5.5 v0.5 with Turbines Size L Helmet 5	47.26		4265.93	

Discussion and Conclusions

Tests show that the Leatt® Turbines reduce the mean peak rotational head acceleration on oblique impact compared to a helmet of the same model with no turbines.

4.3 m/s Frontal Impact (sagittal plane)

At 4.3 m/s frontal impact the Leatt® Turbines reduced rotational acceleration by 12% and linear acceleration by 8%.

4.3 m/s Side Impact (coronal plane)

At 4.3 m/s side impact the Leatt® Turbines reduced rotational acceleration by 25% and linear acceleration by 14%.

4.3 m/s Rear Impact (sagittal plane)

At 4.3 m/s rear impact the Leatt® Turbines reduced rotational acceleration by 28% and linear acceleration by 8%.

6.1 m/s Frontal Impact

At 6.1 m/s frontal impact, the Leatt® Turbines reduced the mean peak rotational and linear acceleration of the head by 11% and 4% respectively.

6.1 m/s Rear Impact

On rear impact at 6.1 m/s the Leatt® Turbines showed a reduction of mean peak rotational acceleration of 38%. Additionally, an overall reduction in energy transfer to the head is observed with the Leatt® Turbine in place (Figure 4-3).

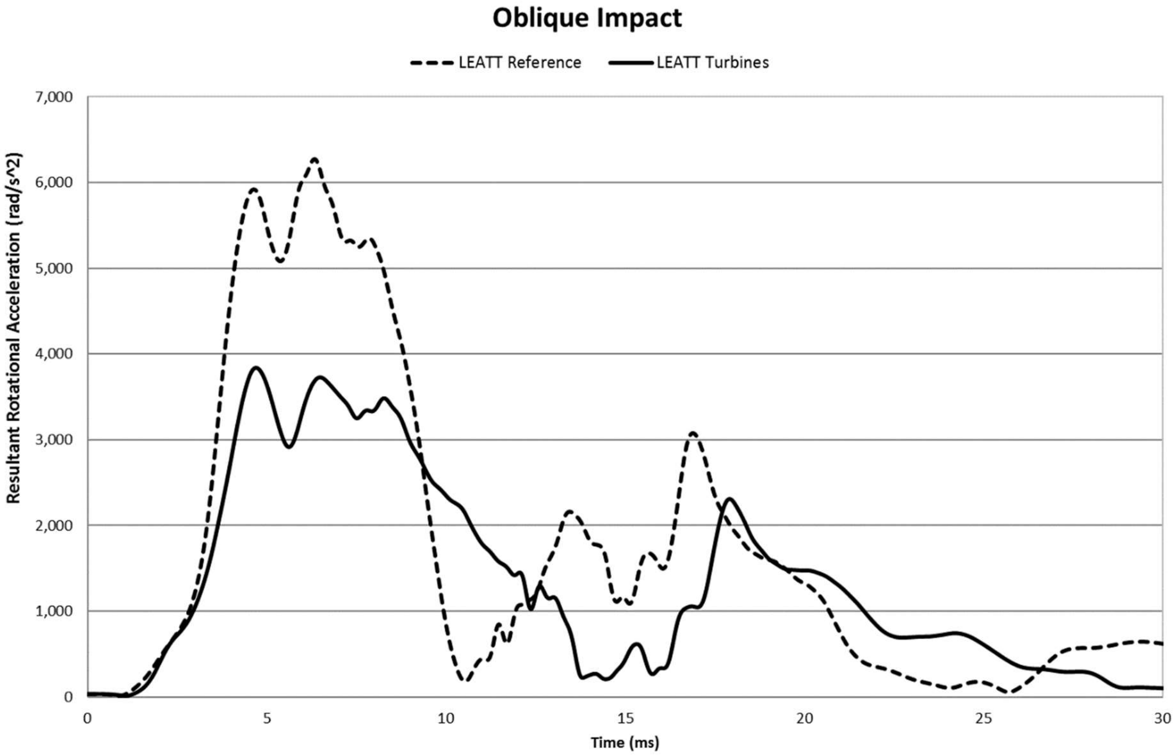

Figure 4-3: 6.1 m/s rear oblique impact - illustration of transferred energy reduction

It is encouraging to observe that for all oblique impact tests performed, the Leatt® Turbines resulted in peak rotational acceleration values below 5900 rad/s², which relates to a <50% risk for MTBI. Additionally, a value below 4600 rad/s² (correlating to a 25% risk of MTBI) was observed for the 6.1 m/s rear impact test, compared to a baseline value of 6371 rad/s² (+- 70% risk), indicating a reduction of approximately 45% in MTBI risk for that specific impact.

Low speed linear impact tests

Results for the low speed linear impact tests conducted at 1 m/s, 2 m/s and 3m/s are presented below (Figure 4-4).

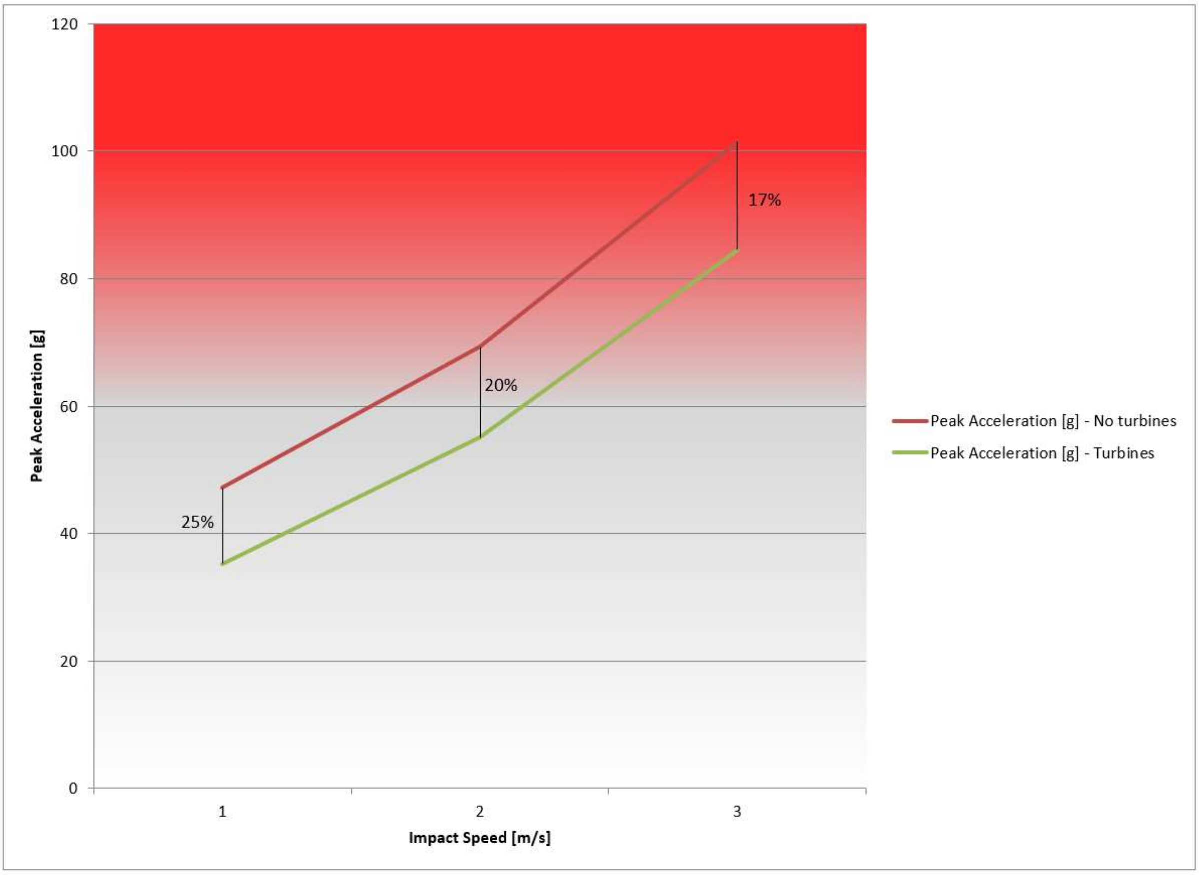

Figure 4-4: Low speed linear impact results

Discussion and Conclusions

Tests show that the Leatt® Turbines reduce the mean peak linear head acceleration at low speed impacts compared to a helmet of the same model with no turbines.

Reductions of 25%, 20% and 17% were observed for impact speeds of 1 m/s, 2 m/s and 3m/s respectively. The gradual reduction in performance with increased impact speed demonstrates that the Leatt® Turbines was designed for optimal linear performance for low speed impacts. Conversely for high speed impacts, the Leatt® Turbines optimally reduces rotational acceleration imparted to the head.

Chapter 5

Conclusions

This document summarizes research and development underpinning the design of the Leatt® Turbine System.

A discussion of the relevant literature was provided, as well as of the relevant injury mechanisms pertaining to head injuries related to concussion and/or MTBI.

A presentation of the tests conducted during the validation of the Leatt® Turbine System was provided.

This study shows that the Leatt® Turbine System is an effective system for reducing the severity of injury mechanisms related to concussion and MTBI as documented in literature. It conforms to and surpasses all commonly accepted injury assessment reference values and injury criteria for MTBI through significant reduction in measured head linear (at low speed) and rotational acceleration (at high speed).

Finally, this document serves as a reference for interested readers in terms of understanding the research, development and design rationale behind the Leatt® Turbine System.

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