White Paper: Research and Development Efforts towards the Production of the Leatt® GPX 5.5 MX Boot

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Declaration by Independent Reviewers

We, the undersigned, hereby acknowledge the credibility of the work conducted in this document and declare that the work contained in this white paper is the authors' own original work.

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Date: November 2018

Declaration

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

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Abstract

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Boots are commonly used in motorcycle riding in order to protect the rider from various external forces and elements. These elements include factors like abrasion, heat and cold. The more challenging aspects of boot development resides in protecting the user from the external forces that may be imparted via the foot into the ankle and lower leg. Whilst most high-end motorcycle boots protect adequately against abovementioned external elements, they often fail to protect the user in a biomechanically correct way from external forces imparted to the Foot, Ankle and even the Knee.

This White Paper summarizes research, development, and performance verification activities conducted by Leatt Corporation. Individuals involved in the work include Dr. Chris Leatt, Biomedical Engineers Cornel de Jongh and Pieter Keevy, Industrial Designer Carel Meyer and boot development expert Gian-Paulo D'Agostini. Field trials were also conducted from an early stage in the development process to help develop and assess the Leatt ® GPX 5.5 MX Boot.

Background research provided information on Ankle trauma, Ankle dynamics, and the coupled forces and motions involved in dynamic events resulting in an understanding of injury mechanisms and injury tolerance levels associated with loading of the Ankle as well as impact below the Foot. Tests were conducted with the

proposed device measured against a popular top competitor boot to ensure that the device would have superior and biomechanically correct protection against Ankle injury and Knee injury.

Traditional high-end boots are designed with the premise that good Ankle force reduction equates to a stiff and rigid boot around the Ankle area. In contrast to this the Leatt® boot was designed to allow for adequate and natural Ankle movement allowing for optimal levels of proprioception whilst riding and walking. Whilst allowing for movement, the boot was however designed to lock out at the correct Ankle position in Ankle inversion and eversion to prevent fractures and/or ligament injuries. In addition to this the boot was designed with superior heel cushioning for optimal impact absorption. The combination of inversion/eversion control and heel absorption has also shown a reduction in **Knee forces** compared to traditional "stiff" boots.

This document is intended to answer common questions asked by users, institutions and the public. In AMA (American Motorcycle Association) sanctioned MotoCross and SuperCross events, the total number of lower extremity injuries may be as high as 9% of all injuries. 40% of these injuries are ligamentous and relate mostly to ACL, MCL and Meniscus injury [7]. In a study conducted on 1500 off-road motorcycle accidents, 344 cases resulted in ligamentous injury, of which 206 or 59.9% occurred in the lower extremities, especially on the Knee (42.4%) and Ankle (24.3%) [2]. In addition to above, Tibial plateau fractures, Fibular fractures, malleolar injuries, ACL rupture and medial meniscus tears are common injuries related to a pivoting Foot on an outstretched leg when cornering [2]. A rigid boot may transfer some of these ground forces to the Knee due to limited natural movement or "energy release" in the Ankle area.

Correctly understanding and implementing counter-measures to biomechanical aspects of Ankle and Knee injuries related to off-road motorcycle riding and boot use, may aid in lowering the incidence of these injuries. Encouraging is the fact that, it has been shown that the Leatt® GPX 5.5 MX Boot does offer major benefits to riders/athletes, especially as it relates to inversion Ankle injuries as well as secondary Knee injury risk.

Acknowledgements

We would like to express our sincere thanks to the following people and organizations, whom have contributed to this project:

- Dr. Koos Marais - Orthopedic Surgeon - Ankle Specialist. MBChB; MMed (Ortho).

- All the volunteers taking their time to ride with the device and fill out valuable questionnaires during the development process.

Dedications

To all of those who have shown a keen interest and belief in what Leatt Corporation stands for: "Their ability to incorporate pure science, engineering and passion into the development of motorsport safety products."

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Nomenclature

Variables

N	Newton
Nm	Newton-Meter

Abbreviations

IAR	Instantaneous Axis of Rotation
ROM	Range Of Motion
DOF	Degrees Of Freedom
MX	Motocross
PKB	Prophylactic knee braces
SX	Supercross
H III ATD	Hybrid III Anthropomorphic Test Device

Chapter 1

Introduction

1.1 Background

Lower extremity injuries are extremely common in extreme sports such as MotoCross or SuperCross (MX or SX) [1],**Error! Reference source not found.**. The human Ankle and Knee are two of the most commonly injured areas in the human body in above mentioned sport types and off-road riding in general, and is constantly exposed to loading, bending and/or rotation acting in coupled fashion. Traditional off-road motorcycle boots have generally been designed with the premise of protecting the Foot and Ankle from external forces by stiffening up the area around the Ankle. Completely constraining the Ankle within a "sleeve or pipe", however, creates a twofold problem; firstly, proprioception [3][4][5][6] of the Foot may be lost creating a loss of "feeling" and comfort in riding and walking. Secondly, and more importantly, axial loading through the Ankle and into the Knee resulting from an impact below the Foot may be increased resulting in a higher risk of Ankle and Knee trauma during loading of the Foot. To the authors' knowledge no research has been conducted taking these aspects into consideration in the development of a motorcycle boot. Therefore, this hypothesis is a first in the industry.

In AMA (American Motorcycle Association) sanctioned MotoCross and SuperCross events, the total number of lower extremity injuries may be as high as 9% of all injuries. 40% of these injuries are ligamentous and relate mostly to ACL, MCL and Meniscus injury [7]. In a study conducted on 1500 off-road motorcycle accidents, 344 cases resulted in ligamentous injury, of which 206 or 59.9% occurred in the lower extremities, especially on the Knee (42.4%) and Ankle (24.3%) **Error! Reference source not found.**. A study by Khana et. al [7] suggests the same trend. In addition to above, Tibial plateau fractures, Fibular fractures, malleolar injuries, ACL rupture and medial meniscus tears are common injuries related to a pivoting Foot on an outstretched leg when cornering **Error! Reference source not found.**. A rigid boot may transfer some of these ground forces to the Knee due to limited natural movement or "energy release" in the Ankle area.

An off-road boot in general should be designed to allow for controlled but natural Ankle movement with a definite lockout position in inversion and eversion, together with good heel absorption, allowing the transfer of loading mechanisms which may result in above mentioned Ankle and Knee injuries, through controlled energy release.

The design rational of the Leatt® GPX 5.5 MX Boot included consideration of methods to unload the bony structures of the Ankle joint complex using a controlled energy release system with alternative load path technology, transferring and dispersing impact forces away from the Ankle in a safe way. This included consideration of the secondary effects of load transfer such as loading directed through the Tibia and into the Knee. These effects were evaluated through testing of the device and comparison of it to an existing high-end MX boot through evaluation of injury criteria and AIS (Abbreviated Injury Scale) risk for inversion deformation and Ankle and Knee axial loading.

The Leatt® GPX 5.5 MX Boot has been designed by a team of specialized professionals to optimize its performance for Ankle and Knee protection in extreme sports. The design includes input from orthopedic surgery, biomedical engineering and mechanical engineering and from competitive sporting professionals. This, in conjunction with testing and constant reference to human reaction to and tolerance of various quasi-static loading scenarios, ensured that the device design was optimized through multiple design iterations.

1.2 Motivation

Lower limb injuries, including Ankle and Knee injuries are some of the most common injury types in extreme sports such as off-road motorcycling. Injuries in this area may often cause a rider great discomfort, significant recovery times and even permanent disability or an inability to continue his/her sporting discipline. It was for these reasons that a device was designed to help protect people from the aforementioned injuries.

Additionally, the development of a boot that raises the bar in terms of comfort, Ankle movement, freedom and feel (proprioception), whilst optimally protecting the user, served as motivation for this project.

1.3 Objectives

The research, design, and testing underlying the Leatt® GPX 5.5 MX Boot focused on overall efficacy in creating an effective and reliable product. The Leatt® GPX 5.5 MX Boot Research and Development (R&D) rationale is presented in this paper, and the objective is to elaborate on each phase of development. Common questions regarding various aspects of the Leatt® GPX 5.5 MX Boot, such as injury mechanisms and the product's ability to prevent them from occurring, are addressed.

The specific objectives for this study can be summarized as:

- The identification of relevant knowledge in the fields of Ankle anatophysiology, kinematics, impact mechanics and injury mechanisms through an extensive literature review.
- The presentation of the Leatt® GPX 5.5 MX Boot design rationale.
- The presentation of representative tests conducted on the Leatt® GPX 5.5 MX Boot and discussion of their results.

1.4 Outline

Chapter 2 discusses some of the relevant literature reviewed for this study, including literature on the anatomy and physiology of the Ankle. The injury modalities and mechanisms of injury associated with the Ankle are discussed. Options for the protection of the Knee and associated challenges are also described.

In Chapter 3 the general and specific rationales for the design of the Leatt® GPX 5.5 MX Boot are discussed. The general rationale includes considerations such as fit and comfort, energy release through alternative load path creation and impact protection.

Chapter 4 forms the body of the document and offers a presentation of the testing conducted on the Leatt® GPX 5.5 MX Boot. This includes impact tests conducted to assess forces through the Ankle joint, forces directed towards the Knee, and Knee-specific forces. Injury thresholds of the Ankle in inversion as well as for axial load transfer are evaluated against above mentioned experimentally obtained parameters. Further analysis was conducted by means of fatigue testing of the product component under riding conditions as well as actual riding tests by professional riders.

Chapter 2

Literature Review

This chapter discusses Ankle biomechanics, focusing on the main Ankle injuries sustained in extreme sports such as off-road motorcycling. A short introduction to Ankle anatomy is presented, followed by Ankle injury modalities along with motorcycle Ankle/Foot protection options and their challenges.

2.1 Anatophysiology of the Ankle

2.1.1 Anatomy of the Ankle

Osteology and joint anatomy

The Ankle joint or talocrural joint is a hinged synovial joint formed where the distal end of the leg or shin (Tibia) meets the superior surface of the uppermost bone of the Foot (talus) and slots in between the lower ends of the Tibia and Fibula (Figure 2-1). This large hinge joint allows for primarily up-and-down movement (plantarflexion and dorsiflexion respectively), although when taking the range of motion of the Ankle and subtalar joints (talocalcaneal and talocalcaneonavicular) together, the Ankle joint complex functions as a universal joint [8][9] with inversion and eversion as well as pronation and supination movements being possible.

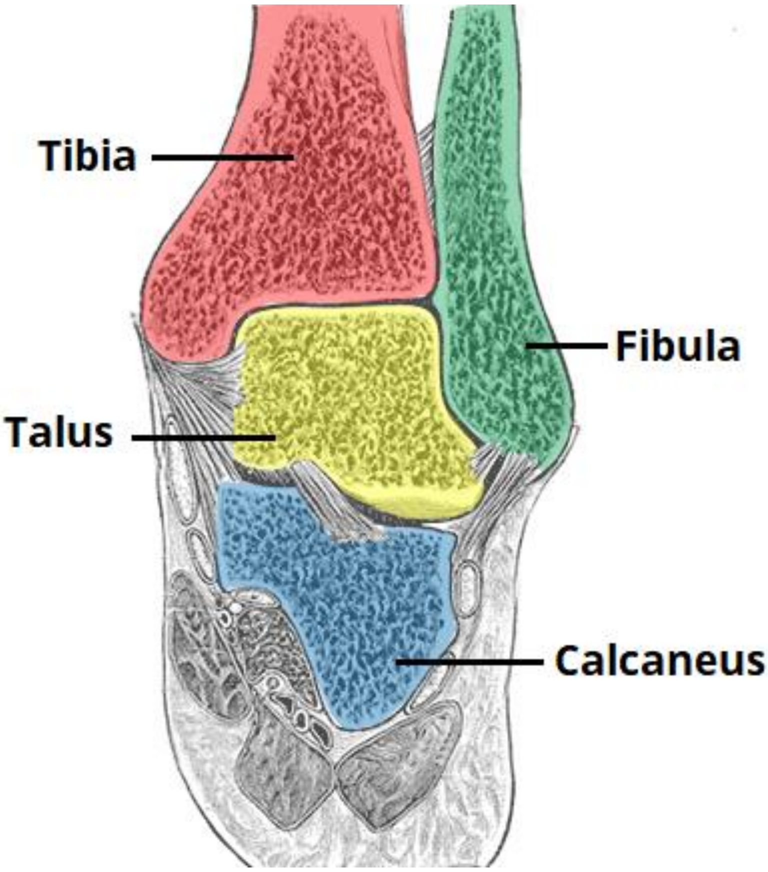


Figure 2-1: Frontal plane section of the bones of the Ankle joint Error! Reference source not found.

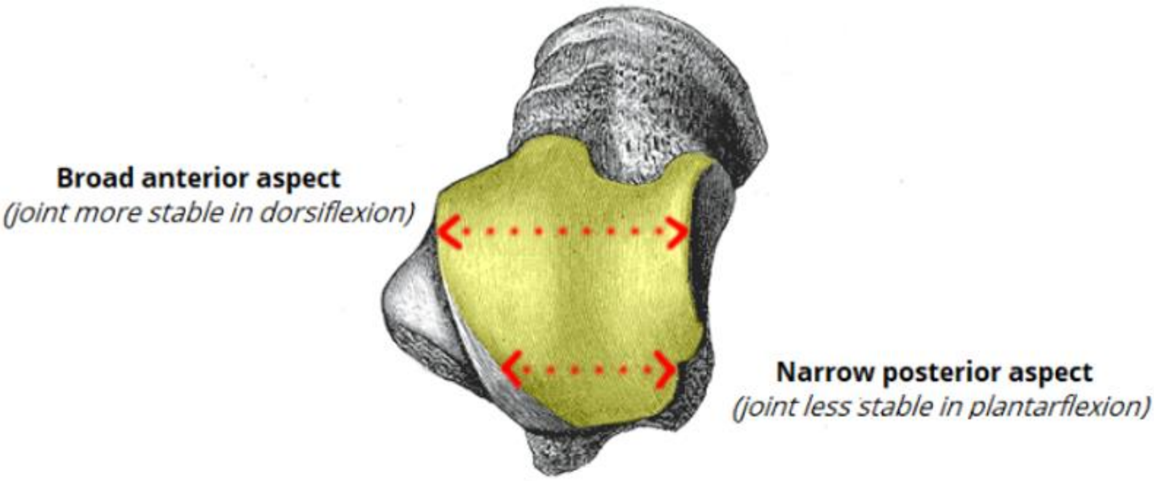


Figure 2-2: The talus sliding aspects [10]

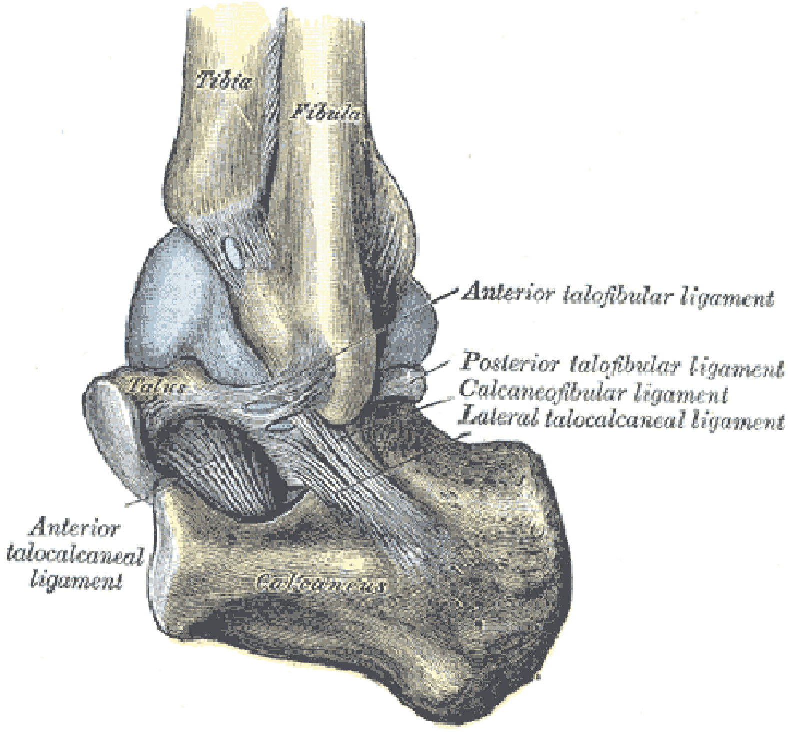


Figure 2-3: Anatomy (Osteology) of the Ankle joint [9]

The talus provides for plantar and dorsiflexion. The anterior aspect of the talus joint surface is broad, allowing for a very stable joint during dorsiflexion, whilst the posterior aspect is narrow, creating a less stable joint during plantar flexion (Figure 2-2). This creates a scenario whereby injuries (dislocations and ligament ruptures) are more likely to occur during contact with the ground with a plantarflexed Foot.

Ligaments of the Ankle joint

Ligamentous structures located laterally from the joint, limit excessive inversion and eversion of the Ankle joint as well as maintaining joint stability.

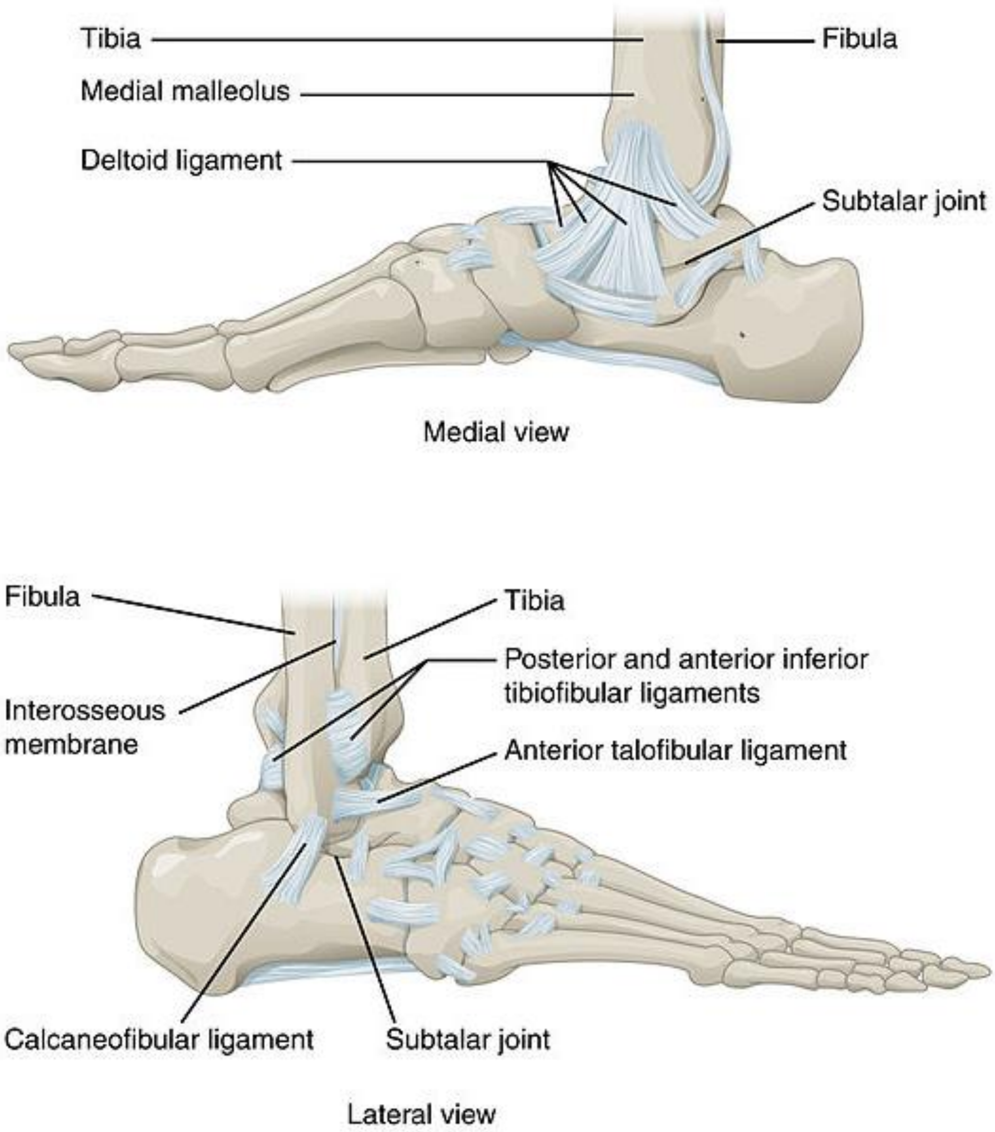


Figure 2-4: Ligaments of the Ankle joint [10]

The two sets (groups) of ligaments that govern the movement and stability of the Ankle joint are:

Medial Ligament Group

The medial ligament (or deltoid ligament) is attached to the medial malleolus (a bony prominence projecting from the medial aspect of the distal Tibia).

Consisting of four ligaments, which fan out from the malleolus, it attaches to the talus, calcaneus and navicular bones. The primary action of the medial ligament is to resist hyper-eversion (outwards rolling) of the Foot.

Lateral Ligament Group

The lateral ligament originates from the lateral malleolus (a bony prominence projecting from the lateral aspect of the distal Fibula).

It resists hyper-inversion (inwards rolling) of the Foot, and is comprised of three distinct and separate ligaments:

Anterior TaloFibular – spans between the lateral malleolus and lateral aspect of the talus.

Posterior TaloFibular – spans between the lateral malleolus and the posterior aspect of the talus.

CalcaneoFibular – spans between the lateral malleolus and the calcaneus.

In this study we will focus mostly on the lateral ligament group, as it has to do with resisting the major injury mechanism of the ankle, namely inversion.

2.1.2 Ankle Kinematics and Kinetics

Kinematics

The Ankle joint is a complex multiplanar joint allowing multiplanar Foot and Ankle motion which can act in isolation or coupled to create complex movements.

The Ankle joint allows for inversion and eversion of the Foot in the frontal (coronal) plane, plantar and dorsiflexion in the sagittal plane and abduction and adduction in the horizontal (transverse) transverse plane.

Various studies cite the range of motion of the Ankle in all planes of motion (Table 2-1) [11][12][13][14]. Surpassing these values under applied load might result in various injuries of the Ankle and may even result in displaced injuries to other areas of the leg such as the Tibia, Fibula or Knee.

TABLE 2-1: ROM OF THE ANKLE [11][12][13][14]

	ROM			
Mechanism	**[7]**	**[8]**	**[9]**	**[10]**
Plantarflexion	50°	--	40°-55°	50°
Dorsiflexion	20°	--	10°-20°	20°
Inversion	35°	30°	23°	30°
Eversion	25°	20°	12°	10°

The most commonly evaluated forces related to Ankle movements are during walking (resulting in normal joint loading and movement), but also during abnormal loading of the Ankle, in order to relate injuries to mechanisms of causation. In the latter, the typical movements resulting in injurious Ankle joint motion include landing directly on the bottom of the Foot from a height (with plantar or dorsiflexed Ankle position) causing high axial load through the Ankle joint (unstable or stable), and twisting or rolling the Ankle after stepping or landing on a non-uniform surface causing hyper-inversion or hyper-eversion of the Foot.

Joint contact forces and joint loading vs joint orientation

The Ankle joint complex bears a force of approximately five times body weight during stance in normal walking, and up to thirteen times body weight during activities such as running [13]. When a rider lands directly on his/her feet after ejecting from a bike during a jump, or even whilst standing on the Foot pegs when landing a jump, it can be appreciated that the load on the Ankle can increase significantly beyond abovementioned load factors.

Additionally, take into consideration that the Ankle may not be perfectly straight or aligned at the time of loading, resulting in an unstable joint, which subsequently relates to a non-uniform tensile load distribution to one of the lateral ligament groups.

Similar to other joints in the body, the Ankle joint increases its overall stiffness function in rotation as the speed and angle of moment application to it is increased (illustration of this characteristic shown in **Error! Reference source not found.** below) [3][4][5][6]. This is especially relevant when evaluating inversion and eversion moments in the Ankle joint. Inversion rotation of the Ankle (usually coupled with adduction of the Foot) is the most common method of tearing Ankle ligaments and fracturing the Fibula and/or Tibia [15]. This built-in biomechanical characteristic of the Ankle joint (stiffness increase), acts as a natural barrier against this injury mechanism (via proprioception). The ability of the joint to stiffen on load application is influenced by factors such as muscle pre-tension and tonic muscular activity. These factors in turn point to proprioception related to awareness and control of the Foot's position relative to the body's universal coordinate system and its environment

[16][17]. Proprioception and accompanying neuromuscular feedback mechanisms provide an important component for the establishment and maintenance of functional joint stability. Lack of proprioception may be a common problem in Ankle injuries and improving this ability result in a decrease in the risk of injury [18].

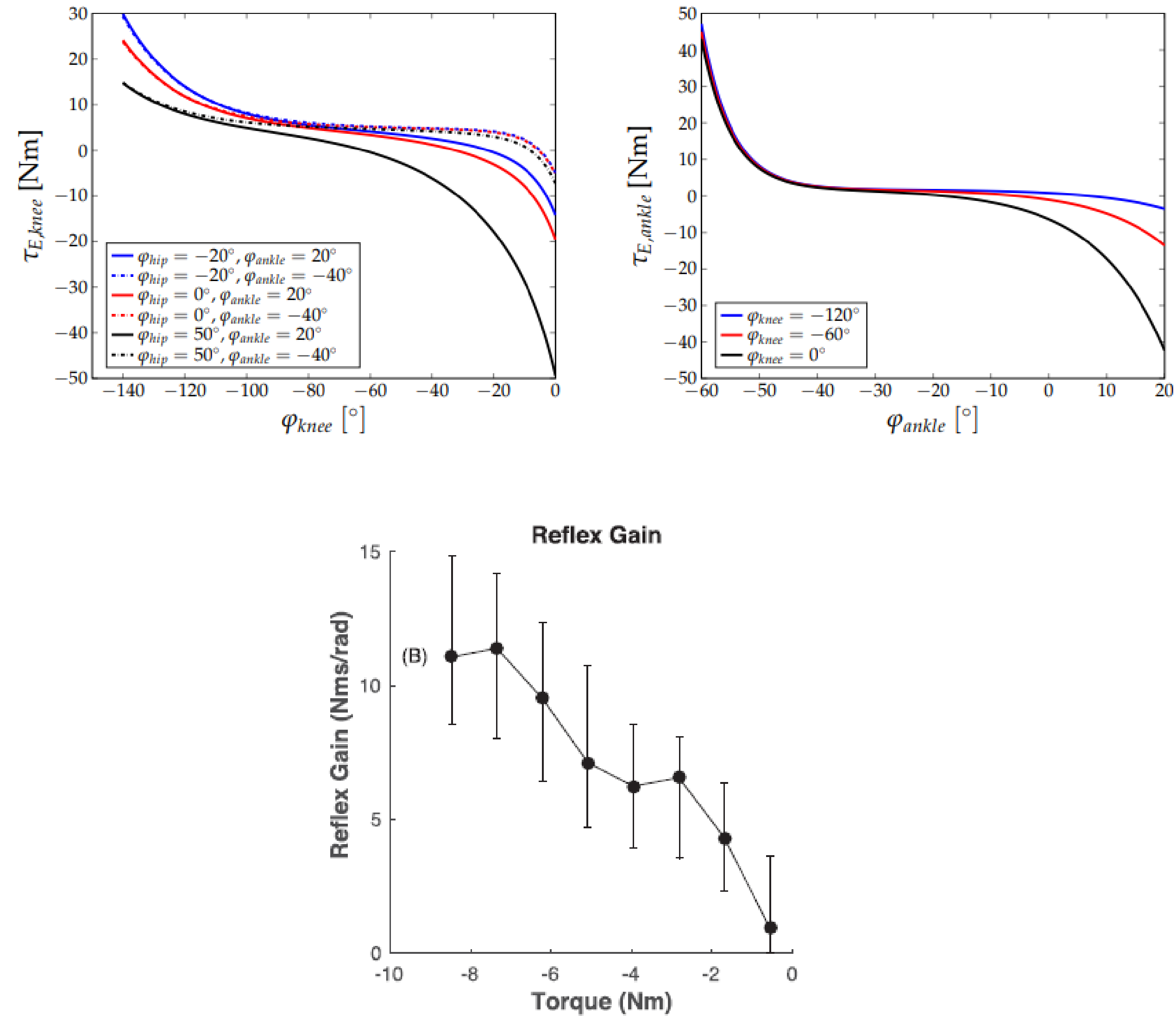


Figure 2-5: Illustration of Ankle joint stiffness function increase as function of rotational torque and applied rotational velocity [4][5]

With abovementioned Ankle joint motions taken into consideration and illustrated in Figure 2-6, it can be appreciated that excessive inversion/eversion and/or axial loading can lead to injury and needs to be mitigated in order to reduce the risk of these injuries from occurring. Injury thresholds for the major Ankle injury mechanisms will be discussed in Section 2.2.

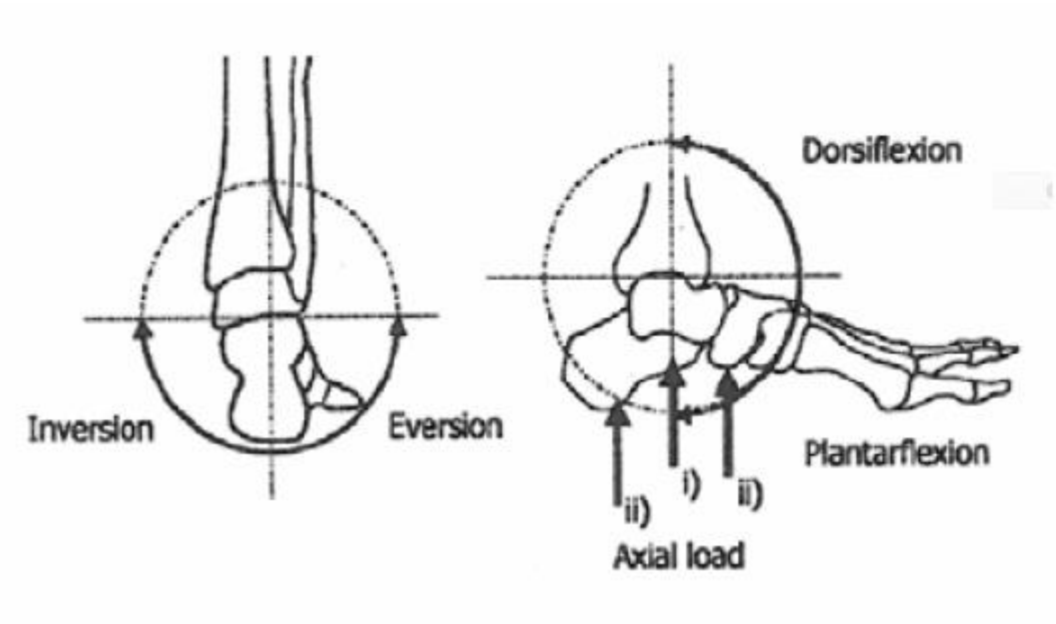


Figure 2-6: Typical Ankle joint loading vectors

In order to design a boot that takes into consideration the major Ankle injury modalities, whilst not adversely affecting adjacent anatomical structures of the leg (such as the Knee) or Foot, it is important to identify and isolate the most relevant forces that may contribute to injury limits being exceeded. For the design of the Leatt® GPX 5.5 MX Boot, forces related to lateral ligament group and Fibular injuries during inversion, as well as axial loading injuries to the Ankle (e.g. pilon fractures) and/or Knee as a result of high-energy impact, was considered the most important. Thus, for the remainder of this study, the focus will be on the structures mentioned above and the forces and mechanisms related to injury of these structures.

Consideration of methods used to restrict excessive force to these structures is thus given in this study and results in the presentation of the Leatt® GPX 5.5 MX Boot as it stands today.

2.2 Injury Modalities

To develop a protective motorcycle boot, it is necessary to understand the mechanisms of Ankle injury and major injury vectors. The design rationale behind the Leatt® GPX 5.5 MX Boot has been modeled on the commonly used Lauge-Hansen Ankle injury classification system (Table 2-2) in use worldwide by Ankle surgeons [19]. Other classification systems commonly used include the Dennis-Weber system [15], although these systems have more or less the same mechanisms related to injury type.

TABLE 2-2: LAUGE-HANSEN ANKLE INJURY CLASSIFICATION SYSTEM [19]

Category	Stage
Supination external rotation	1 Injury of the anterior inferior tibiofibular ligament
	2 Oblique/spiral fracture of the distal fibula
	3 Injury of the posterior inferior tibiofibular ligament or avulsion of the posterior malleolus
	4 Medial malleolus fracture or injury to the deltoid ligament
Supination adduction	1 Transverse fracture of the distal fibula
	2 Vertical fracture of the medial malleolus
Pronation external rotation	1 Medial malleolus fracture or injury to the deltoid ligament
	2 Injury of the anterior inferior tibiofibular ligament
	3 Oblique/spiral fracture of the fibula proximal to the tibial plafond
	4 Injury of the posterior inferior tibiofibular ligament or avulsion of the posterior malleolus
Pronation abduction	1 Medial malleolus fracture or injury to the deltoid ligament
	2 Injury of the anterior inferior tibiofibular ligament
	3 Transverse or comminuted fracture of the fibula proximal to the tibial plafond

Table 2-2 above indicates the resultant Ankle motion because of an externally applied force (injury mechanism) as well as the resultant typical injury and the grade of severity thereof. Supination (inversion) together with adduction and inversion coupled with external rotation are the two most common injury mechanisms of the Ankle and may result in lateral ligament group fractures as well as Fibula and/or Tibia fractures (see below) [15].

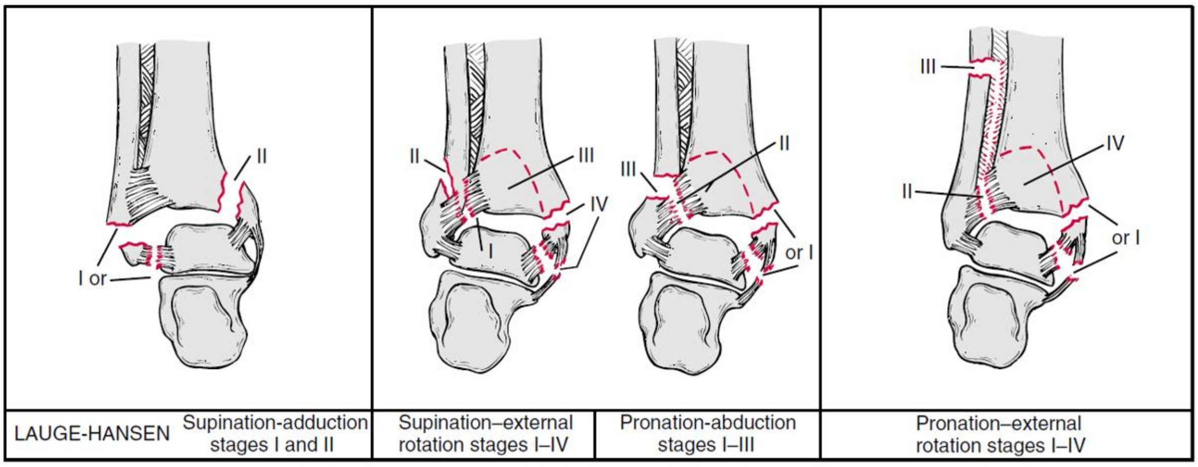


Figure 2-7: Lauge-Hansen Ankle Injury Classification Illustration [15]

In a study conducted by Hanna et al. [20] on the major injuries associated with injury mechanisms resultant from motorcycle riding in general, approximately 56% of Ankle injuries are fractures of the Fibula, all associated with inversion of the Ankle, mostly on a plantarflexed Foot. This can be related back to two very common mechanisms in motocross riding; using the boot as a pivot when sticking out the Foot around a corner, as well as landing after a high-speed jump with the Knee extended and the Ankle in a non-neutral axial alignment in both the sagittal and frontal plane. ***The latter can then be classified in a simplified manner as inversion with adduction coupled with axial loading***. The latter was identified as the major coupled mechanism to be controlled by the Leatt® GPX 5.5 MX Boot.

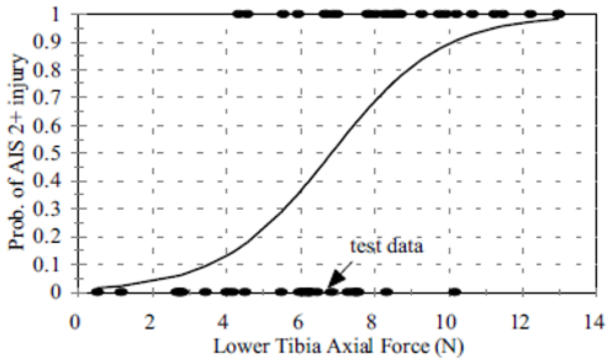
Injury thresholds for the Ankle and Knee

Once the mechanisms of injury to be minimized together with the prevalence of each of these mechanisms are understood, an understanding of the tolerance limits of the structures exposed to these mechanisms is needed. This enabled the authors to design a boot system that would keep loading transferred through the Ankle via typical injury mechanisms within the acceptable load limits and thereby reduce the risk for injury associated with exterior overloading mechanisms. In addition to this it was also important to identify injury thresholds of the adjacent structures of the lower limb which might possibly be affected due to load transfer away from the Ankle. In this case, the Knee was the most obvious and vulnerable adjacent structure.

Injury thresholds and injury risk curves used for the Ankle in axial loading and inversion/eversion are well established and published [21][22][23][24].

TABLE 2-3: INJURY CRITERIA RELATED TO VARIOUS INJURY MECHANISMS OF THE ANKLE

	Loading Tolerance/Limit /Injury Criteria			
Mechanism	**[21]**	**[22]**	**[23]**	**[24]**
Axial Loading [N]*	8000	8000	7293-8115	8000
*Measured in Distal Tibia				
Inversion [Nm]	16	40	40	--
Eversion [Nm]	40	40	40	--



$$p(AIS\ \ 2+) = \frac{1}{1+e^{4.572-0.670F}}$$

where F = lower tibia axial force

Figure 2-8: Probability of AIS2+ injuries to the Calcaneus, Talus, Ankle and Midfoot due to axial loading of the lower Tibia

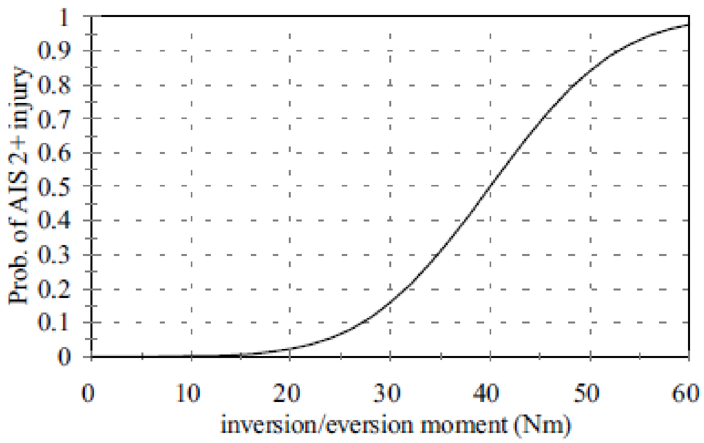


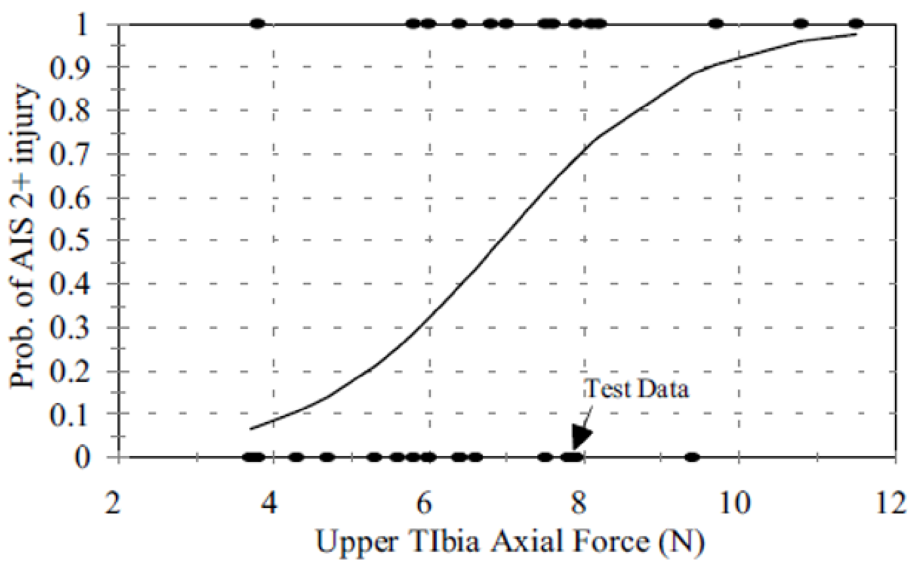
Figure 2-9: Probability of AIS 2+ Ankle injury as a function of subtalar joint moment due to inversion/eversion

Adjacent structures – the Knee

As mentioned above, adjacent structures along the load chain might also be influenced by loading below the Foot. In this case, the Knee is the most likely structure to be influenced due to excessive axial loading and/or valgus deformation imparted due to non-efficient management of Ankle forces. Injury thresholds for the Knee are well published in literature and are commonly used in the design of various systems including PKB's (prophylactic Knee braces) and motor vehicle interior (dashboard design etc.) design. These Knee values, however, should also be evaluated in the development of a boot, due to forces that may be imparted from the Foot through the Ankle and into the Knee. The injury criteria for the injury mechanisms found to be relevant to the development of the Leatt® GPX 5.5 MX Boot are summarized in Table 2-4 below [25][23].

TABLE 2-4: INJURY CRITERIA FOR RELEVANT INJURY MECHANISMS [25][23]

Mechanism	Loading Tolerance / Limit Injury Criteria	Injury Type
Valgus Def [25]	120 Nm @ 13 deg	MCL/Meniscus
Axial Load [23]	8kN @0-20deg flexion	ACL,MCL/Meniscus/**Tibial Plateau + Condyle Fractures**



$$p(AIS\ \ 2+) = \frac{1}{1 + e^{(0.5204 - 0.8189F + 0.0686mass)}}$$

F = upper tibia axial force

Figure 2-10: Risk of AIS 2+ Tibial plateau or condyle injury as a function of upper Tibia axial load [23]

To conclude the current chapter, it can be summarized that the following tolerance limits were used to evaluate the Leatt® GPX 5.5 MX Boot's ability to withstand loading mechanisms related to Ankle and Knee injuries.

Ankle

Axial load measure at distal Tibia on HIII

Inversion/Eversion bending moment as measured on HIII

Knee

Axial load transferred to the Knee measured at proximal Tibia as well as distal Femur

It should be noted that no allowance for muscle reaction was made with the values reported in Table 2-3 and Table 2-4. Browner et al. [15] discussed the effect of late muscle activation on Ankle loading limits. Soni et al. **Error! Reference source not found.** reported a significant increase in Knee joint loading tolerance with the onset of muscle activation during impact. The choice to use passive (no muscle activation) values as injury tolerances was made to ensure a worst-case scenario, resulting in a boot with a significant safety tolerance.

The tests conducted on the Leatt® GPX 5.5 MX Boot to evaluate these effects are discussed in Chapter 3 and Chapter 4.

Chapter 3

Rationale for the Design of the Leatt® GPX 5.5 MX Boot

3.1 Introduction

The design rationale of the Leatt® GPX 5.5 MX Boot is based on common Ankle and Knee injury classification systems as presented in Section 2.2 and as used by Ankle and Knee surgeons as well as biomedical engineers.

The design criteria used in the development of the Leatt® GPX 5.5 MX Boot are as follows:

- To decrease the number and severity of the most significant Ankle injuries through injury prevention or the reduction of the grade of injury without compromising the Knee.
- To optimize proprioception by finding the optimal compromise between safely increasing Ankle inversion/eversion motion within non-injurious ROM (Table 2-1), whilst simultaneously decreasing/controlling Ankle and Knee axial forces. All the above whilst maintaining comfort, rideability and maneuverability.
- To prevent extreme ranges of Ankle motion producing / associated with injury through controlled lockout of the boot within the correct planes of motion.
- Above will be achieved by creating an Alternative Loadpath™ with the lockout mechanisms transferring Ankle bending moments (inversion/eversion and dorsiflexion/plantarflexion) and dispersed components of axial loading due to the allowed bending of the Ankle, away from the Ankle and into the upper

areas of the boot, where it is safely dispersed through absorption into the materials covering less vulnerable loading zones with more musculature over large force distribution areas.

- This should result in decreased axial loading in the Ankle and the Knee as well as bending moment control within safe injury limits.
- To optimize energy absorption and dispersion through the sole of the boot, subsequently reducing induced axial loads carried to the Ankle.
- To absorb lateral impact forces directed to the boot through impact absorbing materials.
- To ensure that the device accommodates a wide range of Foot/lower leg types while still allowing safe and comfortable use with the intended safety functions not being compromised.
- Allowing medial boot contact by the rider with the motorcycle, without intervening structures or surfaces, so as to have better feel and control of the motorcycle.
- To protect against impact related injuries to the Ankle and Foot, through CE certified impact absorption areas.
- To accommodate knee brace usage (PKB).

The Leatt® GPX 5.5 MX Boot, designed with these parameters in mind, fulfills these design criteria.

3.2 Allowable ROM

The Leatt® GPX 5.5 MX Boot can allow for a larger than normal Ankle range of motion (approximately 0° or 0°-15° adjustable inversion, 0° or 0°-10° eversion, 10° plantarflexion, 10° dorsiflexion). Inversion/eversion lockout can be adjusted by polyurethane stoppers to accommodate personal preference in terms of lockout position. Stoppers include a full lockout (0°) or "free" (0°-15°) stoppers.

The Leatt® GPX 5.5 MX Boot was designed to be compatible with most motorcycle types as well as all PKB's and allows riders an adequate range of Ankle joint movement, effectively "releasing or breaking up" axial loads which will usually be transferred through the Ankle and Tibia and into the Knee whilst locking out prior to reaching injury thresholds for the Ankle in inversion/eversion. Subsequently the above mentioned also allows for ease of walking, riding and optimal proprioception (feeling). Leatt® GPX 5.5 MX Boot prototypes were tested extensively by riders under racing conditions and the test riders reported a good range of movement and comfort whilst maintaining proprioception levels not experienced using any other boot.

3.3 Alternative Loadpath Technology™ (ALPT) makes a return

Alternative Loadpath Tehcnology™ (ALPT) in the Ankle refers to the ability of the Leatt® GPX 5.5 MX Boot to redirect, to adjacent structures, the forces applied to the Ankle joint in crashes or collisions. These forces are usually in the form of inferior-superior orientated loading to the Foot which will, in the case of a completely unrestrained Ankle, result in either an inversion with adduction mechanism in the Ankle, or in the case of a significantly restrained Ankle (such as with most traditional boots), an axial loading injury to the Ankle or Knee due to the impact load vector not being able to "escape" or be "released" into smaller component vectors.

The force diagram shown in Figure 3-1 illustrates the difference in force distribution between a rigid boot and a non-rigid boot with controlled injury prevention lockout. The latter creates a stable system which transfers loading otherwise resulting in Ankle inversion and/or Knee axial loading injuries. The former shows that a rigid boot transfers all impacts (stepped or Ankle twisting forces or direct inferior/superior forces) straight through the Ankle and potentially into the Knee as axial force, exposing both these joints to injuries as discussed in Section 2.2.

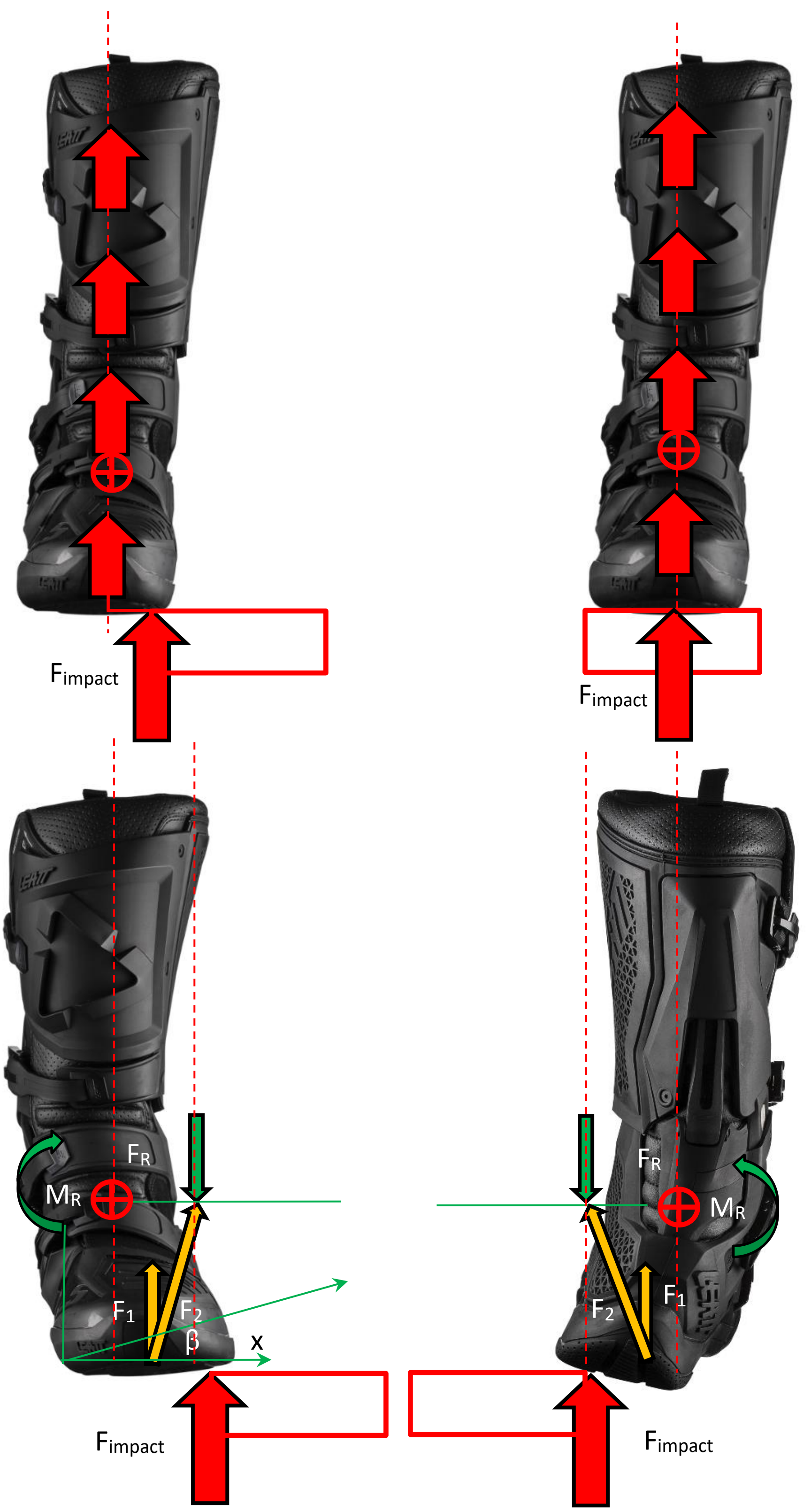


Figure 3-1: Ineffective load path distribution in a traditional highly rigid boot vs Alternative Loadpath Technology™ (ALP) in the Leatt® GPX 5.5 MX Boot

The force diagram illustrated above can be expressed using the following basic equation:

Sum of forces acting on medial lockout mechanism on inversion:

$$F_{impact} = F_1 + F_2 = M_R + F_R$$

Sum of Moments around the lateral lockout mechanism on inversion:

$$M_R = F_R - x.(F_1 + F_2 \cos\beta)$$

where:

F_{impact} the impact force acting from below the boot

F_1 the decreased released component of the impact force acting axially

F_2 the decreased released component of the impact force acting normal to the Ankle inversion angle and counteracted by the lockout

In summary the design rationale of the Leatt® GPX 5.5 MX Boot is to control axial forces imparted to the Ankle and Knee joint through *ALPT* and hyper-inversion limitation. This is attained through the utilization of a lockout mechanism operating in conjunction with stiff materials and engineered contoured surfaces to increase overall stiffness of the system in engineered areas for optimal load transfer efficiency. The applied axial impact load is thus dispersed or "broken up" into two smaller load vectors, with only a small percentage of the initial axial load, transferred through the Ankle joint (F_1), with the remaining vector (F_2) being counteracted by the lockout mechanisms reaction forces (F_R and M_R).

Specifics on loading parameters and force reductions will be presented in Chapter 4.

3.4 Material /Absorption Considerations

The Leatt® GPX 5.5 MX Boot is designed to bring the inversed Ankle to a controlled stop upon load transfer through a soft PU stopper in the lateral mechanism and a slotted stopper on the lateral overlapping surfaces of the heel counter and the calf piece.

3.5 FlexLock Lockout Design

The Leatt® GPX 5.5 MX Boot is designed with a lateral lockout mechanism as well as a simplified medial lockout mechanism. These mechanisms have self-aligning properties because of their floating, vertically oval shaped pivot and lockout points.

The medial and lateral lockouts have been designed to coincide on lockout angle with the two sides having inverted lockout positions (top lockout medial vs bottom lockout lateral, and vice versa), creating a virtual "seesaw". This enables the Ankle to be protected within a cage-like lockout with forces being directed away from it via ALPT as discussed in Section 3.3 above.

These lockouts are not instant however, as a degree of movement to "escape" the axial impact force vector is allowed initially before lockout occurs.

Figure 3-2: FlexLock Lateral Lockout Mechanism

Two lockout options can be accommodated based on rider preference or based upon the possible prevalence of an existing or chronic injury or Ankle pathology. Adjustment is made via interchangeable pins or “shims”, one allowing for a permanent locked or fixed position, the other allowing a predetermined degree of inversion/eversion within allowable averaged ROM limits as presented in Table 2-1.

3.6 Sizing and fit

The Leatt® GPX 5.5 MX Boot is designed for various Foot sizes ranging from US size 8 to size 14, with core size (size around which the boot was developed and the first Foot last was modeled for fit) at US 10.

With regards to fit, the Leatt® GPX 5.5 MX Boot was designed to offer a comfortable fit with a wide toe box but low profile for ease of changing gears.

Buckles are replaceable as well as the sole.

Chapter 4

Testing of the Leatt® GPX 5.5 MX Boot

4.1 Dynamic Impact Testing

4.1.1 Introduction

The rationale for these tests is derived from the "design rationale" (Chapter 3) that underpins the Leatt® GPX 5.5 MX Boot design, and incorporates the beliefs, theories, and expertise (gained through biomechanical knowledge and experience in the field) of the physiologically correct dynamic interaction between a rider and a motorcycle boot.

As discussed in Section 3, it is believed that a boot should allow for some movement at the Ankle joint, thus releasing some of the axial impact energy into different force components/vectors, henceforth not transferring all axial loading through the Ankle joint and into the Knee as one concentrated force vector.

It should thus be the primary function of a boot system such as the Leatt® GPX 5.5 MX Boot to prevent or reduce the likelihood of the following injuries:

- Pilon Fractures of the Ankle due to excessive axial loading through the Ankle joint
- Hyper-inversion related injuries of the Ankle
- Hyper-eversion related injuries of the Ankle
- Inversion / adduction coupled with axial loading through the lower leg
- Axial loading through the Knee which may result in tibiofemoral joint, severe bony injuries or Knee ligament rupture.

- Injuries because of impact, such as soft tissue injuries, bruising, contusions, cuts and abrasions during off-road motorcycling and biking activities.

The likelihood and severity of above-mentioned injury mechanisms should be shown, through the testing presented, to be reduced via a reduction in the relevant measured Ankle and Knee force and moment parameters. Sufficient reduction of above-mentioned forces and moments (as well as injury risk probabilities), will validate the presence and efficacy of the ALPT™ employed in the design of this boot.

It has been determined, by experimentation with different combinations of materials and fabrics that, in addition to the above, device constituent materials and fabrics used as padding and coverings play a significant role in the dynamics of force attenuation, transmission, duration and redirection away from the Ankle and Knee joint complex through the device and towards the larger reinforced structural components of the boot (as discussed in Chapter 3). These factors however have not been isolated for separate evaluation in these tests and are addressed and evaluated in the CE certification of this device. All devices therefore are tested as sold and as a system, adjusted as closely as practicable to their optimal described working configuration.

Lastly, the device is evaluated using fatigue analysis in a custom designed fatigue test rig. The ability of the device's lockout mechanisms to withstand ingress of soil and moisture whilst being operated is evaluated through rider testing.

4.1.2 Dynamic Impact Testing for Ankle Response

Test Objective

To determine the efficacy of the device to reduce the forces transferred to the Ankle joint complex via pure axial loading (flat impact) and inversion/axial loading mechanism (stepped impact). This test will indicate the efficacy of the ALPT™ system. Ankle bending moment as well as Ankle and Tibial axial force were measured. The device will be evaluated for both Ankle lockout settings, namely "fixed" and "free", interchangeable via replaceable lockout "shim" (as discussed in Section 3.5). Boot position relative to the impact plate was kept constant for repeatability.

Evaluation Criteria

The device shall effectively transfer a significant portion of the impact force and/or inversion/eversion bending moment away from the Ankle joint as compared to the baseline scenario (standard shoe). Efficacy will thus be measured via a percentage reduction in above parameters as well as the percentage reduction in Risk of AIS2+ injury. Reduction in injury risk will be evaluated for Malleolar fractures, Ankle ligament injuries, Calcaneus, Talus, Ankle and MidFoot fractures. 3 runs per test was conducted and the average values were used.

Notes

The input impact force for the flat impact tests were set to correspond to a baseline (shoe only) lower Tibia response of approximately 7000 N, which results in a 50% risk for AIS 2+ Ankle injury (Figure 2-8). For the stepped impacts (inversion mechanism), the Tibia response was set to 12000 N (95% AIS 2+ injury risk) to initiate high inversion bending moment and assess the efficacy of the device in keeping inversion moments below or close to the injury threshold of 40 Nm.

One Leatt® GPX 5.5 MX Boot was used per test. The device was fitted to the CSIR Landward Sciences (Council for Scientific and Industrial Research) military blast impact test rig as illustrated below in Figure 4-1. A standard instrumented 50th percentile Hybrid III Anthropomorphic Test Dummy (HIII ATD) was used for all testing, using Ankle, Lower Tibia, Knee and Lower Femur load cells measuring force and bending moments within 6 DOF. All data was filtered using the SAE J211-1 test protocol. All tests were conducted, and all data processed by CSIR Engineers and Technicians.

Figure 4-1: Test setup used

Flat Impact Tests:

Figure 4-2: Flat impact tests for three scenarios

Data Presentation and Evaluation – Flat Impact Tests

Input Force

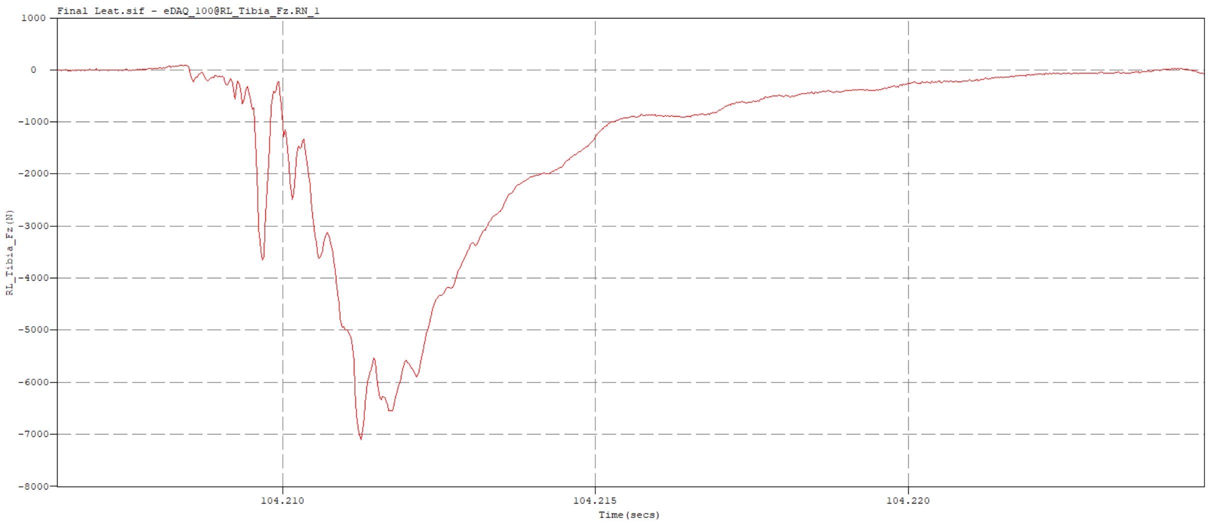


Figure 4-3: Flat Input force- Lower Tibia Fz

Results

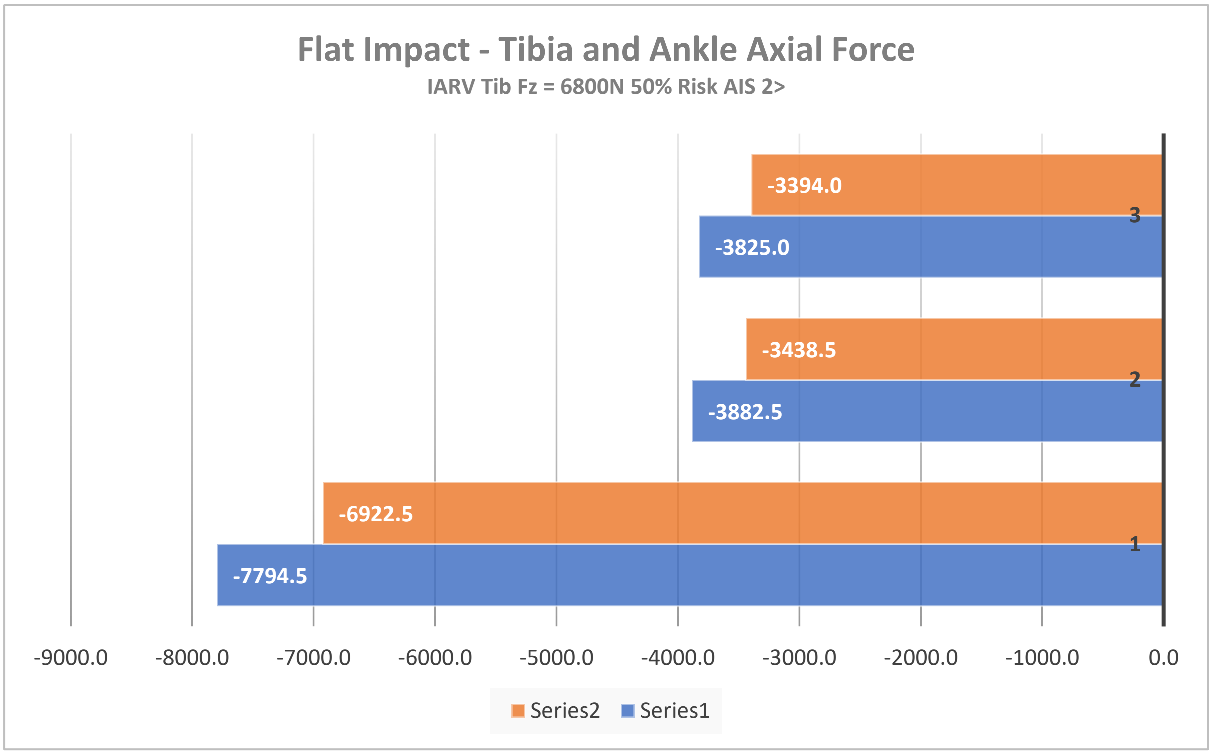


Figure 4-4: Lower Tibia Fz and Ankle Fz [N] for flat impact tests

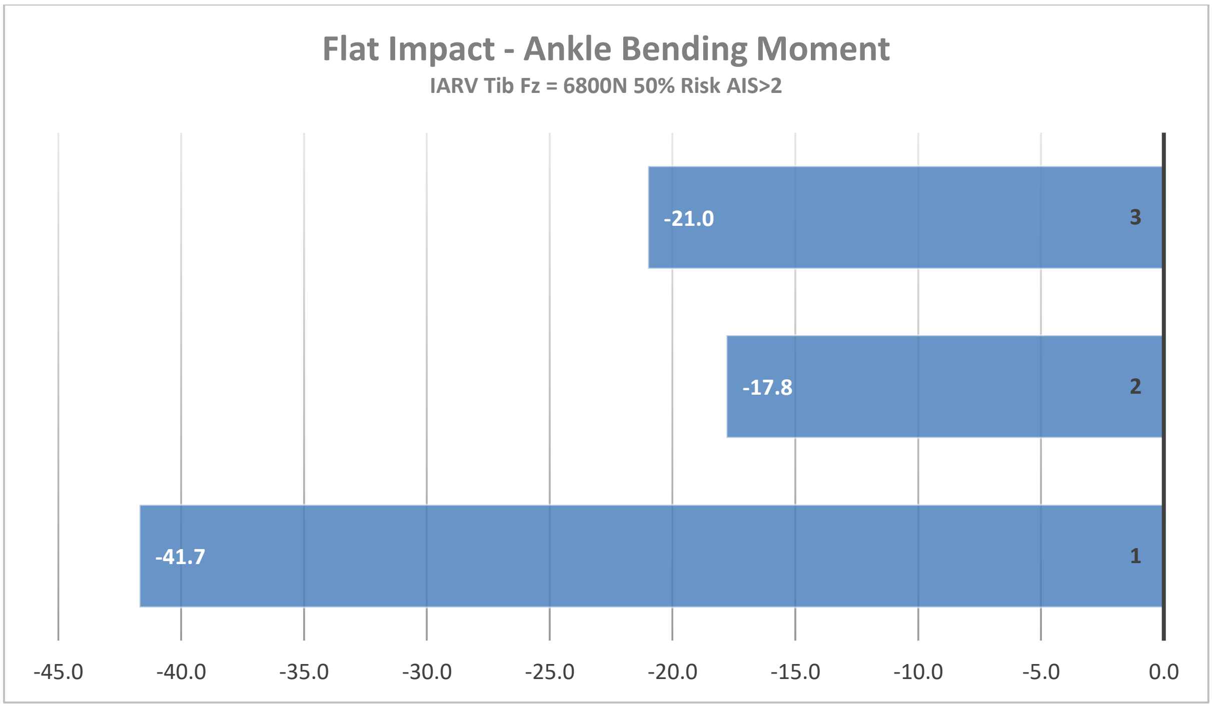


Figure 4-5: Ankle bending moments Mx [Nm] for flat impact tests

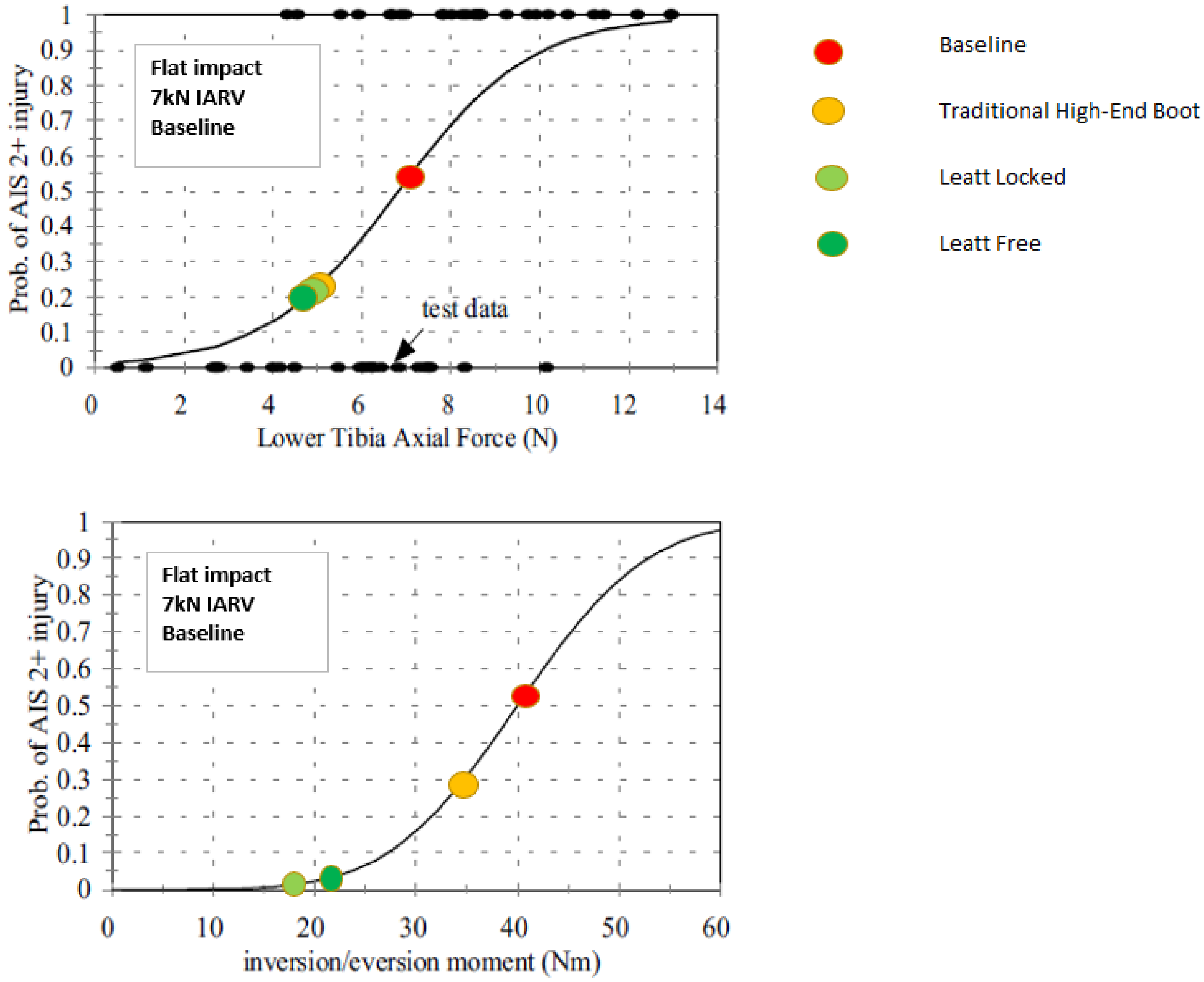


Figure 4-6: Injury Risk Response Curves - Flat Impact Tests

Above – Risk of Calcaneus, Talus, Ankle and MidFoot Fractures

Below – Risk for Malleolar fractures and Ankle ligament injuries

Stepped Impact Tests:

Baseline Leatt "locked" Leatt "free"

Figure 4-7: Stepped impact test setup

Data Presentation and Evaluation – Stepped Impact Tests

Input Force

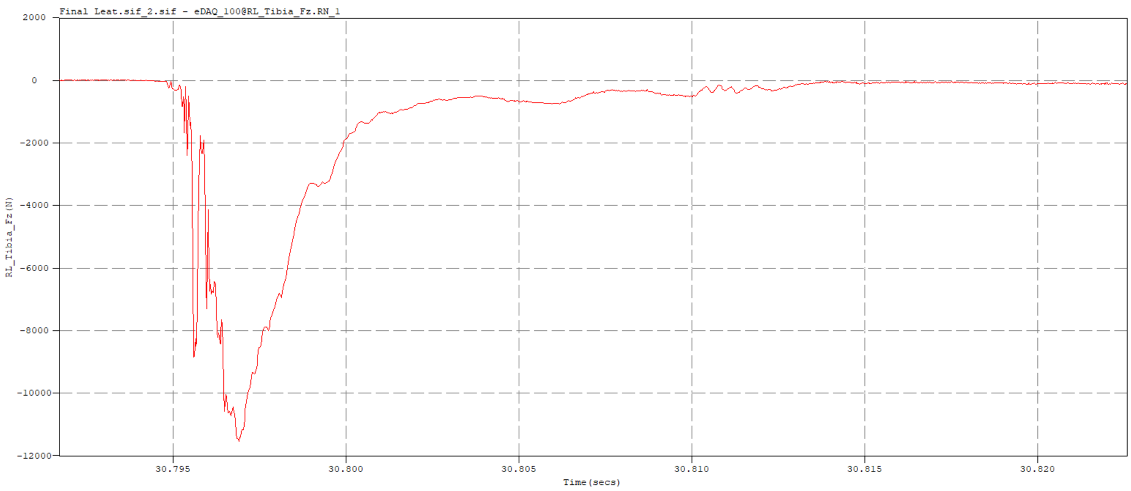


Figure 4-8: Stepped Input force- Lower Tibia Fz

Results

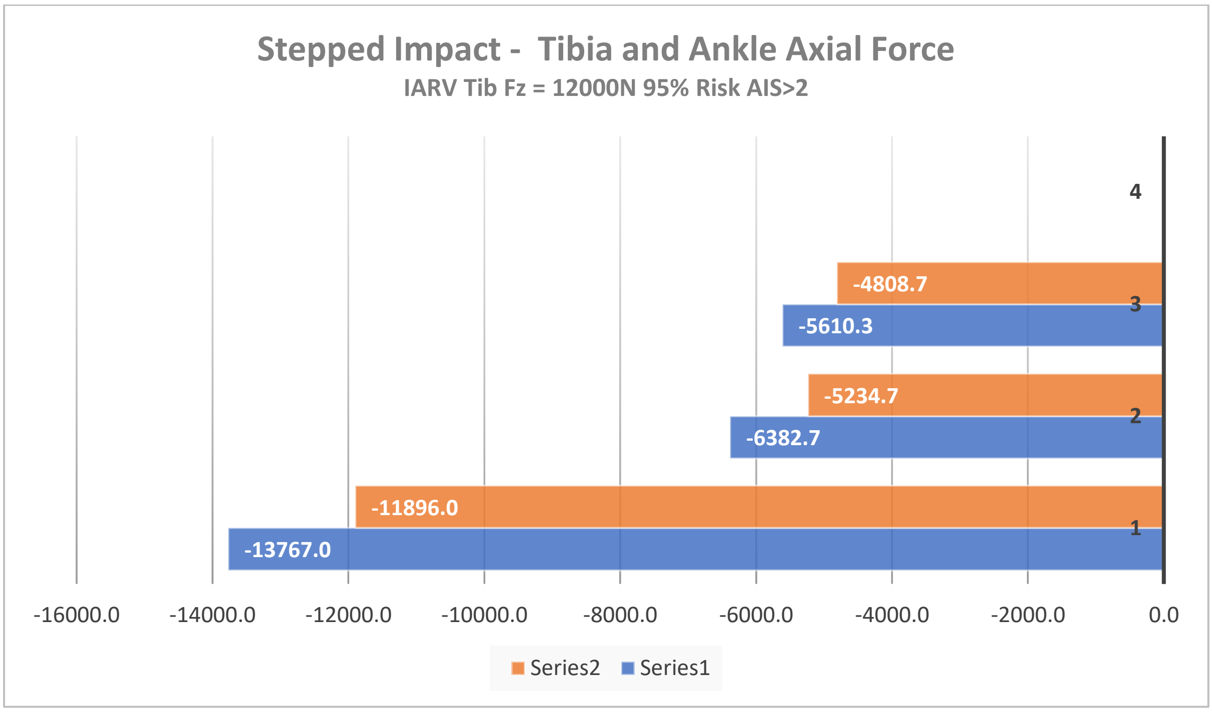


Figure 4-9: Lower Tibia Fz and Ankle Fz [N] for stepped impact tests

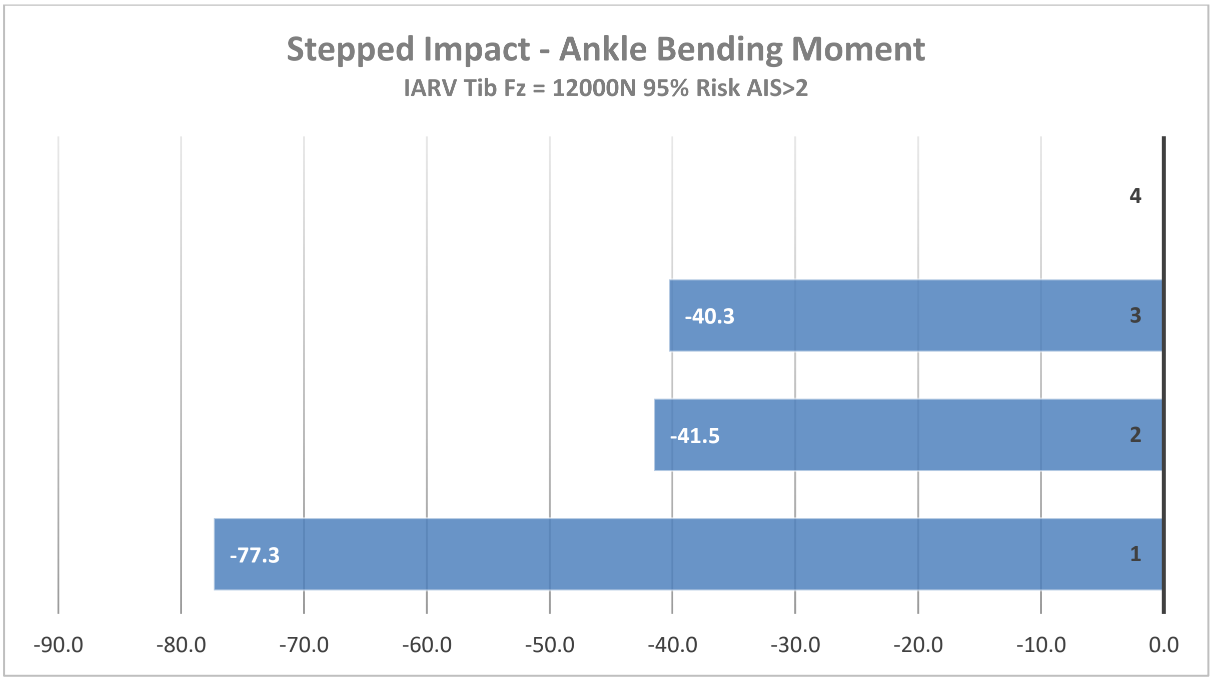


Figure 4-10: Ankle bending moments Mx [Nm] for stepped impact tests

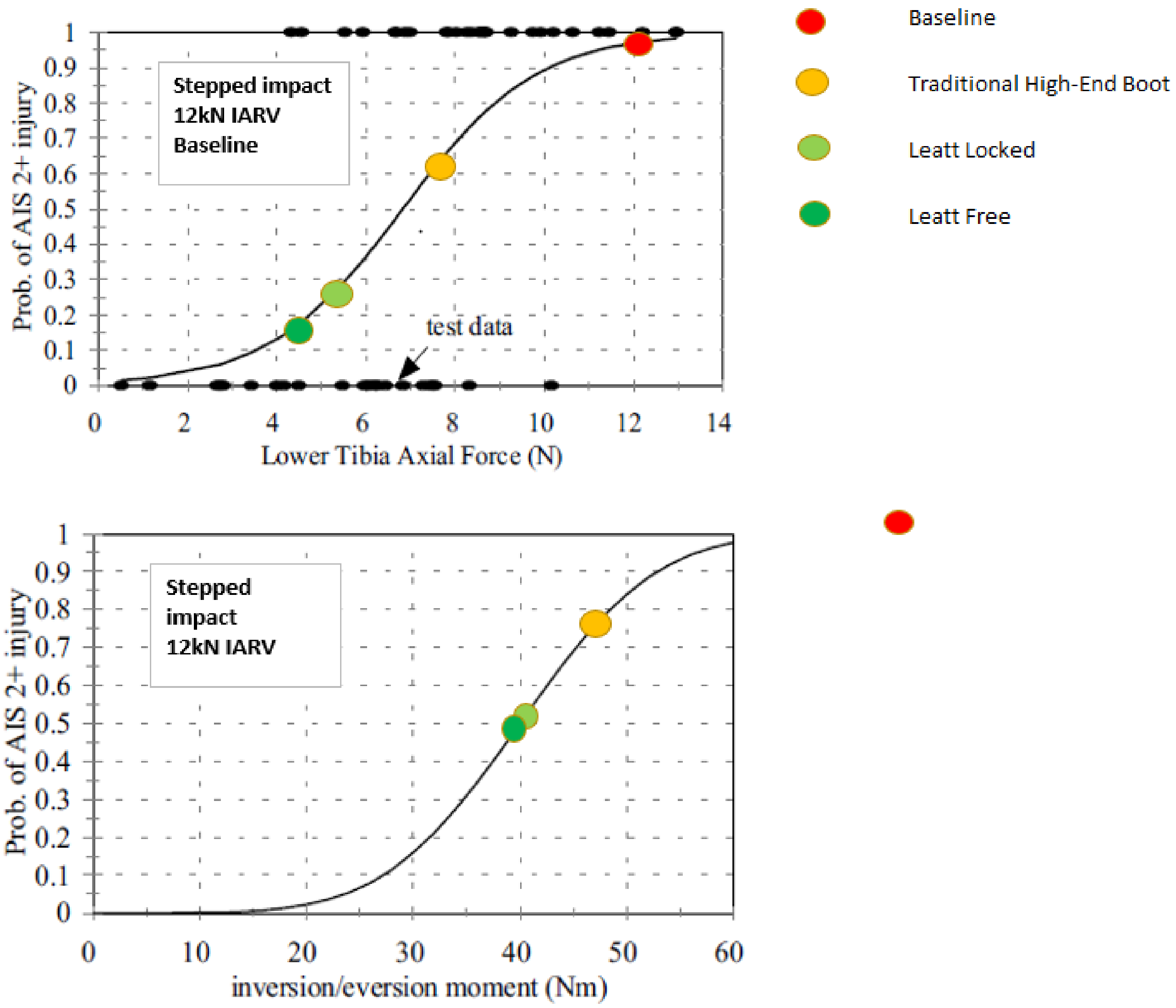


Figure 4-11: Injury Risk Response Curves - Stepped Impact Tests

Above – Risk of Calcaneus, Talus, Ankle and MidFoot Fractures

Below – Risk for Malleolar fractures and Ankle ligament injuries

Figure 4-12: A stepped impact test with Leatt® GPX 5.5 MX Boot

Discussion and Conclusions

Flat Impact Tests

The Leatt® GPX 5.5 MX Boot reduced Tibia and Ankle Axial loading by 51% for the "free" setting and 50% for the "fixed" setting compared to the baseline test (Figure 4-4). Assessing the reduction in inversion injury mechanism, the Leatt® GPX 5.5 MX

Boot reduced Ankle bending moments by 49.6% for the "free" setting and 57.3% for the "fixed" setting (Figure 4-5).

Whilst it might seem counterintuitive that there is a significant reduction in Ankle bending moment for an impact that, according to initial logic, will not initiate bending, it was clear to see from the test data that a significant axial loading event on the unstable Ankle can in fact initiate a large bending moment component. This bending moment is thus significantly stabilized by the addition of a boot with controlled Ankle movement allowance.

The risk of Calcaneus, Talus, Ankle and MidFoot Fractures was reduced from 55% baseline to less than 20% with the boot in the "free" setting, whilst the risk for Malleolar fractures and Ankle ligament injuries were reduced from 53% baseline to less than 5% with the boot in the "free" or "locked" setting.

Compared to a high-end traditional boot also tested, the Leatt® GPX 5.5 MX Boot reduced the risk of Calcaneus, Talus, Ankle and MidFoot Fractures from 25% to less than 20%, whilst the risk for Malleolar fractures and Ankle ligament injuries were reduced from 29% to less than 5% with the boot in the "free" or "locked" setting.

Stepped Impact Tests

Additionally, for the stepped impact, specifically focusing on assessing the reduction in inversion injury mechanism as well as the transference of axial load up and through the Ankle joint, the Leatt® GPX 5.5 MX Boot reduced Ankle bending moments by 47.9% for the "free" setting and 46.3% for the "fixed" setting (Figure 4-10). Ankle axial loading was reduced by 59.2% for the "free" setting and 53.6% for the "fixed" setting, whilst axial loading transferred to the lower Tibia was reduced by 59.6% for the "free" setting and 56% for the "fixed" setting.

The risk of Calcaneus, Talus, Ankle and MidFoot Fractures was reduced from 95% baseline to less than 20% with the boot in the "free" setting, whilst the risk for

Malleolar fractures and Ankle ligament injuries were reduced from 100% to less than 48% with the boot in the "free" or "locked" setting.

Compared to a high-end traditional boot also tested, the Leatt® GPX 5.5 MX Boot reduced the risk of Calcaneus, Talus, Ankle and MidFoot Fractures from 60% to less than 20%, whilst the risk for Malleolar fractures and Ankle ligament injuries were reduced from 76% to less than 48% with the boot in the "free" or "locked" setting.

From these results it is clear to see that the Leatt® GPX 5.5 MX Boot is indeed effective in diverting axial force away from the Ankle joint through the allowance of controlled movement before lockout occurs through the lockout mechanism. It can be noted that for the "fixed" setting the boot response is somewhat closer to a traditional boot, with slightly less efficacy in axial load reduction compared to the "free" setting due to increased Ankle restraint. However, the reductions in Ankle bending moment and risk of AIS 2+ injury is still significant compared to baseline and the high-end traditional boot evaluated. The "free" setting resulted in the optimal combination of reduction in axial load and bending moment through the Ankle joint.

There were promising signs that in addition to reducing Ankle forces, the device might also reduce Knee forces. This was observed through a reduction in the axial force directed through the Tibia and towards the Knee joint (59.6% reduction in Lower Tibia force with the boot in its "free" setting). To confirm this, another series of testing was conducted, focusing on the forces through Knee joint, which will be discussed in the next Section.

4.1.3 Dynamic Impact Testing for Knee Response

Test Objective

To determine the efficacy of the device to reduce the forces transferred to the Knee joint complex via axial loading from a stepped surface. It is hypothesised that a traditional stiff boot will increase axial loading to the Knee due to the load being focussed through one "channel", compared to the Leatt® GPX 5.5 MX Boot, which will allow for energy "release" and ALPT™ to disperse the axial load into smaller components directed away from the unidirectional impact axis.

Secondarily to evaluating Knee response, Ankle response was also recorded.

The HIII ATD was placed in position representing the riding posture of a motorcyclist. The Tibia angle was measured to be kept constant at 72° for all tests to maintain repeatability.

Evaluation Criteria

The device shall effectively transfer a significant portion of the impact force away from the Ankle joint as compared to the baseline scenario (a military boot was used for this test) as well as compared to a high-end traditional boot evaluated. Efficacy will thus be measured via a percentage reduction in axial loading transferred through the Knee and Ankle joint. In addition to this the reduction in bending moment measured in the Ankle will be measured.

Notes

The input impact force for these stepped impact tests were set to correspond to a baseline (a military boot only) lower Tibia response of approximately 5500 N.

One Leatt® GPX 5.5 MX Boot was used per test. The device was fitted to the CSIR Landward Sciences (Council for Scientific and Industrial Research) military blast impact test rig as illustrated below in Figure 4-1. A standard instrumented 50th percentile Hybrid III Anthropomorphic Test Dummy (HIII ATD) was used for all testing, using Ankle, Lower Tibia, Knee and Lower Femur load cells measuring force and bending moments within 6 DOF. All data was filtered using the SAE J211-1 test protocol. All tests were conducted, and all data processed by CSIR Engineers and Technicians.

Figure 4-13: Test setup used for Knee analysis

Data Presentation and Evaluation – Knee Response Tests

Input Force

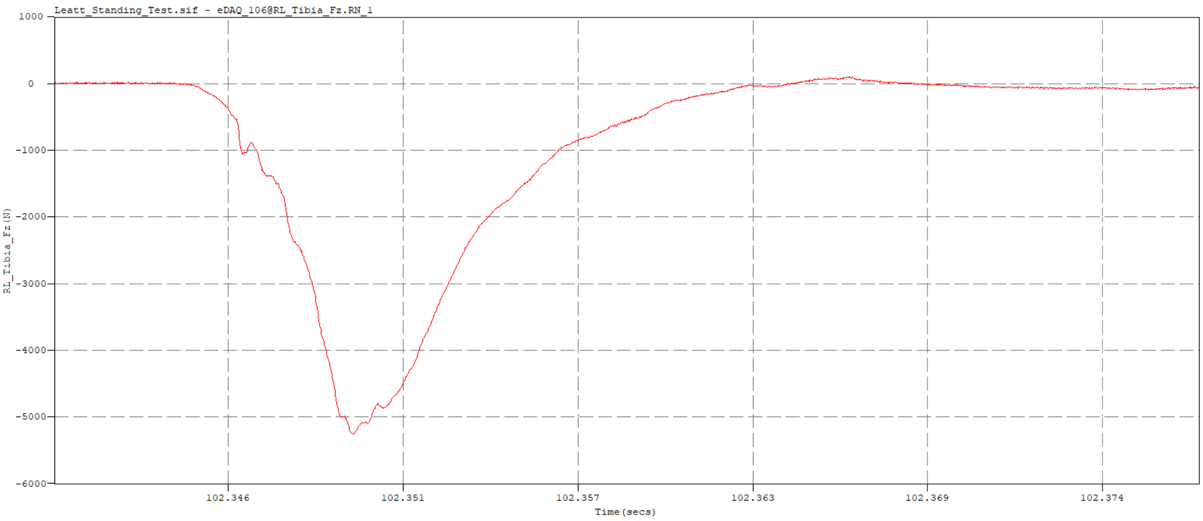


Figure 4-14: Stepped Input force- Lower Tibia Fz

Results

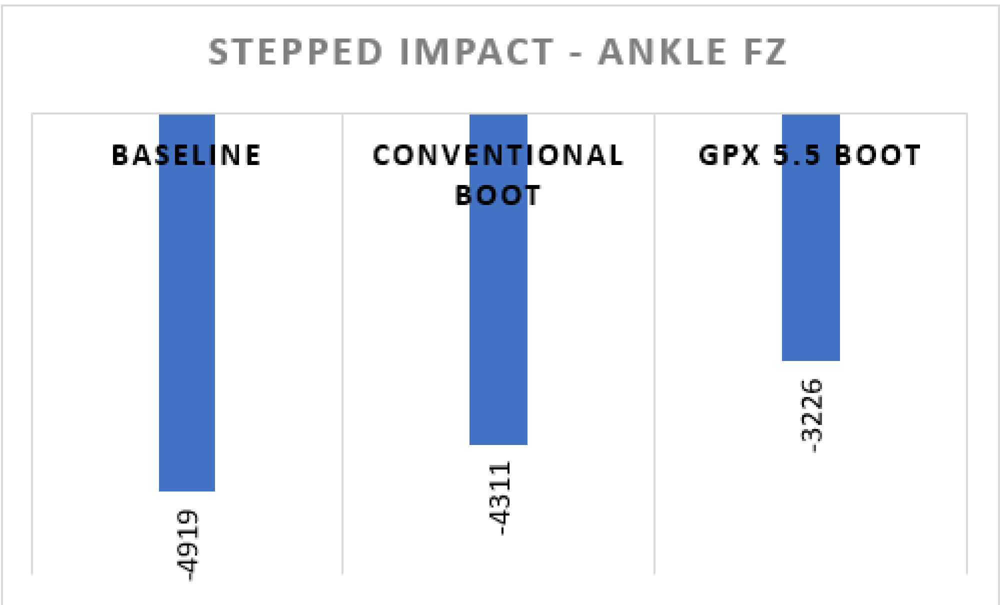


Figure 4-15: Ankle Response - Axial Force Fz

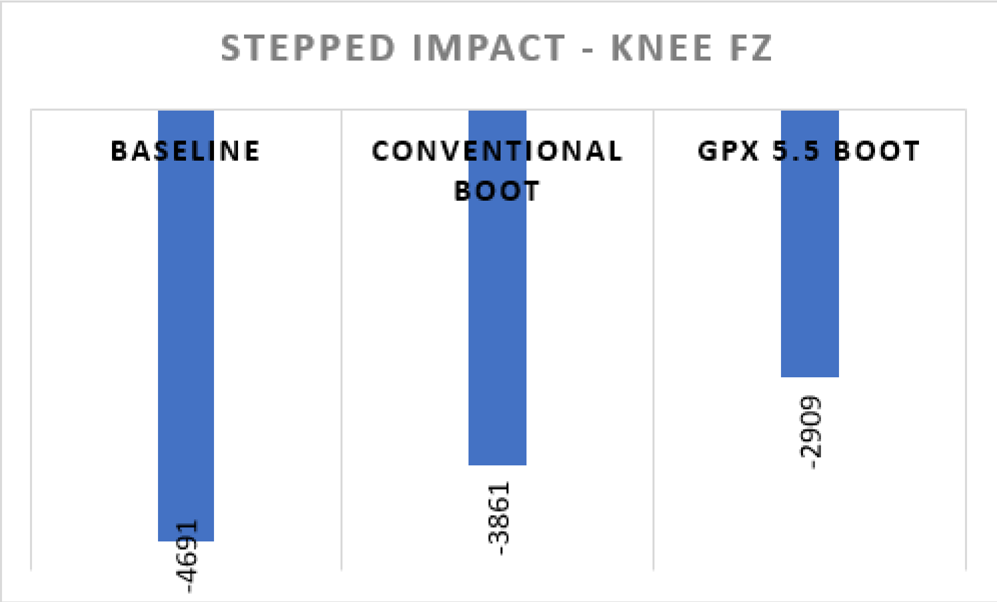


Figure 4-16: Knee Response - Axial Force Fz

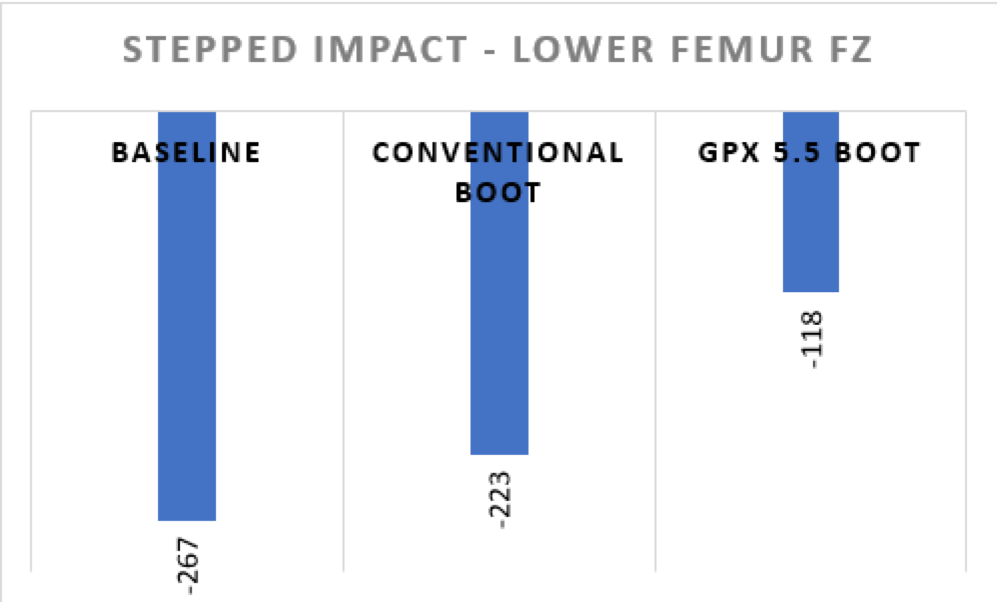


Figure 4-17: Distal Femur Response - Axial Force Fz

Discussion and Conclusions – Stepped Knee Response Tests

In the above presented test results, the Leatt® GPX 5.5 MX Boot reduced Ankle axial loading by 34.4% for the "free" setting compared to the baseline tests and by 25.2% compared to the high-end traditional boot tests (Figure 4-15).

Although the Knee was slightly bent in the test series presented (see Figure 4-13) resulting in axial force dispersal from the Tibia through the Knee and into the Femur, significant reduction in measured lower Femur force was observed. The Leatt® GPX 5.5 MX Boot reduced Femur axial loading by 55.8% for the "free" setting compared to the baseline tests and by 47.1% compared to the high-end traditional boot tests (Figure 4-15).

Lastly, Knee forces were measured. It was found that the Leatt® GPX 5.5 MX Boot reduced Knee forces by 38% compared to the baseline test. In addition, the device reduced Knee axial forces by 24.66% compared to the high-end traditional boot tests (Figure 4-16).

From above results it is clear to observe that the Leatt® GPX 5.5 MX Boot is extremely effective in reducing forces transferred from below the boot into and through the Knee joint. It can thus be concluded that injury risk in the Knee related to axial load injury mechanism will be significantly reduced.

4.2 Fatigue Failure Analysis

In addition to the testing conducted, fatigue analysis was done on the boot using the Leatt fatigue test rig (Figure 4-18).

The fatigue test rig allows the boot to be "walked" with extreme dorsiflexion/plantarflexion moment applied to it. 15,000 test cycles were completed to evaluate wear and possible material weakness on the moveable areas of the lockout mechanism. No significant wear was noticed after 15,000 cycles on abovementioned area.

Figure 4-18: Boot fatigue testing setup

100,000 test cycles were completed to evaluate wear and possible material weakness on the toe flex area. No visible deterioration was observed on any of the abovementioned components (Figure 4-19).

CURRENT CYCLE	
New start time	12:28
New Total time running [mins]	2029
Hours running	34
New Total Cycles done	**101463**
Stop time (if needed)	16:11

Figure 4-19: Screenshot of test counter after 100,000 cycles

Chapter 5

Work in Progress

Rider testing - continuous

Rider testing is a continuous process and constant feedback is provided regarding boot wear, resistance to soil ingress and ease of soil egress, as well as functionality and safety aspects.

A range of riders, both professional and amateur are continuously providing feedback in order to improve the product.

Chapter 6

Conclusions

This document summarizes research and development underlying the design of the Leatt® GPX 5.5 MX Boot.

A detailed discussion of the relevant literature was provided, as well as of the relevant injury mechanisms pertaining to motorcycle crashes and typical Ankle and Knee injuries related to the discipline.

The design rationale behind the Leatt® GPX 5.5 MX Boot was discussed, and details such as Ankle ALPT™, load release through impact force vector dispersion as well as the lockout mechanisms employed to control Ankle forces, were presented.

A presentation of the validation tests conducted during the development of the Leatt® GPX 5.5 MX Boot was provided.

Through this study it was shown that the Leatt® GPX 5.5 MX Boot is an effective boot, employing a unique method to distribute and control forces applied to the Foot, in order to minimize Ankle and Knee loading. It conforms to and falls safely within all commonly accepted injury criteria for the Ankle and Knee as discussed in the literature survey presented in Section 2.2. This is achieved through significant reduction in bending moments and impact force typically applied by common injury mechanisms. Specific areas in which the device's efficacy is demonstrated are:

- Reduction in axial loading transferred to the Ankle through ALPT™.
- A subsequent reduction in injury causing bending moments applied by hyper-inversion loading to the Ankle joint, through ALPT™, energy transfer and physical control of the allowable range of motion via an adjustable lockout.
- A significant reduction in the risk of AIS 2+ injuries of the Ankle and Foot.
- Reduction in axial loading transferred to the Knee through ALPT™.

- A significant reduction in forces measured in the Ankle and Knee as compared to a traditional high-end competitor boot.

Finally, this document serves as a reference for interested readers about the research, development and design rationale behind the Leatt® GPX 5.5 MX Boot.

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