REVVING UP RIDER SAFETY: REDUCING THE RISK OF HINDFOOT HYPER-ROTATION IN THE MOTOGP

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REV'IT!

Revving Up Rider Safety: Reducing the Risk of Hindfoot Hyper-Rotation in the MotoGP

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Master Graduation Thesis

MSc Integrated Product Design
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1. ACKNOWLEDGEMENTS

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TU Delft

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REV'IT!

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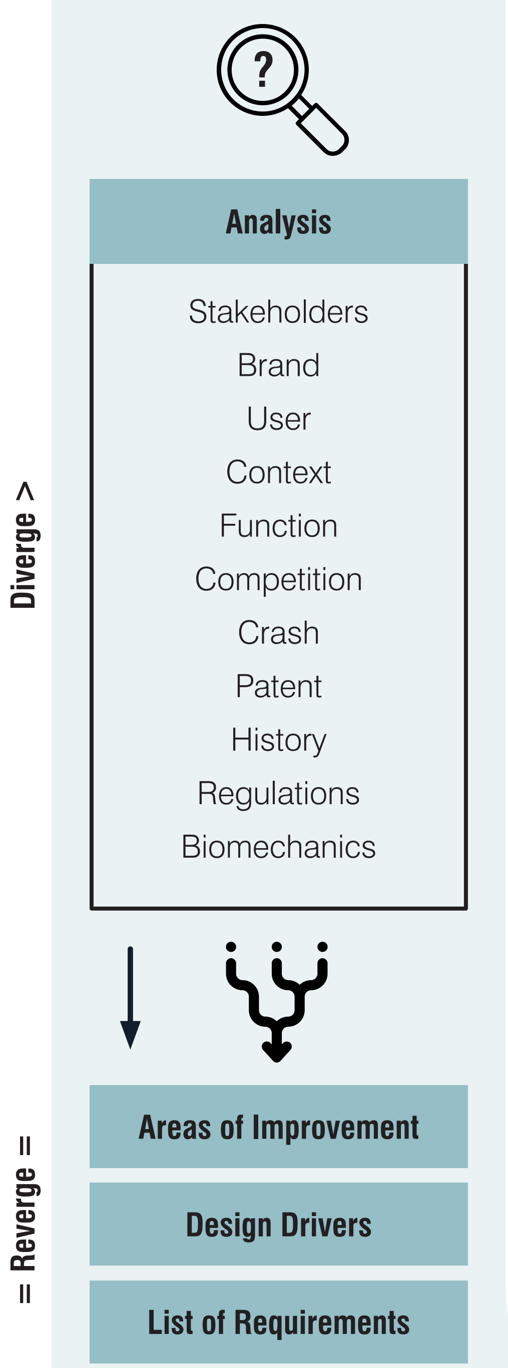
2. EXECUTIVE SUMMARY

REV'IT! would like their first road racing boot on the racetrack before the racing season 2025 for the riders they sponsor in the MotoGP Championship. These riders wear everything REV'IT! from the neck down, except for boots. For boots, they currently have to arrange another sponsor deal with one of the direct competitors of REV'IT!. As contact is already there, the risk of losing the riders to these competitors for the entire sponsor package increases. REV'IT! has experience developing adventure bike boots, race gloves and race suits, but not in terms of motorcycle racing boots. Research, designing, and testing had to be done to get from this point to a race-ready product. This project served as a jump start in this process.

The initial goal was to find and dive into a design problem for a concept of a boot subsystem by executing different types of analyses to pinpoint current areas of improvement based on experience with competitor boots and create a list of requirements and an overview of the design drivers. As REV'IT! stands for quality, technical innovation and solving user problems, it would be fitting to make a boot that is not only as good as its competition but also has an answer for the problems indicated by the riders. The necessary data was collected through interviews with experts, a co-creation and Q&A session and interviews with the REV'IT! Riders, brainstorming sessions, questionnaires, and literature research. Besides the boot requirements and design drivers, four potential research areas surfaced: the outer sole, the closure system, the heat protection, and the ankle joint protection. With the use of an evaluative method, the choice was made to focus on improving the current ankle brace design to be better at protecting the riders against hyper-rotation injury. The problem statement became: "Limiting the damage caused by hyper-rotation of the joints of the lower limb of REV'IT!'s MotoGP riders during a crash with a lightweight, low-profile solution that does not cause any discomfort in terms of pressure or donning and doffing, and does not limit the riders in their freedom of movement and the tactile feel to a noticeable extend."

With in-depth research, ideation, calculations, prototyping, tests and multiple iterations, a final concept was generated that limits hyper-rotation in the direction of inversion and eversion even when combined with plantar and dorsiflexion. 2.1 (when plantar flexed), 7.0 (when neutral), and 3.7 (when dorsiflexed) times more force is required to invert this brace compared to the brace of one of the best racing boots currently available. Meaning this brace absorbs more impact energy during a crash. The concept combines a comfortable, lightweight and low-profile pivoting 3D printed PA11 hard part based on a 3D scan of the rider with six reinforcing Dyneema® strings that mimic the ligamentous structures of the ankle in terms of placement and functionality. It allows for the complete active range of motion in the direction of plantar and dorsiflexion while limiting inversion and eversion in all flexion positions. The strings allow for the personalisation of the amount of limitation based on rider anatomy and preferences.

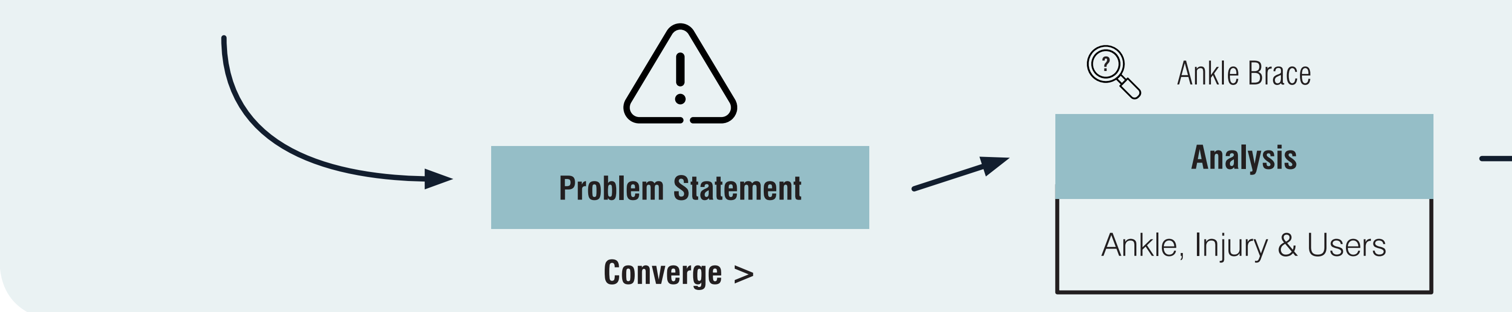
3. PROJECT JOURNEY



The initial assignment, see Appendix 1, was to analyse the factors that influence the design of a MotoGP motorcycle racing boot and summarise this research into a list of requirements and design drivers. Based on the results, the most relevant and fitting subsystem of the boot could be selected to develop a concept design for. The goal was to get the concept up to Technology Readiness Level 4, meaning that the core mechanisms and functions are tested in a laboratory environment.

That is where the journey started. In theory, the design process looks like the cycle shown in Figure 1 (Boeijen et al., 2013). It starts with an analysis to fully define the problem that needs to be solved. Once the problem is defined, the design phase starts and ideas are generated, simulated, and evaluated. Then, a choice is made for the best-fitting solution based on the requirements and design drivers. Because new problems arise or things can often be improved, the iteration process starts, and new ideation loops keep following until the product is good enough or needs to be launched. In practice, this process is not linear as in every small step, iteration occurs, and oftentimes throughout the process, you go back and forth between steps. However, it is an easy to communicate representation.

At the start of this project, the problems were still unknown. Therefore, the first step was to analyse all the different aspects that define the MotoGP racing boot to get an understanding of the context and to identify potential areas of improvement. This phase resulted in a list of requirements and the design drivers for the entire boot. Understanding what goes into the entire boot is important when designing a subsystem. As a nice side-effect, this research could help REV'IT! in the development of the rest of the racing boot. Areas of improvement for the current boots were identified. As it is fitting for REV'IT! to bring something new to the table and solve the problems of the riders, one of these areas was the base for the problem statement. The goal became to generate a concept that reduced the risk of ankle injury due to hyper-rotation. With this choice, a new analysis phase commenced to grasp what the problem entailed. This phase was concluded with a list of requirements and design drivers specifically for the ankle brace. Then the ideation started, first in sketch and partial prototypes and then with full-scale prototypes that could be evaluated in the developed test setup. Expert meetings and calculations supported this process. Multiple iteration loops resulted in the final concept, conclusions and recommendations. The goal was reached and the assignment completed.



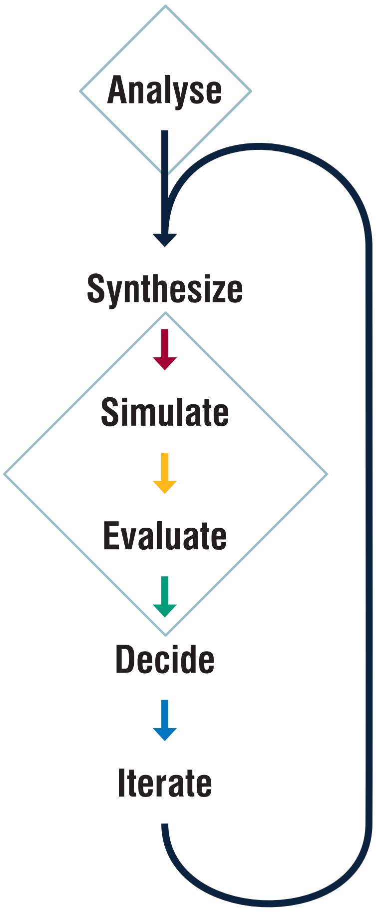
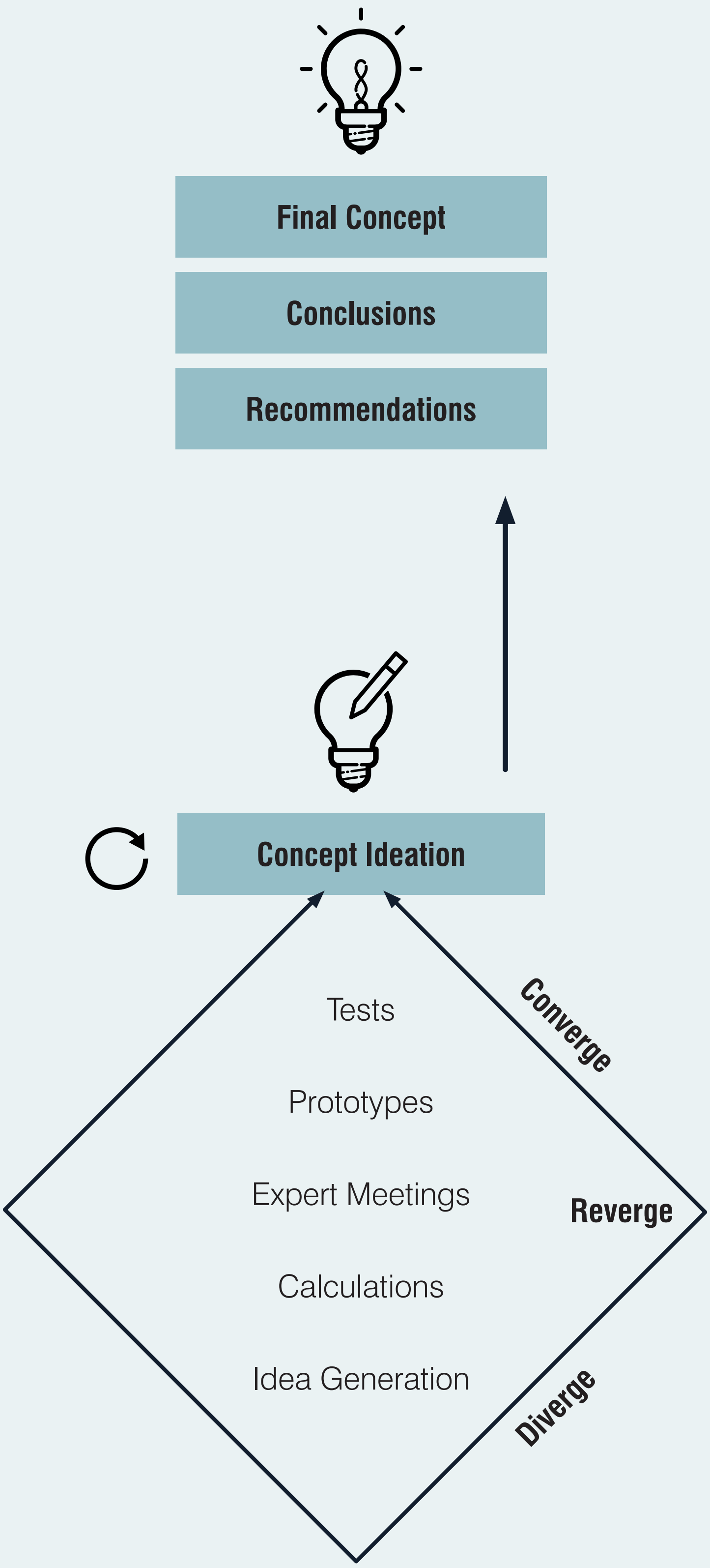


Figure 1. *The Basic Design Cycle.*

The daimond shapes in Figure 1 represent the process of di- and converging. In the analysis phase, the amount of data expands, but only what is relevant for the design is filtered out before the next step can be taken. In the design phase, the same goes for the amount of ideas. Quantity results in quality. In the end, the best ones are selected. For each step, different methods can be applied (Boeijen et al., 2013).




TECH3
Xlite
KTM
AKRAPOVIC

CONTEXT

Before any design can be made, analysing to identify a problem and understand the context in which the design will function is crucial. This section combines all the analyses that served as a base for the latter: a stakeholder, brand, competition, user and user context analysis. The insights and conclusions from this section are part of the foundation of the list of requirements and design drivers.

4. INTRODUCTION

REV'IT! is a Dutch company that has been developing gear for motorcycle riding since 1995 with the goal to make it high-quality, good-looking, and affordable, which was new at the time (REV'IT!, 2019a). Since then, the company has grown to become one of the leading players in the motorcycle apparel industry. They have a strong international focus and built headquarters, showrooms, and dealers all over the world. They are active in 70 countries on 6 continents, but most of their sales come from Europe (REV'IT!, 2018). Throughout the years, their focus has shifted. Aesthetic design is still one of the great strengths of REV'IT!, but now their main goal is to also facilitate the users in their functional needs and to inspire them to ride. They aim to solve their problems with gear that is adapted to the conditions that they ride in, through smart innovative solutions.

Figure 2. *The first Sidi Motorcycle boots from 1969 (Sidi, n.d.).*

The MotoGP World Championship is known worldwide as the highest class of motorcycle road racing. In 1949, the first world championship was organized by the Fédération Internationale de Motocyclisme (FIM) (Zasa et al., 2016). The motorcycles that are used in this championship are specifically built for this event and are unavailable for purchase and not allowed on the public road (Yamaha Racing, 2021). The MotoGP Championship is divided in four classes: the MotoGP (premiere class), the Moto2 (intermediate class), Moto3 (junior class) and the MotoE (electric class) (MotoGP, 2021b). Riding on a circuit is different from riding on the public road. The high speeds and the specific design of the motorcycles call for different riding positions, tactics, and movements. With racing at such high speeds also comes a higher risk of crashing (Tomida, et al., 2005). However, according to Bedolla et al. (2016), crashes in the MotoGP are more prevalent but also less dangerous compared to the ones that occur in traffic, even though they occur at speeds of over 200 km/h. Looking at the research of Jeffers et al. (2004) in traffic accidents still result in severe injury, especially to the foot. Lin and Kraus (2009) claim: "Lower-extremity injuries are most common in non-fatal motorcycle crashes, affecting about 30–70 % of injured riders." Even though these accidents are non-fatal, they still have the most impact in terms of life-long disability, costs, and the ability to continue working in the job you had. The tibia femur, metatarsals, and patella are the most common fractures (Jeffers et al., 2004; Peek et al., 1994). Wu et al. (2019) say that wearing both motorcycle trousers and boots significantly reduces the risk of lower limb injury, but only when worn in combination. They mainly protect against abrasions and lower the risk of ankle or foot fractures.

In 2008 REV'IT! joined the MotoGP Championship as a sponsor of riding gear, out of a passion for racing (REV'IT, 2021a). Besides it being fun, making a name for yourself at big racing events is a smart way to promote your brand. A large group of people get to see their racing heroes wear your brand. Pursuing these sponsorships is a significant investment for REV'IT!, but in the long-term this investment pays out in the growth of sales.

At first, they solely provided the riders with gear, but now they have a racing service coordinator and a mobile racing technology centre at the tracks in which they service the gear and help out the riders in any way REV'IT! can (Schamp, 2021). Because of this special service and the extra attention for the riders, more of them became interested to join REV'IT! and so their group of riders expanded. Now REV'IT! sponsors 8 of the currently 84 (MotoGP, Moto3 and Moto2) riders that participate in the MotoGP Championship.

REV'IT! provides their riders with an semi-unlimited number of one-piece suits, gloves, socks and under suits (Schamp, 2021), depending on the deal. This means the helmets and boots are provided by another sponsor. Until recently, REV'IT! tried to include TCX in their sponsor deal, which is a brand that only specialises in footwear. This means they weren't competing for sponsor deals and could both benefit from this deal. This way, REV'IT! was able to offer the riders a full package and meant their riders didn't have to meet up with their main competitors for their boots. However, in 2021 TCX was bought by the Dainese Group (Visordown, 2020). As Dainese is one of the main competitors that do provide their riders with everything from helmets to boots, making this deal with TCX will no longer be an option. This created a great urgency within REV'IT! to come up with a solution, which is to design these boots themselves.

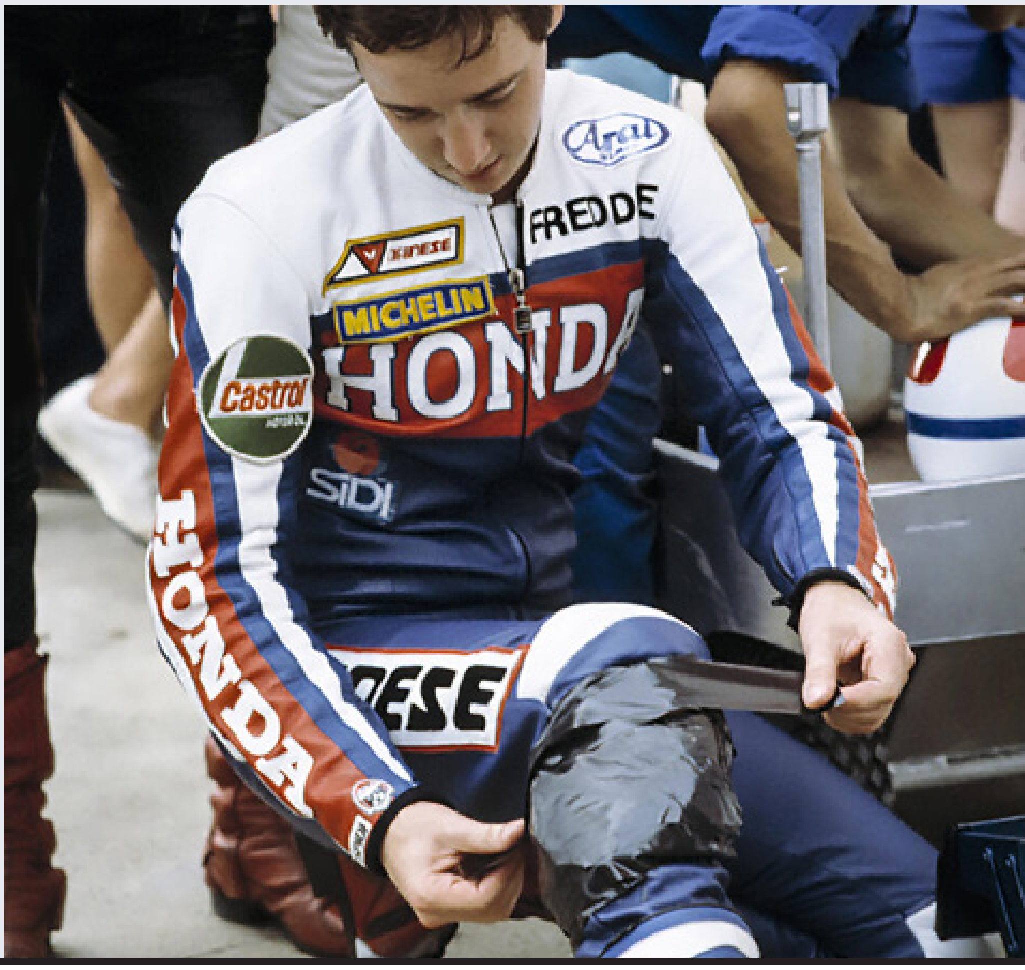
The goal is to have them ready before the racing season of 2024. After that, they would like to bring a consumer variant to the market for the collection of Spring/Summer 2025 (Van Roon, 2022). Many innovations come from the racing world, as there price is less important and the drive to outperform competitors results in smart solutions (digitaltrends, 2019). This context combined with a test panel of expert riders who provide the boots with screen time, make this the ideal process to optimise and promote the boots before they enter the consumer market.

The first pair of riding boots resembled boots used for horse riding (De Wit, 2021), as they were leather sleeves that only provided abrasion resistance, see figure 1. According to Simon Crafer (MotoGP, 2020), a retired rider, crashing and falling on your heels was one of the most painful ways to injure your foot back then. As the speed and lean angles increased, the requirements for the gear grew along. Riders started taping helmet visors to their suits as a DIY knee slider (DemoneRosso, 2021a) (figure 2).

The manufacturers followed their needs and with time the gear became more advanced. Sliders, synthetic leather and recently the airbag system and ankle brace system were incorporated. As a result, the risk of injury has reduced significantly, but it's not zero yet (Campillo-Recio et al., 2021).

REV'IT! has great experience in the development of adventure bike boots and race gloves and suits, but in terms of road racing boots, they are at the start of the analysis phase. To get from this to a race-ready product extensive research is required. The goal of this project was to develop a concept design of a relevant subsystem of the boot. The research and design within this scope serve as a base for REV'IT!'s own development process.

Figure 3. *A rider taping a piece of plastic to his knee to function as a knee slider (DemoneRosso, 2021a).*



5. THE REV'IT! MOTOGP BOOT STAKEHOLDERS

The parties and people that influence this project differ in their level of interest and power. Depending on these levels, a different approach regarding these so-called stakeholders is preferable, as content stakeholders increase the chances of a successful project. An analysis was done based on interviews, observations, co-creation, and literature, which resulted in the overview of Figure 4. The different stakeholders were distributed over the scales of power and interest and so divided into four groups: context setters, key players, bystanders and concerned citizens. These groups should respectively be kept satisfied, managed closely, monitored, and some only be kept informed throughout the development of the MotoGP boots (MindTools, 2018). This process requires continuous research and tailored communication. The following paragraph elaborates on the involvement and management of the stakeholders with the most significant power and interest (green blocks).

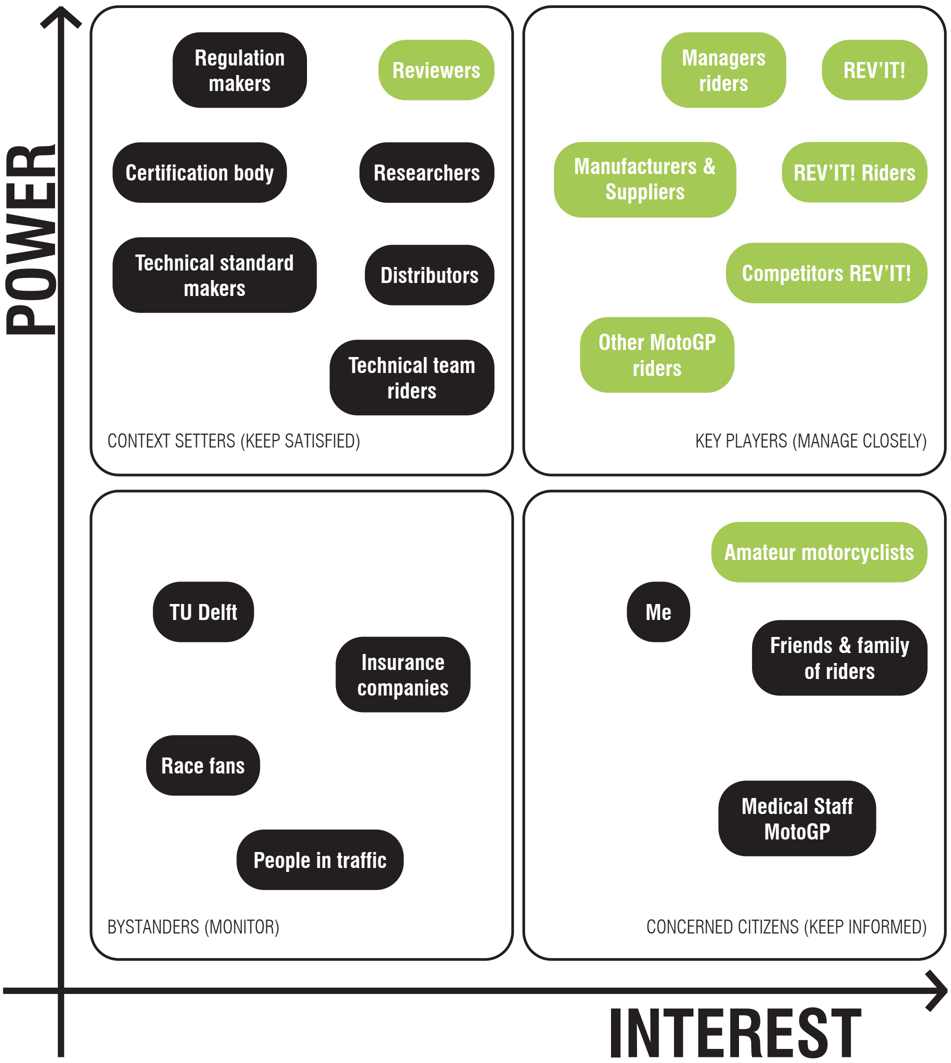


Figure 4. *Overview of the interest and power of the stakeholders regarding the REV'IT! MotoGP race boot project.*

REV'IT!

Naturally, REV'IT! tops in terms of power and interest in the boot project. The company is responsible for the development and has to invest a significant amount of time and money in the hope of a substantial return on investment. They chose the path of first introducing the boots in the context of professional motorcycle racing. In this context, riders get their boots for free as part of their sponsor contract, which means that this step in the development solely comes down to investment and no return (Schamp, 2021). This return should follow further down the line as the MotoGP boot will serve as a base for a consumer version that REV'IT! plans to bring to the market in a few years (Van Roon, 2022). Showing what the product is capable of in this highly demanding user context by making people's racing heroes wear them at the most well-known racing events is a smart way to promote a product among consumers (Dekker, 2021). On top of that, having experienced professional racers test the product and provide feedback creates the opportunity to implement improvements before the consumer boot hits the market. Moreover, labelling the boots as developed in collaboration with MotoGP riders is a marketing boost (DemoneRosso, 2022). With the Dainese Group buying TCX (CMG Staff, 2020), the chance of losing riders to competitors has increased. Since this source of promotion and development is vital for REV'IT!, their interest in this project has only heightened (Schamp, 2021).

REV'IT! Riders

The riders are the primary users who play a central role in developing REV'IT! 's racing boots. They participate in one of the classes of the MotoGP Championship and have a sponsor deal with REV'IT!. Their preferences shape the boot design, and the viability of the project falls or rises with their satisfaction with the final result, hence their high power. A pair of proper racing boots is fundamental for their performance and safety, and so for their careers and physical well-being. Having their boots be provided by REV'IT! would save them time and effort in acquiring and investing in a relationship with another sponsor for their boots (Schamp, 2021).

Managers REV'IT! Riders

At the start of a rider's career, their manager is usually a parent. Once their career takes off and matters like sponsor negotiations become more complex and strategic, they commonly acquire a professional manager (Schamp, 2021). Generally, the managers are concerned with settling on sponsor deals that are in the rider's best interest. This best interest includes performance, marketing, well-being, and income. Their power is significant as they can make the call not to land a sponsor deal based on their satisfaction with what REV'IT! has to offer.

Competitors REV'IT!

Currently, the main competitors in the MotoGP racing boots market are Dainese (including TCX), Alpinestars, Forma and Sidi. Dainese and Alpinestars are the two leading brands in this market and have been in this field for decades (Dainese, n.d.; Alpinestars, n.d.). They are knowledgeable and provide a satisfactory product, but in general, the development of MotoGP racing boots has been relatively slow and conservative (De Wit, 2021). With their experience and knowledge, REV'IT! should be able to generate a qualitative and innovative new product option, which could be detrimental to the market share of their competitors, depending on how these companies react.

Other MotoGP Riders

Riders talk to each other and discuss their experiences regarding gear and sponsors, both good and bad (Schamp, 2021). These talks can convince other MotoGP riders to start looking into REV'IT! as a new sponsor, especially when the downside of having to find an extra sponsor for boots no longer prevails. However, if REV'IT! isn't careful, it could also work the other way around. Keeping close contact with the riders and listening to their needs and wishes is fundamental for keeping them on board.

Manufacturers & Suppliers

The capability, price and planning of the manufacturers and suppliers required for production significantly affect the boot project's cost, timeline, innovativeness, and success. The interest of these parties in the project mainly lies in having a new client with whom to collaborate and do business.

HONOURABLE MENTIONS

Amateur Motorcycle Riders

Technical innovations from the racing world often bleed into the consumer market. The most direct way is consumer versions of the race gear ending up in stores. The target group is people that are more into a sporty look or like to do races on an amateur level. They also value performance and protection, but price, comfort, and aesthetics are of greater importance within this user segment (De Wit, 2021).

Reviewers

People who publicly review motorcycle gear have an enormous effect on the sales of consumer boots. Consumers turn to them for advice on which boots to buy. Convincing reviewers results in convincing buyers and so positively impacting sales (The World Financial Review, 2020).

6. THE BRAND REV'IT!

To get a good understanding of the brand REV'IT!, an analysis was done of the website, social media, and company manuals to identify how REV'IT! wants to portray itself (brand identity) and how people perceive REV'IT! (brand image). The results that were the foundation for the conclusion about the brand image can be found in Appendix 2. This analysis helped identify design drivers and possible points of improvement and formed the basis for choices made within the project, as the final product should fit the brand.

Brand Identity

The name REV'IT! comes from the verb revving, which is a motorcycle term that is defined as: "to increase the operating speed of an engine while the vehicle is not moving, usually to warm it to the correct temperature" (Cambridge Dictionary, 2022) or accelerating (REV'IT!, 2019a). REV'IT! wants to convey that their brand stands for excitement and speed. It is a financially healthy and rapidly growing company. With their international focus, they have spread over 70 countries on 6 continents and are still planning on expanding. They have grown to become a leader in the international market, and they are becoming increasingly known as a benchmark for high-quality product design and a company that constantly challenges the status quo (REV'IT!, 2019a; 2021c; 2022b).

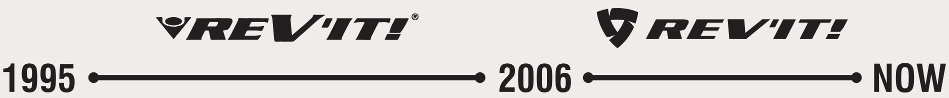


Figure 5. *Timeline REV'IT! logo.*

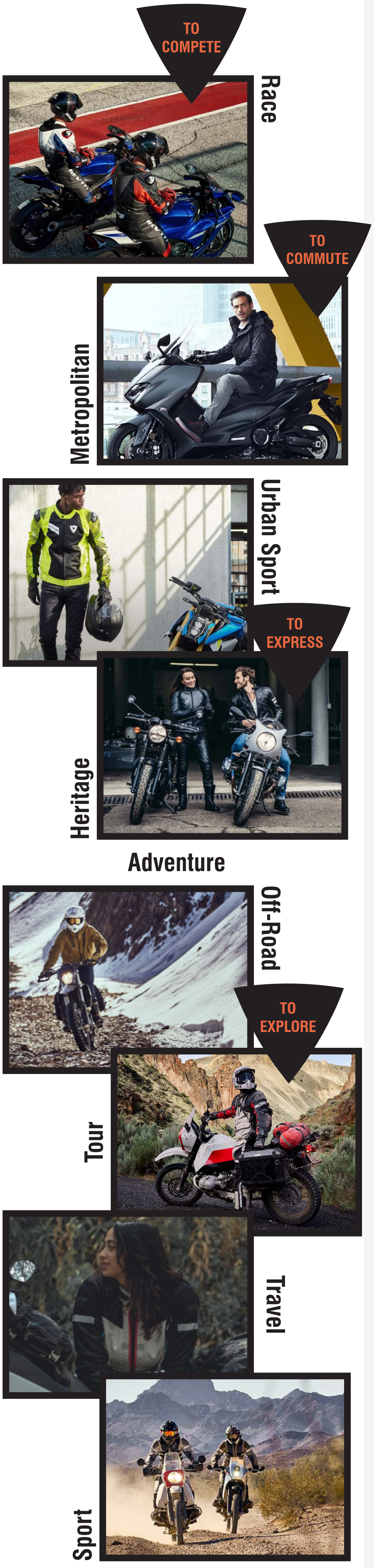
Brand Values

In 2006, the abstract representation of a motorcyclist seen from above in the logo of REV'IT!, was replaced by the REV'IT! Shield, see Figure 5. This shield consists of three parts with different layers of symbolism. The shield itself originally stood for Authenticity, Safety and REV'IT! Aesthetics. Now, it represents their brand values, which are the foundation of their mission; Design, Performance and Innovation. REV'IT (2021a; 2021b) does not only consider design to be about original, pure, recognisable, and matching aesthetics but also about problem-solving by engineering solutions to the challenges they identify by talking to riders. Their goal is for the gear to perform exactly as the user needs it to. This performance is about quality up to a detail level and so safety, comfort, fit, withstanding extreme conditions, repeated in-house testing and improvement. They believe these improvements should be made not only on an aesthetic but also on a technical level, based on research. With this strive for innovation, they want to pioneer progress in their industry with a focus on the user, sustainability, customisation, and industry 4.0 (REV'IT!, 2019b).

Original Meaning Shield

Brand Values

Product Layers



Rider Types

Additionally, the number three corresponds with REV'IT!'s number of defined rider types, nine. These rider types are archetypes of nine different rider categories and consumer market segments who prefer a particular (life) style, type of motorcycle, type of riding and type of conditions. They form the base for the different categories that the product portfolio of REV'IT! is divided over. These riders can be grouped into four clusters based on where their motivation to ride comes from. REV'IT! identified the following motivations: to compete, to explore, to express and to commute (REV'IT!, 2018). "To Compete" combines the Race rider type and the REV'IT! Riders that they sponsor. The latter is a separate category as they have other factors influencing their choice for REV'IT!. This will be elaborated on in the following chapters. This segment is mostly about sports performance. These riders are part of the racing community and are sportive, adrenaline-seeking, competitive riders. They want the gear their heroes are wearing. This is the segment the amateur riders identified in the stakeholder analysis fall under. "To Commute" is the motivation of the Metropolitan rider type. They are practical, rational users who mainly care about their appearance and safety. "To Express" is a shared motivation of the Urban Sport and the Heritage rider type. The first is an expressive sport-oriented driver who wants to belong to a subculture. They are brand driven and generally have an aggressive riding style. The Heritage riders are almost the opposite. They are individualistic, curious, and creative. They care about how they are perceived and base their choices mostly on their emotions. This cluster also comprises the Generic Tech Fashion, which includes the rider jeans that would match the gear of every rider type. "To Explore" is a motivation that drives many riders; Adventure Off-Road, Adventure Travel, Adventure Tour and Adventure Sport riders. This segment includes a range of riders and riding styles, from long trips on normal roads to short off-road adventures. This results in a broad range of varying and changing requirements that the gear needs to be able to meet, meaning the gear should be dynamic.

REV'IT! (2019a) is a world leader within the Adventure segment and a challenger in the Race/Sport segment. Looking at their website and social media, REV'IT!'s target groups in all segments are aficionados, both male and female. However, up until this point, they focus more on the male population in terms of portfolio size and representation; this is shifting, however (REV'IT!, 2021c). On top of that, the target group is diverse in background and, on average, around the age of 30. The content they publish on these media channels has a high production value and radiates that the brand is high-quality, modern, technical, and fashionable.

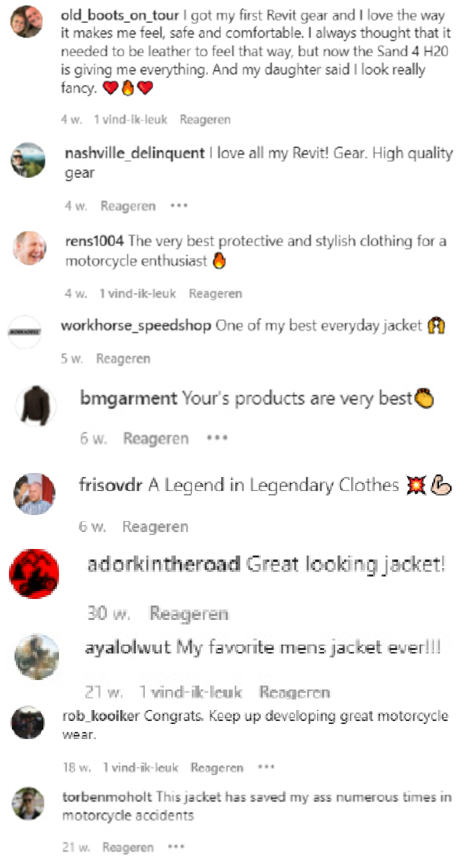
Product Portfolio

From base to top layer, REV'IT! can provide every rider type with gear from neck to toe (REV'IT!, 2022a). Missing in this portfolio are boots for the race segment. Their collection gets expanded and renewed twice a year, which means every year they have a Spring/Summer and a Fall/Winter collection. REV'IT! is planning on introducing their first consumer-oriented pair of race boots in the Spring/Summer collection of 2025, a few years after introducing it on the racetrack (Van Roon, 2023). REV'IT! says their products stand out by their innovative characteristics and distinctive aesthetics within the middle to upper middle price segment (REV'IT!, 2019a).

Brand Image

People generally think of REV'IT! as a high-end technical brand that delivers very good-looking, high-quality products that make people feel safe and comfortable. Almost all comments about the brand were positive and enthusiastic. Many comments about products stated that this was the best product in this category they had ever owned. Their customers seem to range greatly in age (16-60 years old (REV'IT!, n.d.)) even though their online marketing mainly portrays 30-year-olds. People seem to appreciate the diversity of the models and the high-production value of the photos and videos they output. As their gear is rather pricey, which is pointed out from time to time, they are mainly selling to riders with a middle to high income.

There were a few remarks, however. The most frequently mentioned is the one that women do not feel like REV'IT! tailors to their needs in terms of aesthetics and available options. They generally point out that they would like the same gear options as men and something other than pink, sparkles or an animal print on their gear, as it is a stereotypical and old-fashioned belief that all women would not like this. This image does not match REV'IT!'s user-oriented, young, modern, and inclusive identity and is not how they think. REV'IT! reacts to these comments online by saying they are working on it and doing their best, but they will have to show it in practice to change the image that this group has. These complaints are certainly not specific to REV'IT!, as other motorcycle gear brands receive the same feedback. However, the company could be the one to set an excellent example for other brands and could use this to promote their brand identity while making users happy.



Mission

The mission of REV'IT! (2018) is:

"Inspire people to ride: Facilitating the passion for riding through products, services and experiences that add value to the lives of our customers."

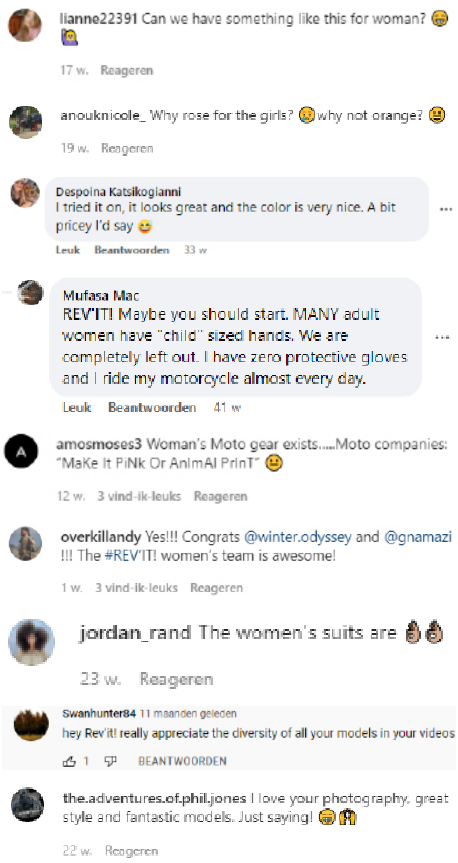
They want to facilitate this by creating gear that allows people to ride better by diminishing (product) limitations, by making them look stylish and feel confident and making them feel safe (REV'IT!, 2019a; 2021b).

Vision

The vision of REV'IT! (2018) is:

"Shaping a sustainable future for riding."

This sustainable future is focused on the people, the planet, and prosperity. They feel they must exercise responsibility in relation to the environment, safety, and society and try to do so through innovation and making the right decisions (REV'IT!, 2021b). Besides thinking about their environmental footprint, REV'IT! also partakes in many charity events.



Generally, racing boots are unisex, even though they are mostly targeted towards men. A few brands make women's racing boots, but these are never the top-segment boots with the best protection and usually have feminine designs (Motorcycle Gearhub, n.d.-a; n.d.-b). As fit is an important factor in the efficacy of the protection of the boot, the need for a racing boot with a focus on the safety, sizing, and aesthetic preferences of women is a gap in the market. Of course, the market is small at this point, but it is growing, and there is the potential that more representation of women will result in the growth of this target group. It could be interesting for REV'IT! to step into this market to counter the previously mentioned image and support their title of being a challenger in the Sport segment. REV'IT! could even try to sponsor a female rider, like Moto3 rider Carrasco (Motorsport, 2022), to promote their design. A few comments on the videos about the women's adventure team were already very positive.

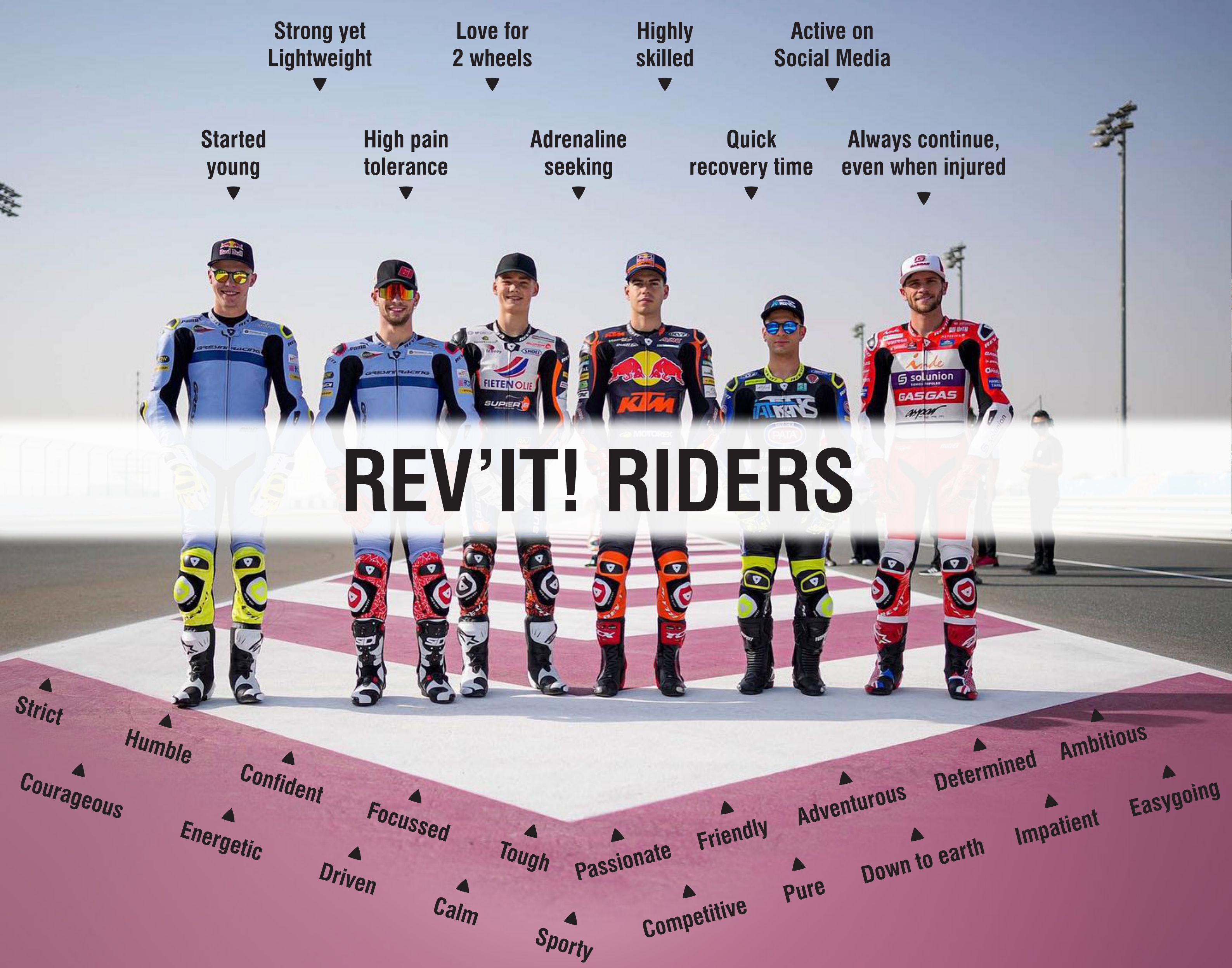
Another comment was about the range of sizes. People felt left out as they were either too big or too small for the REV'IT! products. Naturally, this also comes down to a trade-off as, at some point, the investments required to accommodate for these sizes probably will not be compensated by the revenue that is generated by them. Nevertheless, it could be a topic REV'IT to investigate.

REV'IT! handles the complaints in a kind, helpful and understanding manner. Which only contributes to the good image people have of the brand. Besides a few discrepancies, the brand identity matched the brand image well, which means REV'IT! is doing a good job.

TAKEAWAYS »

- The product should fit the REV'IT! brand values of performance, innovation and design.
- The product should fit the mission and vision of REV'IT! and inspire people to ride and fit in a sustainable future.
- REV'IT! is mainly established in the Adventure segment, but in the Sport segment, there is still room to go from challenger to leader in which the boots could play a significant role.
- REV'IT! is an internationally oriented company, so the users could be from any country of the world, which influences the sizing, the user context and the preferences in terms of aesthetics.
- The consumer market spin-off of the boot should be high-end, technical and in the middle to middle-high price segment unless there is enough added value to step up the price.
- For the consumer market spin-off, it would be interesting to look into high-end racing boots for women and to look for a women representative in the racing world, as this would help the brand image and fit the brand identity of REV'IT!.

Figure 6. *REV'IT! Riders and their typical characteristics (REV'IT, 2022c).*



The REV'IT! Riders

At the time of writing, REV'IT! has a group of 11 road racing riders, of which one races in the MotoGP, six in the Moto2 and one races in the Moto3 class. The others compete in the WorldSBK or other competitions. They are men of 16 to 37 years old from seven different countries and share a long-term passion for riding motorcycles and the goal of becoming a racing legend. Figure 6 provides an overview of all shared characteristics. Nevertheless, they come from different nationalities and have diverging qualities, sizes, personalities, opinions, riding styles, skills and frequencies of injury. Marketing plays a significant role in REV'IT!'s selection of their riders. The rider's image has to match the identity of REV'IT!; ambitious, adventurous, courageous, humble, sporty, friendly, and so forth.

Some countries are represented in the MotoGP by only one or two professional racers. This greatens their chance of becoming a local race hero and puts them in a national spotlight. Selecting these riders for sponsorship could generate significant publicity for REV'IT! within these countries.

7. THE USER

Figure 7. *Co-Creation Session with the REV'IT! Riders (2021).*

Understanding the user is vital for a successful product. What are their values, needs and wishes, how do they behave, and how and where do they intend to use the product? Multiple methods were employed to find the answers to these questions: a co-creation session with eight of the REV'IT! Riders combined with a questionnaire (Appendix 6) and an interview with the Racing Service Coordinator of REV'IT! (Appendix 9) and the product specialist of MKC Moto (Appendix 10). Additionally, the brand image and competition analysis (Appendix 2 & Appendix 3) provided relevant insight into the understanding of the consumer. This chapter summarises and visualises the results of these analyses. The method used to represent the user group was the creation of personas, see Figure 8. Personas are archetypal characters that represent a group of people in a generalised manner to communicate their personality traits, preferences and other relevant user information (Van Boeijen, Daalhuizen, Zijlstra & Van der Schoor, 2013). They are the foundation of many of the design drivers and requirements for the boots.

Personas

The Gifted Rookie

The first persona represents the young, professional riders who are at the start of their potential career and are new to REV'IT!. Their focus is on trying to break through, but it is still uncertain whether they will succeed. They will go to great lengths to reach their goal and cannot afford to be too picky regarding sponsors and gear (Patterson, 2022). For REV'IT!, they are a long-term investment as, in general, unlike a successful rider, a rookie does not generate much attention for the brand, is less knowledgeable regarding gear, and the return on investment is less guaranteed. However, these riders are also less difficult and expensive to contract than well-known ones, making them interesting representatives. With the growing success of a rider comes an increase of interest from REV'IT! 's competitors to get this rider on their team. Providing good gear, building a relationship and going above and beyond for them is the key to keeping these riders on board (Schamp, 2021).

The Respected Expert

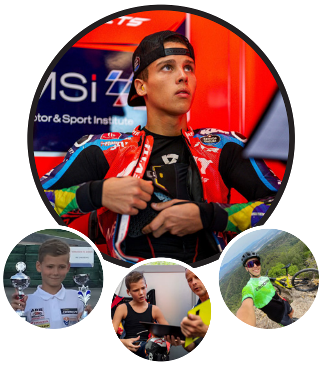
The second persona represents the more experienced rider who has been with REV'IT! for over ten years. They have been the foundation for many race gear developments within REV'IT!. Furthermore, they show the consumer that of all their options, they still choose REV'IT! as their sponsor (REV'IT!, 2021). It is essential that REV'IT! maintains their relationship with these riders and meets their high demand for quality and performance. According to Schamp (2021), personal attention and quality make REV'IT! stand out.

The Invested Amateur

The third persona represents the consumers. They will become the users of the more generalised version of the MotoGP boots. Even though they are out of scope for this project, it is important to understand their needs and wishes early on in the process. Eventually, having to redesign less going from the MotoGP to the consumer boot saves time and money. For this reason, their input is included in the list of wishes, not the list of requirements, of the MotoGP boot.

Figure 8. *Personas representing the users of the MotoGP Boot.*

THE GIFTED ROOKIE



168 cm | 55 kg | 43

17 YRS | ♂

THIS IS ME...

I started with motocross when I was four years old. With the help of my dad, I progressed, and after a while, I also started road racing. This went so well that I could climb up to the Moto3 class. It's really cool to be among these successful riders. I wish to become the best, and I'm doing everything to fight for it. It can be tough, but that's part of it. I know what I'm doing it for.

Rider Level

Gear Expertise

Pickiness Regarding Gear

Likelyhood of Crashing

MY GOALS...

- Becoming a better rider and climbing up to the MotoGP class one day
- Becoming a road racing legacy like Marquéz or Rossi
- Being able to make my career out of this

MY BIKE...

KTM Moto3 Bike

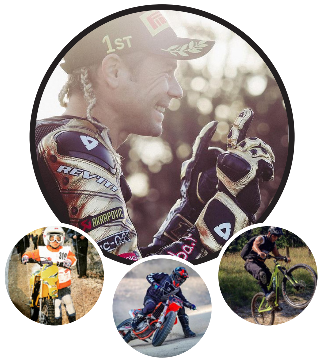
250 km/h

80 kg

60 hp

250 cc

THE RESPECTED EXPERT



170 cm | 66 kg | 38

37 YRS | ♂

THIS IS ME...

Riding motorcycles is my favourite thing to do, and it feels like a dream to have been able to turn it into my career. It wasn't easy though. I had to prioritise and fight for it. It's a mentally and physically demanding environment where you fail more than you win, but that builds resilience and makes me a better rider and person. I love what I do, and I hope to continue for a few more years.

Rider Level

Gear Expertise

Pickiness Regarding Gear

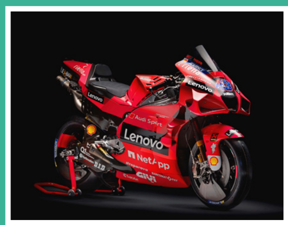
Likelyhood of Crashing

MY GOALS...

- Keeping up my status, winning and becoming a better rider.
- Staying safe and healthy.
- Remaining happy with what I do. I want to make sure I still find the risk and sacrifices worth it.

MY BIKE...

Ducati MotoGP Bike



362 km/h

157 kg

240 hp

1000 cc

THE INVESTED AMATEUR

166 cm | 60 kg | 37

25 YRS | ♀

THIS IS ME...

What started as a practical way to commute grew into one of my main hobbies. I love the speed, freedom, and sense of community that bikes provide. I prefer the sport bike look and value my safety. That's why I generally go for good-looking, high-end and race-oriented gear. My hero is Moto3 rider Ana Carrasco. I don't want to be a professional racer myself, but I like to push my limits.

Rider Level

Gear Expertise

Pickiness Regarding Gear

Likelyhood of Crashing

MY GOALS...

- Improving my riding technique and develop new riding skills
- Staying safe and healthy
- Making many more trips on my motorcycle and exploring the roads around me.

MY BIKE...

Yamaha YZF-600 R6

266 km/h

190 kg

117 hp

599 cc

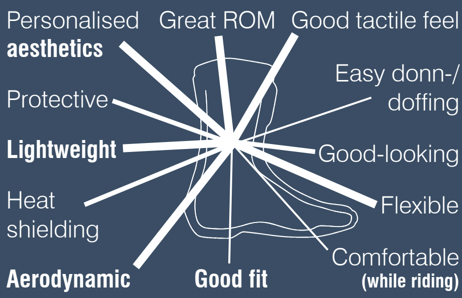
HOW I SEE REV'IT!...

I heard some good things about REV'IT! from other riders, so we contacted them, and now I am really happy to say that REV'IT! is my sponsor. Even though I'm only in the Moto3 class, they treat me with respect, take me seriously, and if I want something, they listen to me. This is different at other companies. However, I think it would be really cool to be one of the big guys of Alpinestars one day, just like Marc Marquéz. Who knows...

HOW I COMMUNICATE...

In groups, I usually don't speak up; I get a little intimidated by the other riders, in general, I'm just happy that I even get gear, and my English isn't that good yet. But, if Michiel personally asks me if everything is okay, I can often come up with a few things.

MY PERFECT BOOTS HAVE/ARE...



I'LL WEAR THEM...

During track training, testing sessions and all the sessions of the race weekends. I don't wear the boots for long periods of time. I usually put them on shortly before riding and take them off a while after I step off my bike, unless we celebrate my win.

HOW I TREAT MY BOOTS...

I try to be careful with how I treat my boots as I get them for free. However, It's hard to control how much they have to endure on the track as I crash quite a lot throughout the year. It's nice that I can go to Alpinestars and get a new pair if something's broken and that I don't have to take care of them myself.

WHY INVEST IN ME?

The gifted rookies are likely to become respected experts in the future. Building a connection, keeping them happy, and supporting them in their development could be a great investment for the future of REV'IT!. It's easier to get a rookie on your team compared to older riders, but once they become successful other brands will start to make interesting offers.

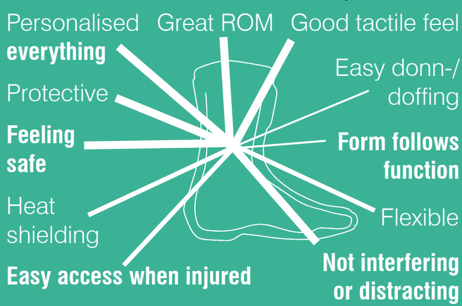
HOW I SEE REV'IT!...

REV'IT! has been my sponsor for over a decade at this point, so they basically are like family to me. I've seen them grow over the years, and together we've been able to create a lot of great gear. I've had other sponsors, but the personal attention, agility and easygoingness of REV'IT! is something you don't really find anywhere else. I plan on staying with them until I stop racing one day. Until then, I will continue to be a proud ambassador of REV'IT!.

HOW I COMMUNICATE...

If something bothers me about my gear, I talk to Michiel so that he can see what can be done about it. I know what I want and REV'IT! listens to what I have to say. They can also always come to me for feedback.

MY PERFECT BOOTS HAVE/ARE...



I'LL WEAR THEM...

During track training, testing sessions and all the sessions of the race weekends. I don't wear the boots for long periods of time. I usually put them on shortly before riding and take them off a while after I step off my bike, unless we celebrate my win.

HOW I TREAT MY BOOTS...

I try to be careful with my boots as a worn-in boot is nicer than a brand-new one, but I don't put special care into maintaining my boots. How long they last depends on when the sole will give out because of the grinding over the floor and the footpegs digging through. A crash can also be the end of a good pair. But luckily, I have a few personalised backup pairs in my trailer.

WHY INVEST IN ME?

The respected experts are not only very valuable promotional-wise, but they can play a key role in the development of race gear with their knowledge and experience. The bond with these riders is already strong, but they are wanted in the sponsor market, so keeping them satisfied is essential.

HOW I SEE REV'IT!...

I feel women are underrepresented and heavily stereotyped in the motorcycle world. Women's gear options are limited, too feminine and usually less protective than their male counterparts. That's why I like brands like REV'IT! that seem to try to show more female representation and step away from stereotypes, which helps. That's why I am really excited for their racing boots to come out.

HOW I COMMUNICATE...

When I'm happy with the new gear I bought, I will post it on my Instagram and recommend this product to all my rider friends. But, when something bothers me, these friends are also the first to know, and I might even avoid the brand the next time I go buy something.

MY PERFECT BOOTS HAVE/ARE...

I'LL WEAR THEM...

When the weather is nice and I go out with a friend on a daytrip to a rural area close to me to drive on swirly dyke roads. On our way we usually stop to grab some coffee. I also wear them during an occasional track day.

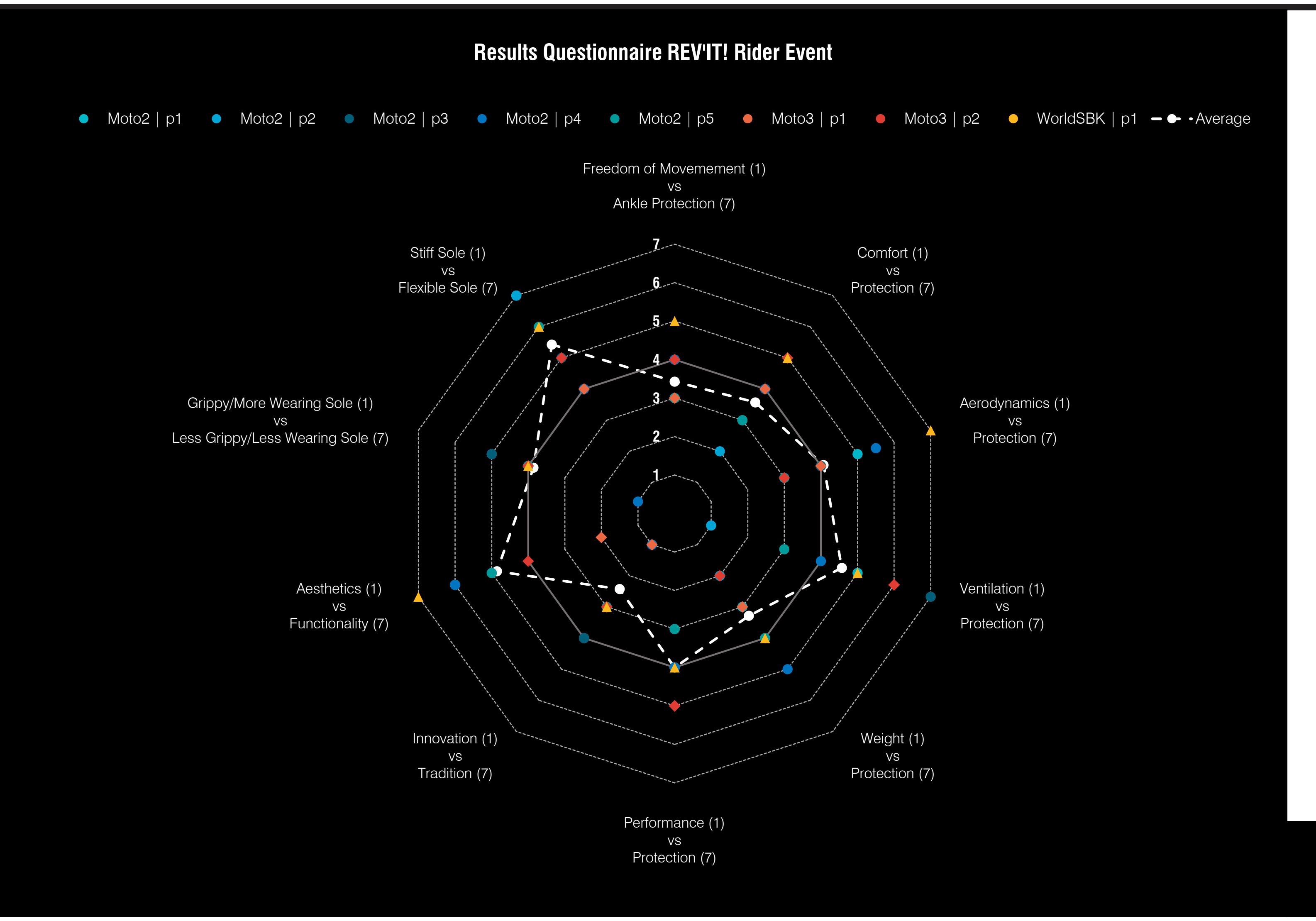
HOW I TREAT MY BOOTS...

As high-end racing boots are a big investment for me, I treat them with great care. My plan is to wear them for years until I can't get them fixed anymore. That's why I like boots that have replaceable parts. I also try to keep them as good as possible by cleaning and treating them regularly and by storing them properly.

WHY INVEST IN ME?

The consumers are the people that will have to provide the return on investments for REV'IT!. Listening to their needs, wishes and feedback and keeping them satisfied is essential as this determines the success of the overall racing boot development project of REV'IT!.

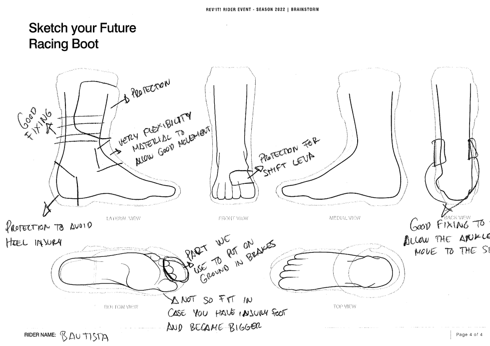
Figure 9. *REV'IT! Riders and their typical characteristics (REV'IT, 2022c).*

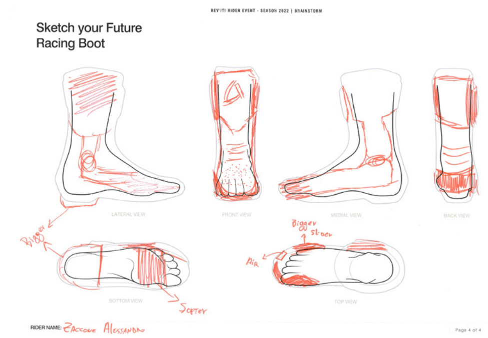


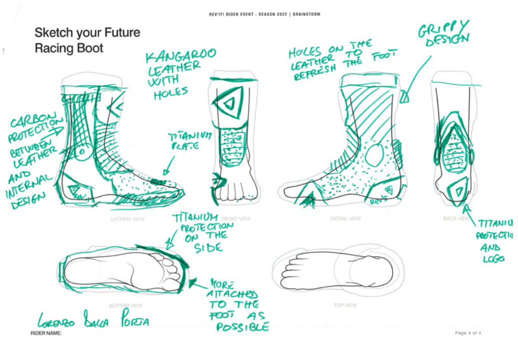
Method

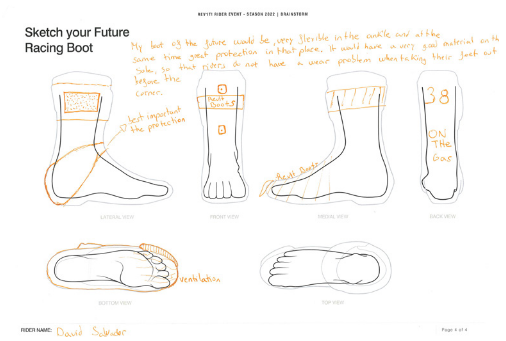
During the Rider Session, the REV'IT! Riders were presented with a printed questionnaire. This questionnaire consisted of multiple Likert scales from one to seven. These scales were based on contradictions in the design of the boot, with one representing a certain design driver and seven a counteracting design driver. The design drivers were derived from the function, competition and context analysis and meetings with REV'IT! Experts. The riders were asked to circle the number that best represents their preferences concerning road racing boots. Talking to other riders was allowed. The results of the questionnaire can be seen in Figure 9.

Furthermore, the riders were presented with a printed booklet combining several templates (see Appendix 4) and asked to draw and note their thoughts on the presented topics. These topics were improvements regarding their race suits and the tactile feel, protection and flexibility of their boots. On top of that, they were asked to sketch their perfect future racing boot. Throughout this phase of the session, the brainstorm rules were explained, and the riders were asked stimulating and out-of-the-box questions to create a creative environment, as time was limited and the riders had no prior experience with creative sessions. The riders were exposed to visual stimuli composed of different types of boots, futuristic sports gear and a word cloud of related words (see Appendix 4).









Conclusions Rider Session

All results of the rider session can be found in Appendix 6. Based on the data collected in the rider session, their shoe sizes range from 38 to 43 and they estimate to use 2 to 15 pairs of boots per year. Figure 9 shows how much their opinions regarding their boots diverge. About some topics there seems to be consensus, like the preference for innovation, a stiff sole and functionality over aesthetics. Furthermore, performance, freedom of movement (FOM) and gripinesss of the sole seem to be equally important as protection, ankle protection and the wear of the sole, respectively. Interesting to note is that, on average, contrary to what different sources indicated, the protection of the boot is considered indispensable. Compared to protection, going from most to least important are the design drivers: weight, comfort, performance, aerodynamics, and ventilation. The weight is, on average, even considered slightly more important than protection, especially for the Moto3 riders. On top of that, the aerodynamics was indicated more important for the Moto3 riders compared to the WorldSBK rider. This makes sense as the higher the racing class, the more power the bike has. So, very small aerodynamic differences that are caused by the boot, are less impactful.

During the co-creation session a few issues with the current boots were pointed out: they do not protect sufficiently against heat, they are uncomfortable to don, doff and wear once you are injured and they do not limit injury to ankles and heels well enough.

TAKEAWAYS »

- The riders share many outstanding characteristics. However, they also significantly differ in their preferences and opinions. That is why personalisation is an important design driver for the boot.
- The young REV'IT! Riders differ from the well-known REV'IT! expert riders regarding requirements, wishes, expertise, rider level and approach. For future research, looking into the desirability of a different boot for the different personas could be interesting.
- Unlike generally thought, the riders care about the protection their boots offer, even at the expense of ventilation and aerodynamics for most riders.
- Compared to protection, going from most to least important are the design drivers: weight, comfort, performance, aerodynamics, and ventilation.
- On average, performance, freedom of movement and gripinesss of the sole seem to be equally important as protection, ankle protection and the wear of the sole, respectively. The riders generally prefer innovation over tradition, a stiff sole over a flexible sole and functionality over aesthetics.
- Heat protection, protection against injury and comfort during injury recovery are areas of improvement for the current boots.

8. THE MOTOGP EXPERIENCE

The findings of this chapter were based on the interview with the Racing Service Coordinator (Appendix 9), an analysis of the racing schedules, MotoGP videos, rider stories and my own experience of being part of a motorcycle racing team. It can be very hectic and crowded around the track, and the conditions are different every weekend. Understanding the context in which the riders use the boots helps relate to the user and their needs.

Racing Weekends

A race weekend is always from Friday to Sunday (see Figure 8). Depending on the class the riders drive in, they get three or four Free Practice rounds, of which their best lap time is compared to the other riders within their class. The best 14 (Moto3 & Moto2) or 10 (MotoGP) go immediately to Qualifying Round 2. The others have to compete against each other in Qualifying Round 1, of which the best two (MotoGP) or four (Moto3 & Moto2) can still go to Qualifying Round 2. This round's end result defines how the grid or starting positions are arranged for the race. The higher they have finished, the closer they get to start to the start line. The final race is about who crosses the finish line first. The winner gets 25 points; from there, 5, 4, 3, 2 and then 1 point gets subtracted for every step downward. The one with the highest points by the end of the season receives the title of MotoGP World Champion (MotoGP, 2021b).

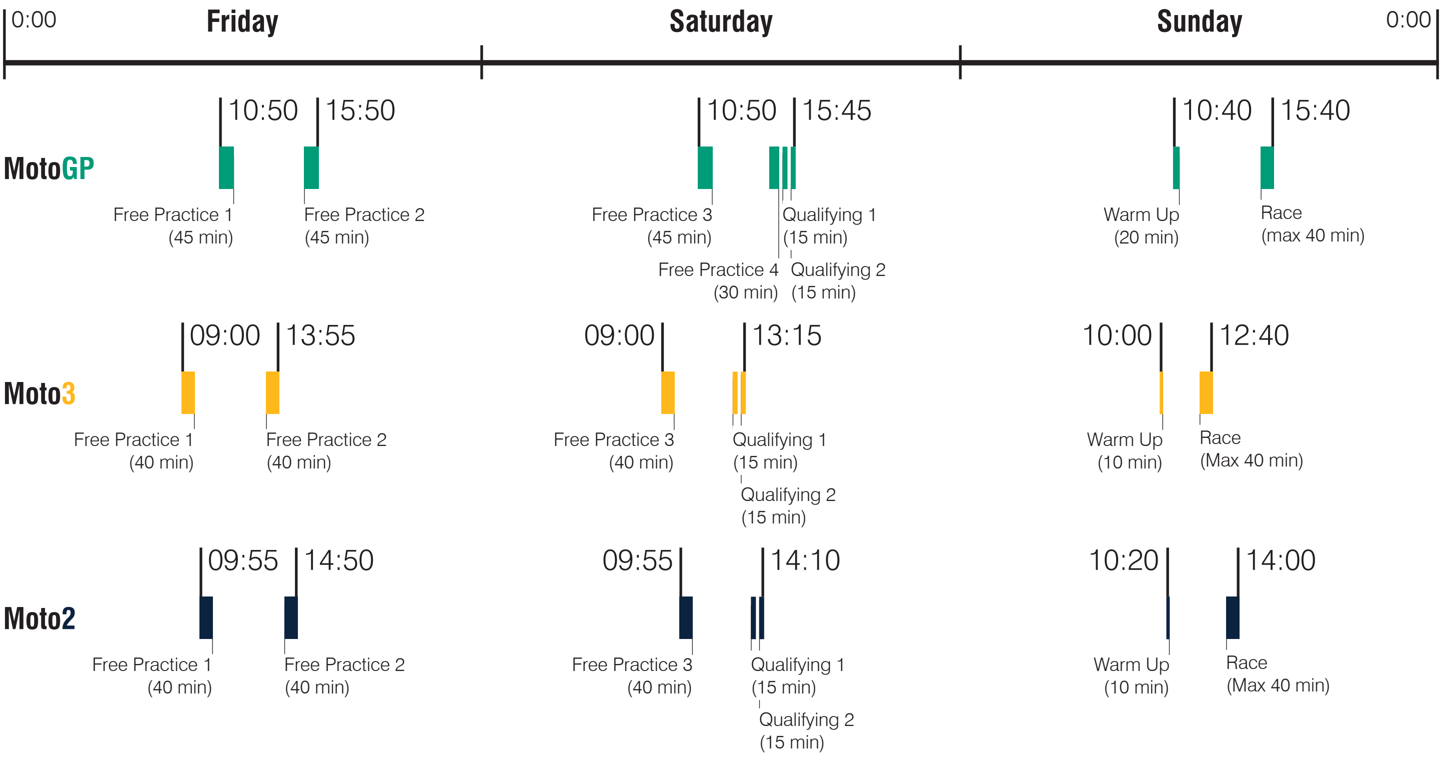


Figure 10. *Race Weekend Schedule Indonesia 2022 (MotoGP, 2022e).*

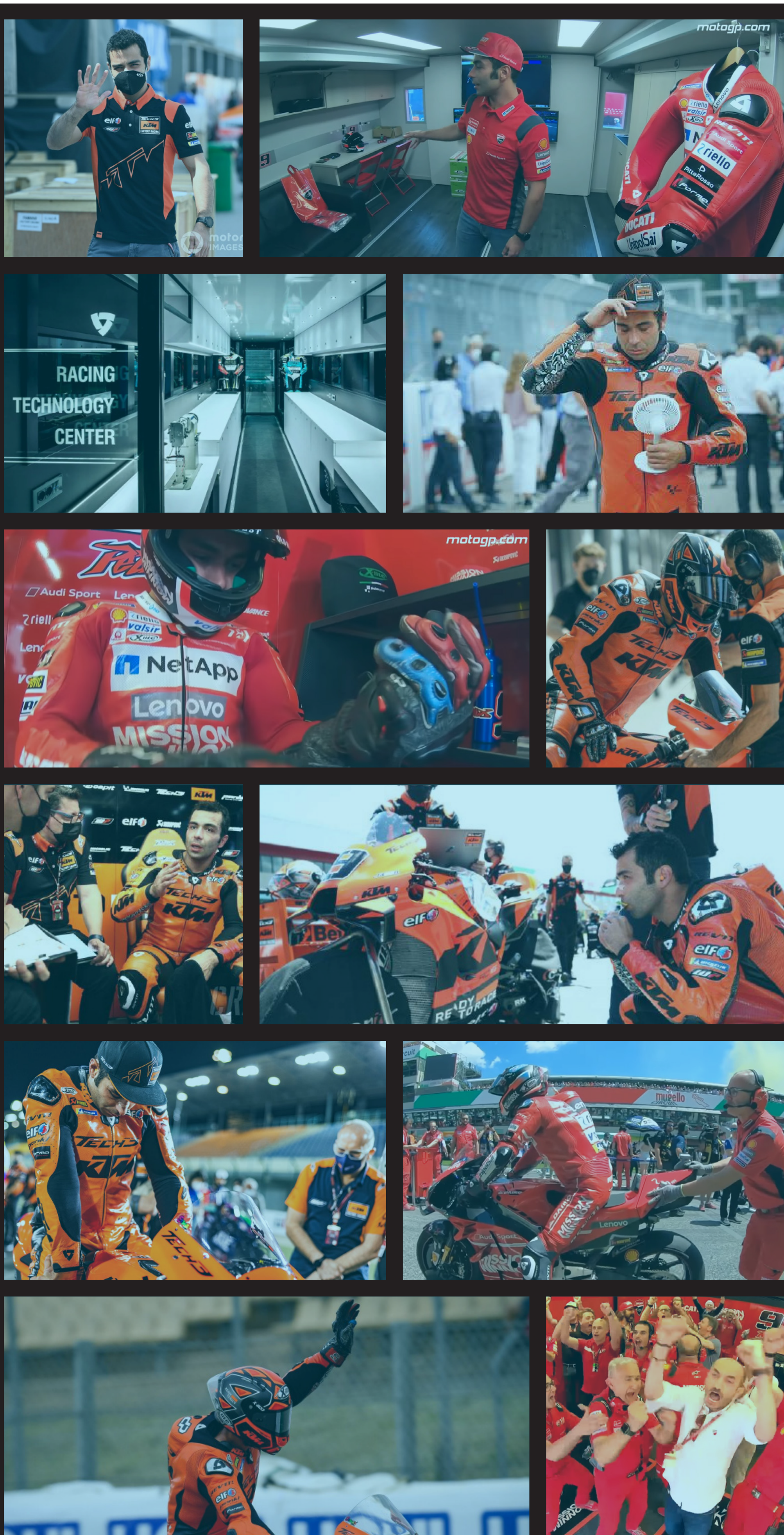
Circuits

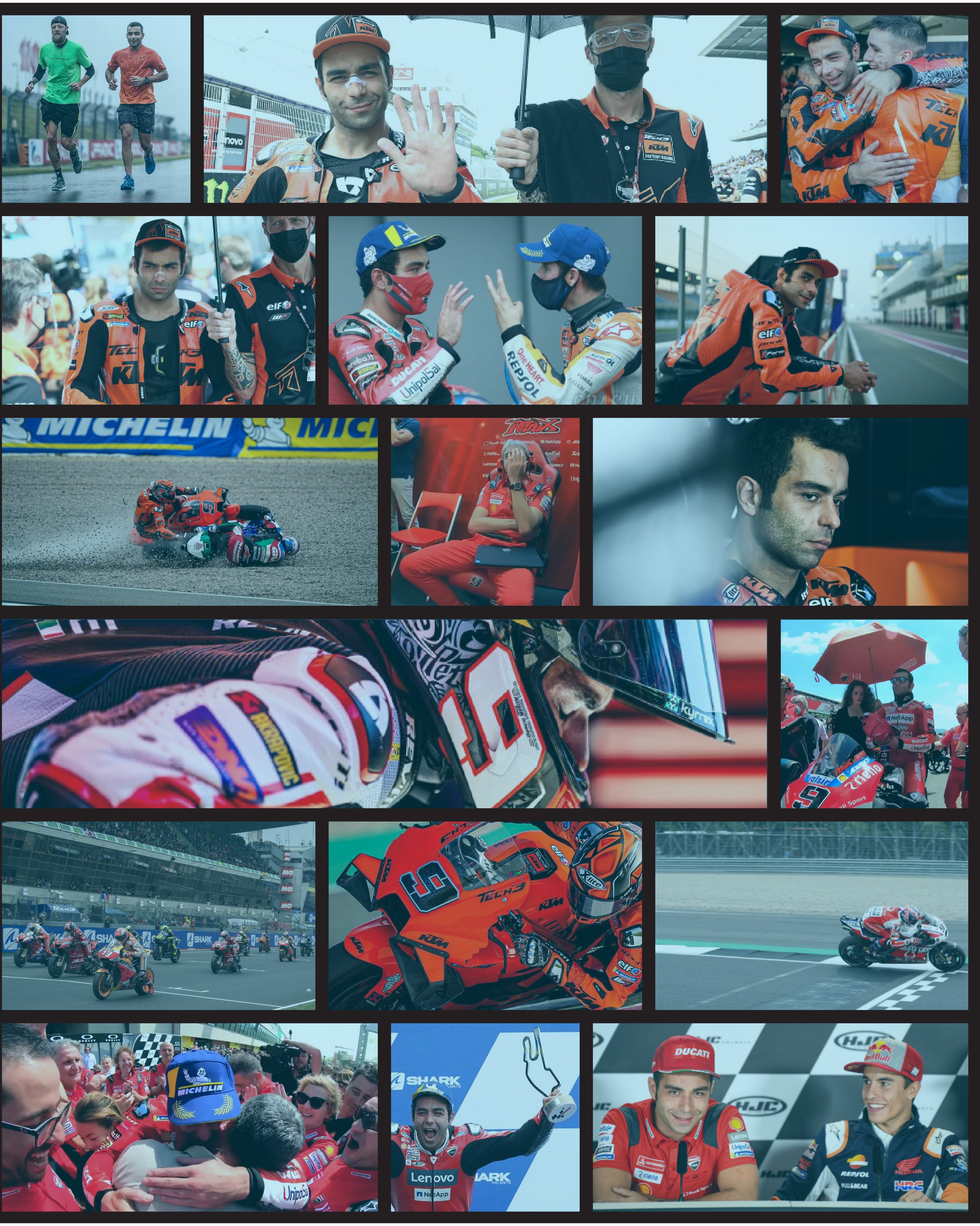
The MotoGP Championship consists of about 20 race events a year and runs from March to November after the testing is finished. These events take place on different circuits and almost every time in a different country. All circuits are entirely outdoors, which means there is no control over the climate conditions during riding. It can be hot, cold, rainy, dry, etcetera. Therefore, ideally, the riders' boots adapt to these changing conditions. However, the riders indicated that this was less of a priority for them in the design of the boots (Appendix 6). The riders are on these circuits for a maximum of 40 minutes at a time for 20 to 30 laps. The tracks are 3,5 to 10 kilometres long. They can be "fast and flowing" circuits, which require a focus on manoeuvrability, or "stop and go" circuits, which require a focus on acceleration and deceleration. Most of the races follow the circuits in a clockwise manner. Consequently, the riders encounter more right than left corners (MotoGP, 2021a, 2021b). As a result, the right boots wear down faster as the riders drag their feet over the asphalt on the side of the direction of the upcoming turn. On top of this, the foot position required to take a right turn results in more wear to the sole of the right boot due to the point pressure created by the footpeg.

The Experience

This collage provides an impression of what a rider experiences during a typical racing weekend and represents the user context (Boeijen et al., 2017). It is clear that racing weekends are intense, with many different impressions, emotions and moments of great demand from the physical and mental state of the riders. The list below describes the chosen images:

1. On the paddock of the race track on his way to his trailer wearing casual sponsor clothing.
2. Inside his private trailer, where he changes and relaxes when possible throughout the weekend.
3. Maintaining physical condition and doing warm-ups are essential for good performance.
4. Meeting fans and media on the track.
5. Being happy to see his teammate of the KTM racing team.
6. Visiting the Racing Service Coordinator of REV'IT! when the suit needs to dry, or repairs are required.
7. It can become hot being in full leather in a warm climate.
8. Some distractions can be very annoying.
9. Rivals on the circuit but not when off the bike.
10. Watching other classes while waiting.
11. Getting ready for a Free Practice.
12. Final rituals during the peak of stress.
13. Pushing it too far and crashing.
14. Disappointing the team.
15. Disappointing himself.
16. Technical feedback meeting to improve the bike setup for the weekend.
17. Waiting for the technical team to finish.
18. Getting into the zone, trying to focus.
19. Waiting for the race to get started.
20. Final stretches and deep breaths.
21. Getting into position.
22. 3, 2, 1.. Go!
23. Racing; strategy, adrenaline and focus.
24. Crossing the finish line first!!
25. Happy fans.
26. Happy and relieved team.
27. Happy and relieved rider.
28. Celebration.
29. Receiving your well-deserved trophy.
30. Answering the questions of the press.




MICHELIN
REPSOL
Lenovo
SHARK
DUCATI

Rituals

Looking at the schedule and pictures, it is clear that the riders have a lot on their plate during racing weekends. There is tremendous pressure on the performance they will have to deliver in a short period of time. The riders try to act on the limits of what is possible. The speed, the adrenaline, the pressure to perform, the small margins, the risk of crashing, the incredible amount of eyes directed at them, and the presence of healing injuries (Bautista, 2021) put a strain on a rider's body and mind. They train extensively and live healthy lives to deal with the physical part, but they all employ different strategies to cope with the mental part.

"Listening to the same song, straddling the bike from the same side every time, performing a particular stretch routine, making the sign of the cross, putting a certain glove or boot on first or holding the right footpeg" (Asphalt & Rubber, 2013), see Figure 11. These are all examples of rituals riders use to remain focused, block out the environment, and give them a sense of control over the uncontrollable ahead of them. Copying the rituals of others is generally seen as a no-go. Nonetheless, some riders do not seem to be bothered by that (Asphalt & Rubber, 2013).

±20 Min

Put Gear On

Figure 11. *The timing of donning and doffing racing gear and the duration of wearing time of the gear (Schamp, 2021).*

Donning & Doffing

Part of the rituals of the riders is putting on racing gear and eventually taking it off. According to Schamp (2021), the riders start dressing up about 20 minutes before riding. When riding is followed by a longer break, as can be seen in Figure 8, they will change back into their casual clothes about 10 minutes after they come off the bike, see Figure 9 for a schematic overview. They will especially change back quickly when it's warm outside (Bautista, 2021) as the riders run hot in their suits due to the physical activity, heat of the motorcycle, thick materials and poor ventilation. Consequently, it means that on the track, there is no need for the gear to be comfortable for more than one to two hours.

Most riders put on their undersuit first, then their socks, back protector, suit, boots, helmet, and gloves. They need to get "into the zone", and having to put a lot of effort into getting a zipper fully zipped up or having to take a hundred steps to put the boot on is annoying and distracting. The less distraction, the better. The new boot should complement the preparations and rituals and be easy and quick to put on and take off so as to not interfere with or even boost the performance of the riders.

TAKEAWAYS »

- Every racing weekend takes place on a different circuit in almost every time a different country. These are countries from all around the world, which means the local climates greatly differ per racing weekend. An area of attention for the boots could be looking into ways to accommodate for these different climates in terms of thermal regulation.
- Most races follow the circuits in a clockwise manner. This means more right corners and consequently more wear to the sole of the right boot due to the asphalt and the footpegs.
- With all of its accompanying facets, racing puts stress on the body and mind of the riders due to a combination of factors. Boots that do not add extra stress due to donning/doffing or even relieve stress by making the riders feel safe will boost the riders in their performance and helps increase user comfort.
- Riders perform rituals to deal with the stress of the uncontrollable. Researching if boots could play a role in these rituals could increase the feeling of ease associated with the product.
- The boots are only worn for about one to two hours, mostly on the motorcycle. Walking and long-term comfort are less prioritised than riding and short-term comfort.
- Riders put on their boots after they put on their suits.


MICHELIN

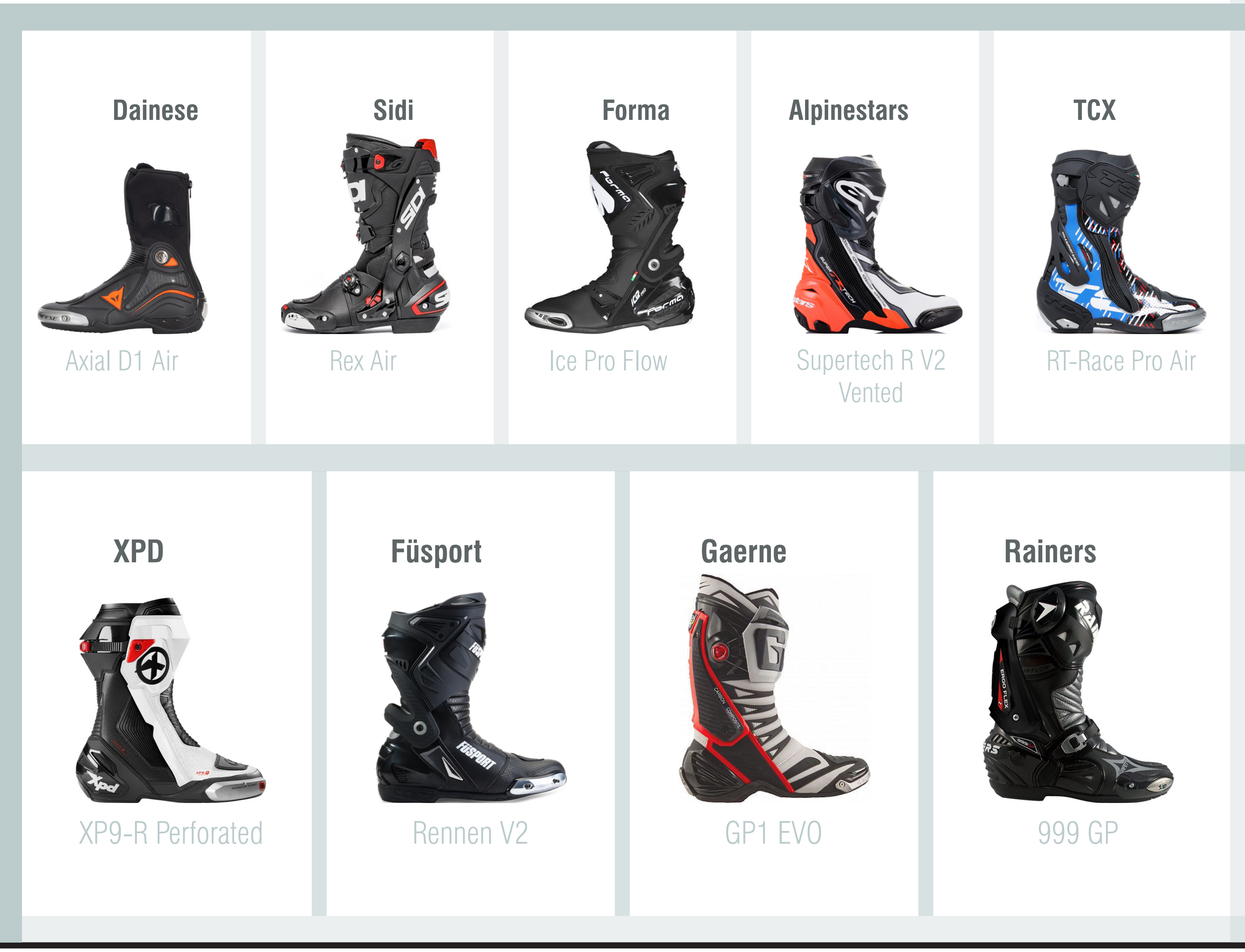
RACING BOOTS

Now that the context boundaries are set, it is necessary to fathom what goes into a racing boot, what makes it a good or a bad one and why the riders even wear them to begin with, for identifying requirements and problems. First, the boots of REV'IT!'s competitors are taken under the loop to learn about their strengths and weaknesses, and then the boots are taken apart on a functional level founded by a crash analysis. This section concludes with a list of racing boot design drivers and requirements, areas of improvement and a new problem statement.

9. THE COMPETITION

As REV'IT! is completely new to the market of high-end road racing boots, it is a good idea to start off with an analysis of the current competition within that market segment. Understanding what the pros and cons per brand are, could teach us what to strive for and what to avoid in terms of design. On top of this, it's relevant to see whether there are any opportunities or threats within this market for REV'IT!. Firstly, an analysis was done to understand which brands and boots could be considered competition. Then, an in-depth analysis was done of the reviews that people leave on websites like Revzilla.com and in the comment sections of review videos on YouTube. The conclusions about the strengths and complaints per pair of boots were noted in the results that can be found in Appendix 3.

Figure 13. *Overview of all boots worn in the MotoGP, Moto3 and Moto2 class (MotoGP, 2022a-d).*



MotoGP Boot Options

The boots that the riders from the MotoGP to the Moto3 Class are wearing this season are the Dainese Axial D1 Air, TCX RT-Race Pro Air, Sidi Rex Air, Forma Ice Pro Flow, Alpinestars Supertech R Vented, GAERNE GP1 EVO, the XPD XP9-R Perforated, Rainers 999 GP and the Fühsport Rennen V2 (MotoGP, 2022a, 2022b, 2022c, 2022d), see Figure 12. See Figure 14 for the distribution among the different brands and classes.

As REV'IT! competes at the highest level with their racing suits and gloves, the boots should match this. That is why, for the competition analysis, only the most present high-end boots and other boots that are currently being worn by REV'IT! Riders were selected to compare, in terms of company and product strength and weaknesses. The boots of XPD also meet these requirements, but they were left out of the evaluation, because of the lack of available information regarding these boots.

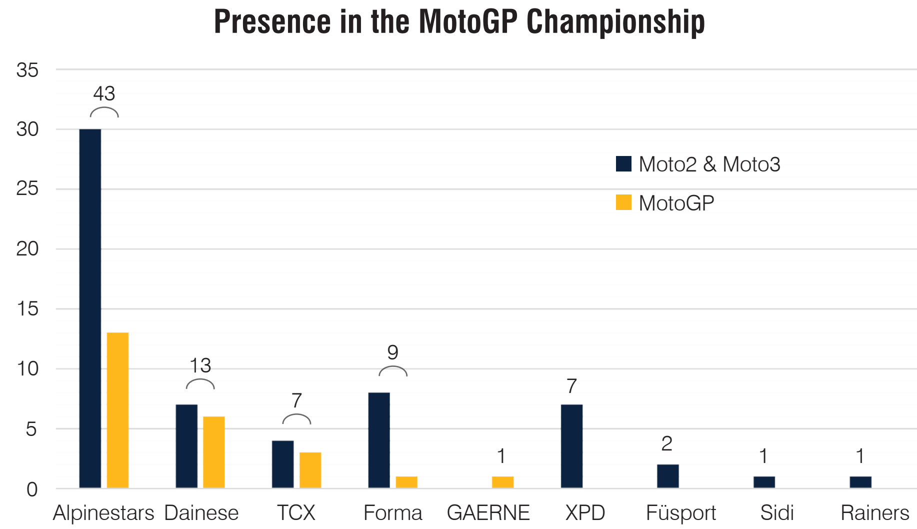


Figure 14. *The number of riders from the different MotoGP classes using the different boots per brand (MotoGP, 2022a-d).*

EN 13634:2017 Protection Level Codes (Table 1)

a | Evaluation of the footwear height.
b | Impact abrasion resistance test.
c | Impact cut resistance test.
d | Transverse rigidity test on the whole footwear.
WAD | Absorption and desorption of water of the insole or insock.
SRA | Slip resistance of the outsole on ceramic tile floor with NaLS.

An overview of all other labels can be found in Appendix 12.

Table 1. *Overview of the characteristics of the main competitors' boots (RevZilla, 2022a,c,e,f,g).*

	Supertech R Vented	Axial D1 Air	RT-Race PRO Air	Rex Air	Ice Pro Flow
Price	$ 499,95	$ 529,95	$ 499,99	$ 499,99	$ 349,00
Weight (Per Boot)	1168 g (incl. inner boot of 364 g - 31 %)	910 g	965 g	1166 g	1167 g
Donning Time	27 s (incl. 15s inner boot)	20 s	35 s	28 s	41 s
Protection Level (CE) EN 13634:2017: a-b-c-d	2-2-2-1	2-1-1-1 (WAD)	2-2-2-2 (SRA)	2-2-2-2	2-1-2-1 (WAD)

Ratings Racing Boots Competitors REV'IT!

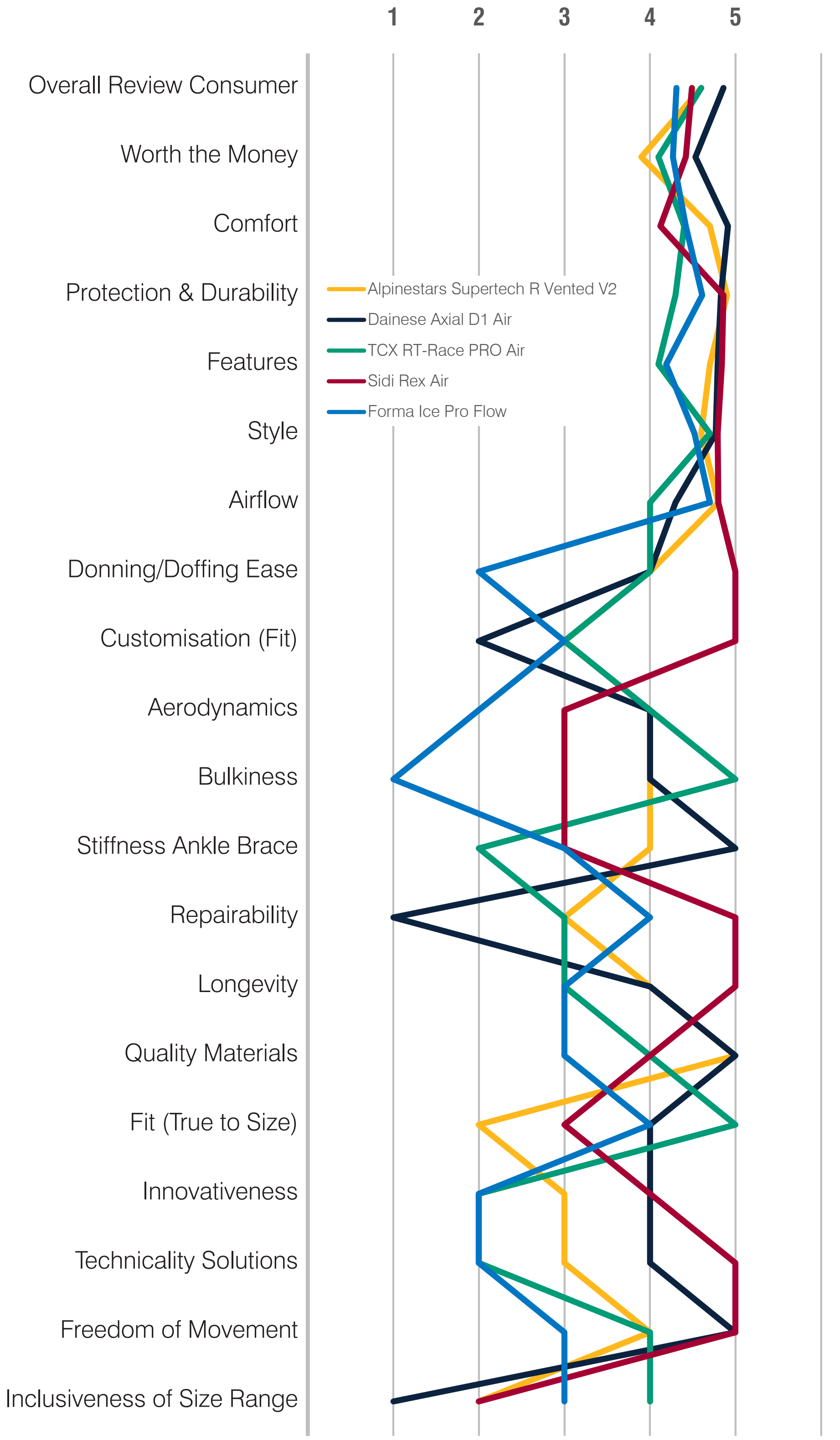


Figure 15. *The Value Curve with ratings of the main competitors' boots on a Likert scale from 1 (bad) to 5 (good) (SidiSport, 2018; MKC Moto, 2019; _AtSpeed, 2020; Champion Helmets, 2018a-b, 2019; Count Greffi, 2020a-b, 2021; Silly Side Down, 2017; Sportbike Track Gear, 2015, 2019a-c, 2021; RevZilla, 2015, 2017, 2018, 2019a-b, 2021 2022a-i; MotoGeo, 2021; RSFinch, 2020).*

The Analysis

All the evaluations of the boots were summarised in ratings on a Likert scale from one to five, with one being bad and five good. These ratings were places on a Value Curve (Van Boeijen et al., 2013), see Figure 15. The topics to rate were based on the review data that was already available and the focus of people's reviews.

Table 1 provides an overview of the prices, weight, donning time and the certification level. The weight was measured by putting the different boots on a kitchen scale. The donning time is an estimation, as this was measured by stopwatch while I put on all the boots.

When it comes down to the companies themselves, they range from under 25 (Forma) to over 300 employees (Alpinestars). Some, like Dainese are active in multiple branches and some, like Sidi, only focus on footwear. Dainese, Alpinestars and Sidi were all founded in the 60's and so are very experienced companies. They all deliver good products. It's just that they all have a different focus. According to De Wit (2021), the consumers base a lot of their choice on how sympathetic they think the brand is and what the riders they like, ride with. It's more important to feel safe than be safe. The market of racing boots is rather traditional and because of that the changes made in this sector are usually not too earth-shattering. Also, the boots develop slowly over time, see Figure 15. The models need to return their investments and outputting new boots too frequently is not worth the investment. Especially in the racing sector the returns are not too high, which prevents major innovation in the racing boots (De Wit, 2021).

Figure 16. *Timeline Dainese Axial D1 (DemoneRosso, 2021b).*

Opportunities

Striving for a boot that would score a five on all the values and combining all of the good qualities of the competition, would be ideal. However, of course there are trade-offs to be made, especially in the limited amount of time REV'IT! has before launching the product. Within the market there is some room for improvement and REV'IT! could add value by bringing more innovation. All the companies claim to be innovators, but groundbreaking changes are rare. On top of that, the safety of the boots can be a focus area. The boots protect and already do a good job, but there is barely any proof to back this up and injuries are still common among riders. Customisation and inclusiveness in terms of sizing and functionality that tailors to the need of all the different kinds of users is something to could set you apart from the competition.

TAKEAWAYS »

- Even the best boots are not perfect yet and could use optimisation in terms of protection and comfort. Special areas of attention are the ankle protection, the fit, the closure systems, the ventilation, and the bulkiness of the boots.
- The output frequency of new boot models and the level of innovativeness in these boots is low.
- Keep the donning and doffing of the boot simple, short, and smooth.
- Many complaints come from the fit of the boots (mostly for people with wider feet). Keep the different calve sizes in mind, preferably find a solution that adjusts to this.
- Freedom of movement is important for the perceived comfort but sturdy boots make people feel safe. They don't care much about the CE-label.
- For the consumer being able to walk around in the boots for a longer period (without them squeaking) and being able to pair the boots with other riding gear is important.
- Most boots are unisex, but the design of a boot based on the safety and preferences of women could be an interesting direction.
- The boots should be comfortable right out of the box (no pressure points, great flexibility and freedom of movement).
- When working with zippers, provide enough elasticity around them, to make it easier to work with.

10. THE BUILDING BLOCKS

At first glance, it might not seem like it, but a road racing motorcycle boot fulfils many different functions. In this chapter, the functions of each part of the boots are elaborated upon. Based on the same argumentation as in the competition analysis, the following boots were included in this chapter: the Dainese Axial D1 Air, TCX RT Race Pro Air, Sidi Rex Air, Forma Ice Pro Flow and Alpinestars Supertech R V2. All findings were based on the rider session, the interview with De Wit, review videos used for the competition analysis, and observations.

Figure 17. *All parts of a racing boot.*

Outer Sole / Outsole

Functionality

The outsole provides grip in the contact between the feet and footpegs, brake lever, shift lever and asphalt. Furthermore, it provides heat protection, absorbs impact energy and dampens vibrations (De Wit, 2021). The main purpose and so the grip and hardness of the material of the outsole differ per area. Some areas are mainly in contact with the footpegs and levers. Here grip, resisting wear from point pressure and protection against the heat of the pegs are most important. For extra grip with the bike, the outsoles even wrap around the edges of the boot as the riders often tilt their feet and position them between the bike and the footpeg (Appendix 7). Other areas are mostly dragged over the asphalt. Here resisting wear and protecting against heat from friction is essential. The heel and lateral side of the sole are mainly used for walking. As walking is not done much, wear is less important, but grip is not. Generally, there is a lot of overlap between these areas, but grip on the bike in all riding positions is most important. Designers play around with types of compound, topology and structure. Another factor in the material selection is the sole's flexibility, as it should not be too stiff nor too flexible. Stiffness provides safety and distributes the grand force of the footpegs and levers over a larger area. Flexibility allows for a better tactile feel and more freedom of movement.

The outer sole has a protruding part at the heel. The footpeg of at least a diameter of 8 mm (FIM, 2021) sits in this crease while braking and shifting. It acts as a reference point for the location of these levers. Some riders feel they do not need it, and some would like it to be bigger, so their opinions diverge (Appendix 6). Consumers generally prefer this heel as they are taught to rest their feet on the pegs while riding to reach the braking lever quicker in case of an emergency.

Requirements

The racing boot NEN norm specifies outer sole requirements regarding the thickness of different areas, profile depth, interlayer bond strength, abrasion resistance and hydrolysis. Furthermore, it provides optional requirements for the sole's grip on asphalt in water and oil (Appendix 12).

Wear

A common complaint is that the soles wear too fast during a race (Alberto Naska EN, 2019). Riders put all their weight on the footpegs and hover slightly above their motorcycle. In other words, tremendous pressure is applied on a minuscule area, significantly damaging the outsole (RevZilla, 2011). Furthermore, this means that sliding off the pegs results in a crash. The pegs have spikey edges on the outer sides to improve grip, but this eats away at the sole even more. However, the most invasive thing the riders do is slide their boots over the asphalt while braking before a corning. Rossi started this trend, and many riders followed. The reasoning behind it is still up for debate. However, the most likely benefits are shifting the centre of gravity inwards, making it easier to turn the bike, braking through friction with the asphalt and the increased frontal area, and therefore drag or letting the blood flow back into the leg (Schamp, 2021). Which part of the sole they put down differs per rider, which makes it difficult to predict where a harder piece of material would be beneficial to reduce wear (Appendix 5). A previous boot of Sidi had a replaceable piece of sole. Some people seemed to like it, but according to the people selling them, this was bought sparingly. On top of that, the screws and other additional parts added weight, reduced the sole's tactile feel, and made them too stiff (Sportbike Track Gear, 2017). The tactile feel of the boot is essential as the riders need to feel where the footpegs and shift and brake lever are located for proper usage. The resistance and vibration of the levers also communicate much about the bike's functionality, like whether the shift lever was pushed far enough to shift gears. The thickness and flexibility of the outsole define this tactile feel.

Flex Area

A segment of the upper is defined as the "flex area" according to the NEN-EN 13634:2017 and the FIM (Appendix 12). This area has to meet less demanding requirements than the rest of the upper regarding impact abrasion resistance, resistance to impact cut, and tear resistance (FIM, 2021), for the simple reason that it is generally not subjected to abrasion or high-energy blunt impacts. As can be derived from its name, the flex area makes the boot more flexible. It allows a greater range of motion that requires less force in the direction of plantar and dorsiflexion. The riders indicated this as a must for their boots (Appendix 6). This makes sense as the analysis of the foot positions of riders while racing showed that riders required the greatest range of motion in this direction compared to the other ankle movements. Shifting, braking, cornering, and sitting in a tucked-in position on the straights are the motions that require this flexibility (Appendix 7). The less force this requires, the less energy it costs the riders, so the better the performance. Consumers also appreciate this boot feature, but for an alternative reason. They consider a flexible boot to be more comfortable (De Wit, 2021). Moreover, the flex areas are often thinner and more open structures, compared to the rest of the upper, that function as an air-inlet for temperature regulation.

Grip Panel

All boots have an area of a distinct material on their medial side. The type of material and size of this area differ per brand, but generally, it is a textured, more abrasive type of microfiber or rubber. It is located where the boot is in contact with the bike, allowing for more grip. The riders clamp themselves to their bikes, and a momentary loss of grip can cause them to crash (Mike on Bikes, 2020). Keeping this area free of protruding parts is essential; the riders could otherwise get caught behind their footpegs or heel guards while changing positions. A plus for consumers is that these areas do not scratch up their bikes (Motorcycle Gear Hub, n.d.-a).

Upper

Functionality

The upper is the outer layer of the boot. In all boots, this layer is made from synthetic leather/microfiber. The advantage of synthetic leather over natural leather is that it is more abrasion resistant, stronger, lighter, and more flexible. This flexibility reduces the break-in period required for a boot to become comfortable to wear (ChampionHelmets, 2019; Sportbike Track Gear, 2019a; GetGeared, 2017). On top of that, this material does not expand over time, unlike natural leather, which is ideal as the boots need to be dimensionally stable to keep the protection in place and to maintain the level of tactile feedback that can be felt (De Wit, 2021). According to De Wit (2021), there is a downside, however. The microfibers are less heat resistant as they will melt at a lower temperature. This is the reason why the boots are equipped with heat shields. These shields should keep out the heat produced by the motorcycle and protect against the heat generated while sliding on the asphalt during a crash. The heat shielding Kevlar layer of Alpinestars, for example, can resist up to 700/800 °C.

Requirements

The upper needs to comply with several requirements to get certified according to the norm NEN-EN 13634:2017. These requirements relate to the height, bond strength between the upper and the outsole, pH value, innocuousness, seam strength, Chromium VI content, color dye fastness, impact abrasion resistance, and cut resistance. The FIM (2021) stated a few additional requirements in their regulations regarding abrasion and tear resistance and seam strength. See Appendix 12 for the exact requirements. For the safety of the riders, there should be as few protruding parts on the upper as possible, as everything that sticks out can get caught behind the bike, potentially resulting in a crash. For during a crash, it is important that the only parts that protrude are the sliders, as they prevent the more grippy parts, like the sole and upper, from grabbing the asphalt while sliding, resulting in more dangerous tumbling. These sliders also protect the upper from damage.

Perforation

In MotoGP racing, the uppers are generally perforated. The small holes provide ventilation for moisture and temperature management. According to De Wit (2021), this significantly affects the boots' ability to keep feet at a comfortable temperature. The difference in the consumers' ratings of the airflow of the perforated and non-perforated versions of the boots confirms this statement (Appendix 3). According to the riders, there is indeed a difference, but especially in warmer climates, it is insufficient in preventing overheating. The opinion about the importance of the ventilation of the boots differs per rider (Appendix 6). A downside to the perforations is that the boots rapidly get drenched in rainy conditions. That is why in these conditions, some riders opt for non-perforated boots, but most riders do not care (Bautista, 2021).

Aesthetics

The riders can select the print and colour of their preference for the upper to express themselves and stand out in the group of riders. The riders prefer functionality over aesthetics (Appendix 6). However, their suits and boots show that someone invests time in the print design.

Ankle Brace

Functionality

During a crash the riders are at high risk of an injury caused by hyper-rotation of the ankle joints. Considering the finding of the crash analysis (Appendix 11), the most problematic rotations in this scenario are inversion and eversion (rotating the ankle in- and outwards, respectively; movement in the coronal or frontal plane (Yoganandan, Nahum & Melvin, 2015), and abduction and adduction (twisting the foot out- and inwards relative to the lower leg, respectively; movement in the transverse plane (Yoganandan et al., 2015)). For this reason, Alpinestars was the first to introduce a biomechanical ankle brace to their boot. Quickly other brands followed with their own version of an ankle brace. Most of them try to limit the risk of injury caused by hyper-rotation in the direction of inversion, eversion, adduction and abduction, but TCX and Forma also try to limit plantar flexion and dorsiflexion (moving the foot downward and upward relative to the lower leg; movement in the sagittal plane (Yoganandan, Nahum & Melvin, 2015)). However, according to the LMU (2019), there is no relevant link between plantar and dorsiflexion (xflexion) and injury mechanics data when it comes to road racing rider injuries.

TCX, Forma and Sidi put the brace construction on the outside of the boot while Alpinestars and Dainese attached it to the inner boot. Having the system closer to the skin makes it more effective in injury prevention due to tolerances. Furthermore, the structure is less exposed and therefore less likely to get damaged during a crash. And there is no risk of getting the structure caught behind a part of the bike while riding and crashing (De Wit, 2021).

The materials used are carbon fibre (Dainese) and TPU (the rest). The first is lighter and stiffer than the latter.

Range of Motion vs Protection

All structures are rigid, which is good for energy absorption and so protection, but bad for the freedom of movement that is required for riding (Appendix 7). Ideally a boot with this structure allows for some degrees of movement and gradually blocks it before the injury angle is reached. The structure of Alpinestars consists of two hinge points on both the lateral (outer) and medial (inner) side of the foot to allow for plantar and dorsiflexion. The upper hinge point on the medial side slides up and down to allow for some in- and eversion (xversion). Dainese has one hinge point on each side of the foot that can both slide slightly in any direction along the sagittal plane. This allows for limited xversion in any foot position. Dainese and Alpinestars both patented their solutions (Dainese (WO0221954A1, 2002); Mazzarolo (WO02052969A1, 2002). Sidi, TCX and Forma also use one sliding hinge point on both the lateral and medial side of the boot. TCX indicates to allow for movement of 15 % of inversion and 18 % of eversion. What that means in terms of degrees is uncertain. Forma allows for 30 degrees of plantarflexion and 15 degrees of xversion. Other brands do not communicate this information.

Despite current solutions, ankle injuries prevail, mostly in the form of torn or overstretched ligaments. The NEN norm states nothing about hyper-rotation protection, but experts expect this to change.

Closure System

Functionality

The FIM (2021) states that: "The boots should have a means of fastening to secure them to the foot (a slip-on boot is not acceptable)." In other words, a closure system is required to prevent the boots from flying off during a crash. Naturally, keeping the protective parts in place is fundamental for the efficacy of the protection of the boots (Sportbike Track Gear, 2019a). The design of the closure system defines the comfort experienced while putting on and taking off the boot (donning and doffing).

Types of Systems

Alpinestars and TCX have boots with a side-entry from the lateral side, Forma a side-entry from the medial side, Dainese a back-entry, and Sidi a top-entry. Back and side-entry are supposedly the most comfortable to don/doff when injured. Top-entry is very painful in this scenario (Bautista, 2021). This entry type also complicates adjusting the socks and suit inside the boot. Despite a microfiber cover, the zippers of the lateral side-entry are prone to damage during a crash, potentially reducing their longevity (Sportbike Track Gear, 2019c). Having a zipper on the medial side of the foot, with which the riders clamp onto the bike, could interfere with the tactile feel, create pressure points on the foot and risk getting the zipper system caught on the bike.

The closure system generally consists of a speed lacing system with a padded tongue to tighten up the inner lining for a snug fit, a zipper on the outside (the upper), some Velcro and a buckle around the calf. The only exception is Sidi, whose micro-adjustable closure system consists of three buckles that can be tightened separately (RevZilla, 2022d). The first-mentioned system is less bulky yet more work, and the latter is the opposite.

Alpinestars has an inner boot that can come out, which lets users put on and adjust this boot first and then pull the outer shell over. This results in a good fit, but it also makes the boot heavier and bulkier.

Encountered Problems

Many previous versions of side-entry boots with zippers on the upper received negative feedback due to the great amount of force required to close up the zipper (RevZilla, 2022b). For this reason, stretch panels were placed near the zipper. They increase the ease of donn-/doffing, make the boot more flexible and reduce the wear of the zipper.

The speed lacing system allows the adaptation of the fit over a larger area and includes a smart mechanism that blocks the release of the strings when tightened. For the first version of Alpinestars boots, it was a common complaint that the lacing system would break. The lace was strong enough, but the supporting structure was not.

The buckles at shin height should allow for various calf sizes. Many complaints about boots come from people that cannot close the top because of their bigger calves. Dainese and Sidi generally do not have this problem. Dainese's boots remain slightly below the calf and have stretchy Velcro straps to connect the front and the back part of the ankle brace, and the Sidi boot has a big top opening. The buckles are sunken into impact protectors to keep them intact during a crash and are made from aluminium by TCX and TPU by the rest.

Lasting Board

The lasting board is the layer between the inner and outer soles. It is a stiff piece of material that makes the boot more comfortable and safe. As the riders put all their weight on the footpegs, the pressure on the bottom of the feet would be very high if it were not for the lasting board. It distributes this force over a larger area, which reduces this pressure to a comfortable level. They even reduce the chance of the footpegs penetrating the foot in case of a crash. Furthermore, the lasting board provides transverse rigidity, which is required by the racing boot NEN norm (Appendix 12). Transverse rigidity protects the foot from being crushed in a sideways manner by the weight of, in most cases, a bike. For all the abovementioned reasons, the highest possible stiffness would be ideal, especially along the width of the lasting board. However, this is not ideal for the tactile feel of the footpegs and shift and brake levers and limits the freedom of movement while riding and walking. Even though walking around is not a priority on the circuit, the NEN norm still requires the boots to be comfortable to walk in for five minutes at four kilometres an hour and climb stairs for one minute (Appendix 12). Therefore, flexibility in the front area of the lasting board is necessary, as this allows for a normal heel-toe stride. For that reason, the lasting board of, for example, the TCX boot, is thinner in the front. How flexible the riders want their sole depends on preference (Appendix 6). However, consumers generally want more flexible soles that allow for more comfortable walking (Appendix 3).

Sliders

Functionality

During a crash, sliding over the asphalt is ideal as the gear protects the skin well enough against abrasion wounds. However, high impact and the twisting of ankles are more challenging to protect against. In case a piece of the gear grips the asphalt while sliding, the rider starts to tumble. At high speeds, this dramatically increases the risk of injury due to high energy impacts and hyper-rotations. That is why continuing to slide until the rider comes to a stop is ideal (Scamp, 2021). Reducing the friction coefficient of the upper helps, but it will not reach the coefficient of a polymer or metal. For this reason, the boots come equipped with sliders that protrude from the upper and reduce the damage done to the upper, as mentioned before. These sliders can generally be found at the heel, ankle, shin, and toes and are often made from TPU, metals like aluminium, magnesium and titanium or a composite of the two. The metals are better at withstanding heat and provide better abrasion resistance and friction properties, so they slide better. The TPU starts to melt at a certain point, which is why they perform worse at sliding. The choice between the different metals comes down to their price and melting point, with magnesium being the most expensive (De Wit, 2021).

Longevity

Because the sliders stick out, they suffer the most damage during a crash. That is why the sliders are replaceable for all boots but the ones of Dainese. It is a trade-off as the attachment systems add weight and complexity to the boot. The screws used for attachment are different per brand, but they all have Loctite on them to keep them in place. Alpinestars even patented the attachment system of their toe slider (Mazzarolo & Vanin (WO2014049535A1, 2014)). For some boots, different tools are required to replace their different parts. It would improve the user experience to limit this to one.

Toe Slider

All brands have sliders in different locations, but they all have their version of a detachable toe slider. This slider protects the toes in extreme lean angles that keep increasing over time (MotoGP, 2021), as the riders risk sliding their toes over the asphalt. Also in this scenario, it is a must that the toes do not grip the asphalt and increase the risk of the foot sliding off the peg. The design of a toe slider deals with allowing the freedom of movement of the forefoot required for certain positions. A thinner toe slider is advised, as a very thick toe slider could trap the foot between the circuit and the bike while cornering (Appendix 3). For the same reason, keeping the boot as narrow as possible is recommended. Some riders have their toe slider replaced by a thin plate glued or screwed onto the boot. However, the less they protrude, the more likely the upper will suffer damage while sliding.

Vents

On top of the perforated upper, some boots also have vents for extra ventilation. Sidi even has vents that can be opened and closed. These vents impact the climate inside the boot. The boot should be equipped with inlets for cool air and outlets for warm air for the best cooling. These parts add weight and are holes inside the structure, so it is a challenge to maintain the safety of the boots and balance this trade-off. In the MotoGP, the bikes are so streamlined that the cooler air can barely get inside the boots (REV'IT Riders, 2023). That is why even with vents, the ventilation is often not sufficient. With consumers, the cooler air gets inside. However, they are generally not doing the same intense workouts as racers do on their motorcycles. So, the demand for proper ventilation is limited to people in warmer climates and those who generally run warm quickly.

Shift Panel

There is an extra piece of TPU on top of the foot called the shift panel. For all brands, these panels are on both the left and right boot, probably for cost or aesthetic reasons, the lack of complaints and because a small percentage of bikes has their shift lever on the other side. Nevertheless, it mostly has a function on the left boot; shifting gears. While shifting down (so pushing the lever upwards), the panel provides extra grip. Additionally, it protects the upper from getting damaged by the lever, which extends the boot's longevity. Making it as thin as possible is ideal for tactile feel regarding the lever. The rider must feel the lever's location and whether they have pushed it upwards far enough. Making it too thick and large also interferes with the freedom of movement of the toes and could make it start to dig into the skin. The part of the shift panel that curls around to the medial side of the boot increases grip in the contact area between the boot and the motorcycle. Furthermore, it reduces the wear of the upper in this area caused by the lever. Therefore, Alpinestars extended this panel farther back in their V2 of the Supertech R.

Top Gaiter

The top gaiter keeps pebbles from the gravel pit and other debris on the outside of the boot. It is made from the same microfiber as the upper. Alpinestars and TCX reinforced it with over-injected TPU for extra stiffness and to make the boot stick to the suit underneath. Attaching the boot and suit helps distribute the forces that try to ab- or adduct the ankle along the leg, which should protect the ankle better (DemoneRosso: The Dainese Journal, 2021b). The boots of Dainese do not have a top gaiter because they go into the suit to which they are connected through their patented Velcro system. This way, the suit keeps debris out and the boot firmly in place. This in-boot system has a sleeker and so more aerodynamic profile. The weight of the shin protection is moved more proximal to the knee into the suit, and the suit's upper functions as an abrasion protector for the region above the ankle.

Inner Lining

The inner lining is generally made from a synthetic mesh material. This allows for ventilation and has moisture-wicking properties to keep the foot dry. It is a smooth layer that smoothens out the inside of the boot, so the rider will not feel the stitching and other parts of the outer layer. Still, riders always wear socks in their boots (Schamp, 2021). Any friction between this inner layer and the foot can cause blisters. Therefore, wrinkling of the material should be limited to prevent pressure points on the skin. Different areas of the skin can handle different amounts of pressure, so this is something to consider (Goonetilleke et al., 2013). According to the NEN-EN 13634:2017, the inner lining should meet requirements regarding tear strength, abrasion resistance, pH value, Chromium VI content and colour fastness. This is similar to the upper but without the tear strength and the abrasion resistance.

Ankle Protector

Another optional impact requirement is defined for the ankle protector, which comes with the IPA label when done correctly. All boots have some variant of an ankle protector that distributes forces over a larger area to protect the lateral malleoli. Seeing as how the riders land on the sides of their bodies, this is an essential piece of protection. However, also here goes that the boots have yet to receive such a label. Likely this stems from the fact that investing in meeting optional requirements that the riders nor the consumers notice is only worth it once the users start indicating the current protection to be underperforming. Hence the reason some form of ankle impact absorbers is present but is not CE certified.

Toe Box

Similar to the heel box, the toe box prevents the toes from getting crushed in case the bike falls on it, provides transverse rigidity, absorbs high-energy impacts and is not incorporated into the NEN norm. However, the difference with the heel box is that the toes require mobility. The bigger the toe box, the better the crush protection, but it will start to restrict foot movement at some point. Then standing on the footpegs would make the toe box protrude into the foot, making it a very uncomfortable experience. Toe boxes are, therefore, relatively small and do not entirely prevent broken toes (Appendix 18). Possibly swollen toes can be something to consider when deciding on the toe box size. Moreover, the toe box is one of the reasons why a correct fit is so important. If the boot is too long, it will not cover the toes sufficiently.

Shin Protector

All boots except the boot of Dainese come equipped with a shin protector. The shin protector of Dainese has been incorporated into the suit instead of the boot to be able to create a longer more continous surface and to move the weight proximal to the hip joint, changing the inertia of the leg slightly. Optional requirements can be found in the NEN norm and would reward the boots with an IPS label, which none of the boots has. The reasoning behind a shin protector is most likely that it distributes the force over the ankle, shin and knee when falling sideways instead of only the ankle and the knee. Furthermore, it protects in case of a collision with another rider or object.

Heel Box

The heel box is the construction around the heel that absorbs the impact that the heel could endure in a high-energy crash. Riders often fall on their heels with great force, and they almost all indicated to want protection there (Appendix 5). According to Simon Crafar, a former MotoGP rider, the development of the heel box was a much-needed improvement. Back when he was racing, crashing and landing on the heels was one of the most painful experiences that would continue to hurt for weeks (MotoGP, 2020b). Though still an uncomfortable experience, the impact of such a crash is now much less impactful. One of the REV'IT! Riders explained that the heel is an area where no mobility is needed, so it can be made stiff and more prominent if needed. Sidi made an asymmetric bulbous heel box that protrudes to the lateral side. Making the medial side too big interferes with the freedom of movement on the footpegs and limit tactile feel. Others kept it more symmetrical and incorporated it into the overall shape more smoothly. Alpinestars patented a heel impact absorption system (Mazzarolo (WO2009028001A1, 2009)). Besides absorbing impact, it also prevents the heel from getting crushed. The norm does not state any requirements for this part of the boot, so there is no indication of how much force is transmitted through any of the heel boxes.

TAKEAWAYS »

- A racing boot must include the functionality of the following parts: outer sole, upper, grip panel, flex area, lasting board, sliders, toe slider, ankle brace, closure system, top gaiter, vents, inner lining, shift panel, shin protector, ankle protector, heel box and toe box.
- All used boots are made of perforated microfiber/synthetic leather as this has much better qualities.
- The left and right boots differ in functionality and use. Therefore, an asymmetric design could be considered.
- Metal sliders are the best in terms of characteristics.
- Keep the toe slider as thin and long as possible without interfering with the natural movement of the foot.
- Make the toe box as large as possible without interfering with the bending of the toes.
- Make the heel box big and stiff without offsetting the boot too much from the bike.
- Shifter pads should be as thin as possible if they need to be present at all.
- Speed lacing systems work well for adjustment, but mind the quality of the sytem.
- Put Loctite on screws and make them removable with one tool.
- There should be a panel on the medial side of the boot that provides grip.
- Keep the outer shell/the upper of the boot as smooth as possible with little to no edged and prevent pieces that the bike or the asphalt could get stuck behind.
- Attachment of the boot and the suit are ideal for the distribution of forces and keeping the boots in place.
- A separate inner boot increases the weight of the boot, but allows for the ability to swap the outer shell.
- Make sure the ankle brace system is as close to the ankle as possible.

11. WHAT TO PROTECT AND WHY

A small crash analysis was done of six MotoGP crashes, to get a feel for where the impact absorption is mostly needed and what areas are prone to sliding damage (see Appendix 11). In the airbag systems of the rider there are sensors present that measure data like the G-forces, speeds and lean angle, every 25 milliseconds to determine whether to deploy the airbag or not (MotoGP Podcast, 2020). Crash data shows that riders occasionally endure decelerations of 26.1 G when hitting the asphalt (Autopsport, 2019), see Figure 18. The fact that Marquez walked away from this crash and even participated in the next race a few hours later, is testament to the technological advances made in racing gear.

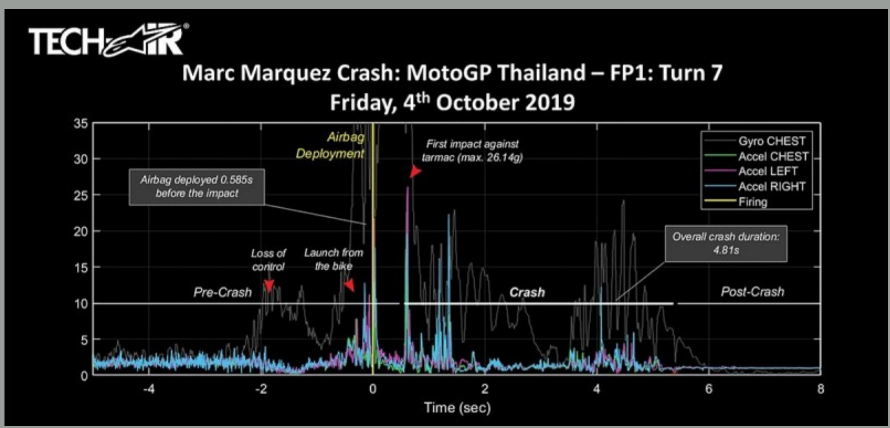


Figure 18. *Crash data Marc Marquez - MotoGP Thailand (Autosport, 2019).*

Figure 19. *A lowside, highside and topside crash (Bedolla et al., 2016).*

Types of Crashes

According to Bedolla et al. (2016) there are four types of crashes: the lowsider, the highsider, the topsider and the collision crash (see Figure 19). A lowsider is caused by a loss of traction in a turn, resulting in the rider falling to the low side of the lean angle and sliding out of the turn. According to the riders (2021) and Schamp (2021) these crashes happen at the highest speeds but are usually the least painful. The gear, however, generally comes severely damaged out of this type of crash (Schamp, 2021). For the gear, however, this is not preferred. A highsider also starts with a loss of traction in the wheels, but in this case the rider corrects it slightly too much which results in a violent flip of the motorcycle and the launch of the rider. These crashes happen mostly at lower speeds, but they can be much more impactful compared to lowsiders as the riders get smashed into the asphalt resulting in high impact forces. The gear usually sustains the least damage in this scenario (Schamp, 2021). The same accounts for topsiders where the motorcycle suddenly decelerates relative to the rider and the rider also gets propelled forward. The most problematic crashes are the collisions with stationary objects or other riders. These are the only types of accidents that are generally fatal (Bedolla et al., 2016).

Accident Parameters

The number of accidents per class differ (Campillo-Recio et al., 2021), see Figure 20. The most accidents, fractures and fractures requiring surgery happen in the Moto3 class. This is expected to be related to the level of expertise, age, desire to make it and how close the Moto3 riders are to one another in terms of racing times.

More accidents occur during racing compared to practicing as the riders typically risk more during races as the stakes are higher and the riders get more fatigued due to the lengths and intensiveness of the race. Other contributing factors to the risk of accidents are the wetness of the track and circuit-specific characteristics, like G-forces, curve characteristics, and the amount of deceleration. In this study the fracture accident ratio was just 1 %, due to the gear and physical health of the riders. But when they do have fractures, about 70 % needs surgery. On average riders return to the track within one to five weeks after a fracture.

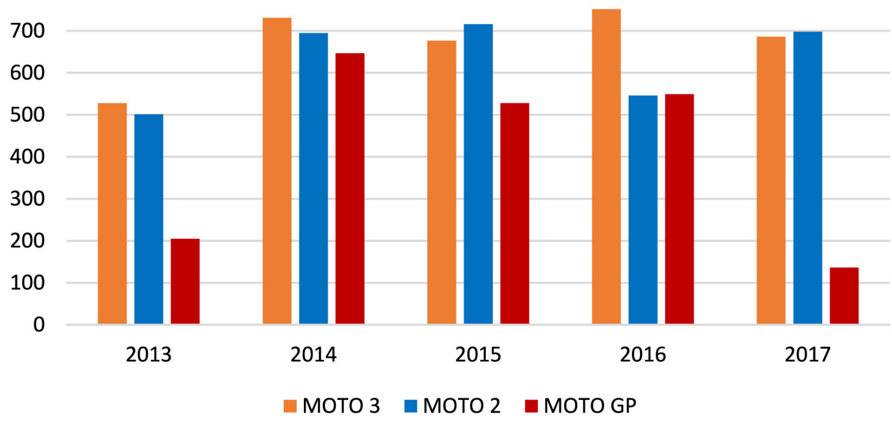


Figure 20. *Number of accidents by class and season (Campillo-Recio et al., 2021).*

Figure 21. *Examples of screenshots taken for the analysis (See Appendix 11).*

Impact on the Boots

As said a small crash analysis was done to investigate the need for the toe and heel box and sliders. On top of that, it was useful to see whether any more protection is needed in certain areas and what would be a good location for the closure system (as keeping this out of the abrasion zone is ideal for the longevity of the boot). For this analysis screenshots were taken of the video “Top 10 Crashes of the Decade” (MotoGP, 2022). The number of crashes was limited to six as this already provided some useful insights and the analysis was mainly done to confirm other findings. Figure 22 shows what a combination off all the crashes looks like for both boots. From this analysis it could be concluded that the toe box and heel box are there for a reason, as almost all impacts where in these locations. The same accounts for the sliders on the lateral side of the boot (toe, ankle, shin) and the heel. The shin protector remained fairly unused, but this is mostly present for collisions. Interesting was that the flex areas remained out of the abrasion zone. This could be an area to consider for the closure system (zipper/buckles), to keep it intact for a longer period of times.

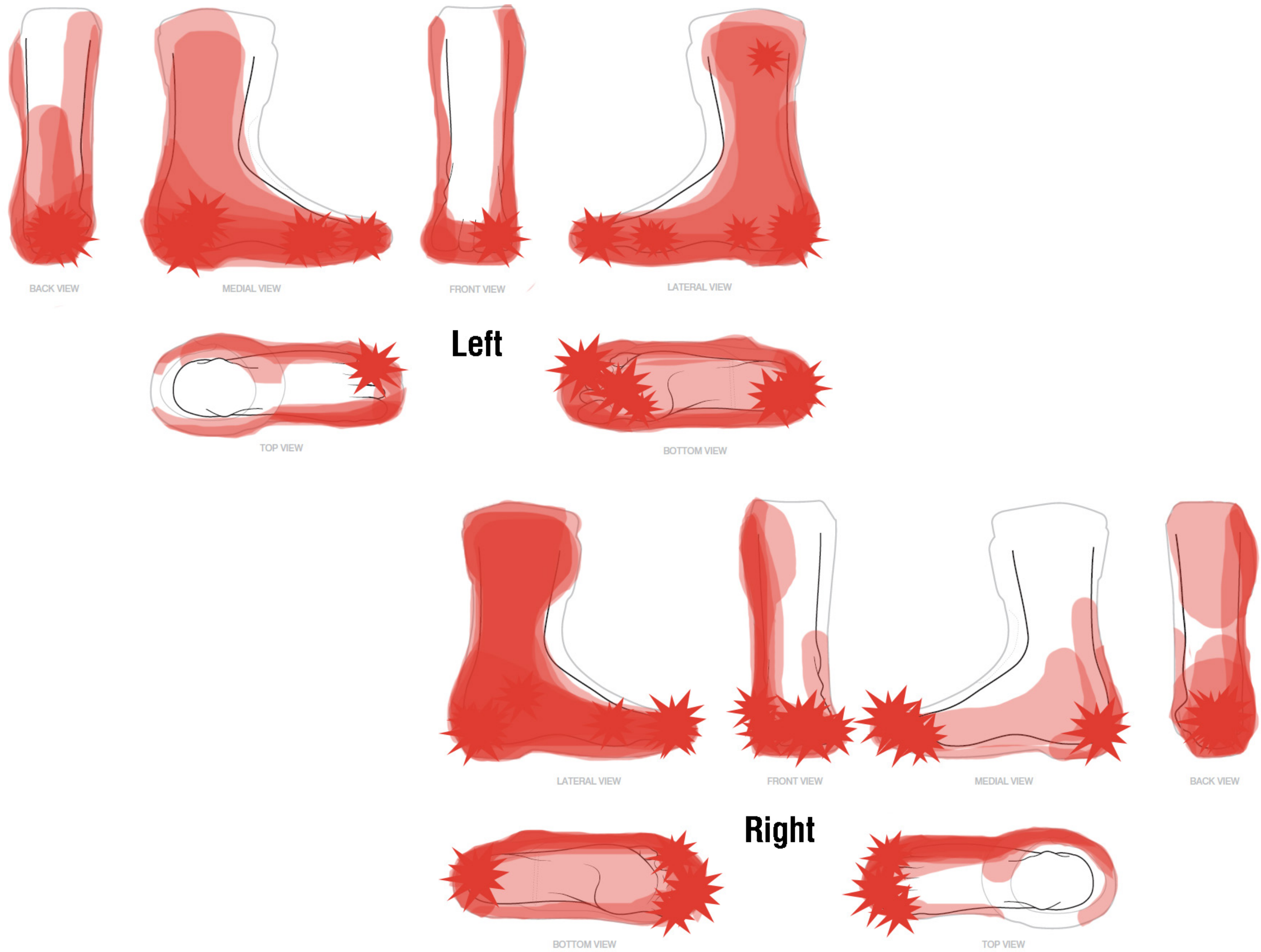


Figure 22. *The boots after 6 MotoGP crashes with the stars indicating impact and the red area the surface that was in contact with the asphalt while sliding (Appendix 11).*

TAKEAWAYS »

- There are four types of crashes: highsiders, lowsiders, topsiders and collisions.
- The toe and heel boxes are essential for impact absorption
- The flex area is not in contact with the asphalt while sliding.
- The medial side is abrased less then the lateral side.
- All around the sides of the foot should be impact protection.
- The riders are so well protected and tough that they could potentially crash twice during one race, which the boots must survive.
- The group of REV'IT! Riders is distributed among the three MotoGP classes, which brings along different problems and more or fewer crashes. An option would be to adapt the boots to the different requirements or to design one boot that considers all the worst conditions from the different classes in terms of safety.

12. BALANCING DESIGN DRIVERS

The design of the boot is a balancing act between different factors. These factors are the design drivers and can be found in Figure 23. They are based on all the previous analyses and summarise all the important connected focus areas. In the design of a MotoGP level motorcycle racing boot the main clusters of design drivers are the safety, comfort and performance of the rider that will be wearing them. Secondary are the aesthetics, longevity, and cost of the boot, which is also important but more for REV'IT! and the consumers than for the REV'IT! Riders. The weight of any of these factors differs per rider, but in general they are considered equally important. If any of the balances are too off, it could have a detrimental effect on the success of the boot.

Performance

The course of a rider's career is highly dependent on their success in racing. At most, the boot should not be detrimental to the performance of the rider and, in an ideal scenario, would even have a positive influence.

Weight

Motorcycle racing is a physically highly demanding sport (MotoGP, 2021). The riders combat this challenge through cardio training and by learning how to save energy. Even after cornering, they use the slight push forward caused by shifting the gears to return to their seat (Alberto Naska EN, 2019). Every extra bit of weight on their body requires extra energy, so it is preferred to keep the weight as low as possible (Appendix 6).

Comfort

What comfort describes in this context is the lack of discomfort (Hertzberg, 1972). This design driver relates to the performance as the discomfort can be distracting during a race, and zero distractions are allowed (Bautista, 2014).

Point Pressure

A factor that has yet to be mentioned is point pressure. Pressure-related pain is generally measured as the pressure pain threshold (PPT) and pressure discomfort threshold (PDT). They are defined as the minimum pressure that induces pain and discomfort, respectively. The smaller the area and the higher the contact speed, the better, as this increases the PPT and PDT (Goonetilleke, 2013). An overview of the exact pressure thresholds of the foot can be found in Appendix 12.

Safety

The safety of the rider is pertinent. Not only is this required from a regulation standpoint, but also because injuries can hinder the riders in their performance. Most professional and amateur riders are not aware of the safety performance level of their boots. However, they should look and feel safe, which is mainly related to the sturdiness, the qualitative look of the boot, the brand image and the experience during a crash.

Other

These design drivers mainly relate to REV'IT! and the consumer market.

Aesthetics

On average, the riders indicated to care more for functionality than aesthetics. However, they get to pick the patterns and colours of their boots. This is a way for them to express themselves and show who they are in this big group of riders. On top of that, it is a major choice factor for the consumer market. It was often mentioned as a strength of a pair of boots if they look good.

Cost

The riders have a somewhat unlimited supply of gear during their racing season, depending on their contract (Schamp, 2021). For them, it is unimportant whether the boots are expensive or not. For REV'IT!, however, sponsoring riders is a great investment. Making the boots exceptionally expensive and having to provide all riders with 16 pairs of boots a season will add up.

Longevity

The longevity of the boots depends on the quality of the materials and the replaceability of parts. The longer people wear their boots, the more comfortable they become as they break in. For Bautista (2021), this was even worth the extra weight of the replaceable parts of the Sidi boot, but for other riders, it was not. The goal is to design boots that do not require a break-in period, like the Supertech R or the Axial D1. Buying high-end racing boots is a big investment for consumers. Making these boots last results in happy customers.

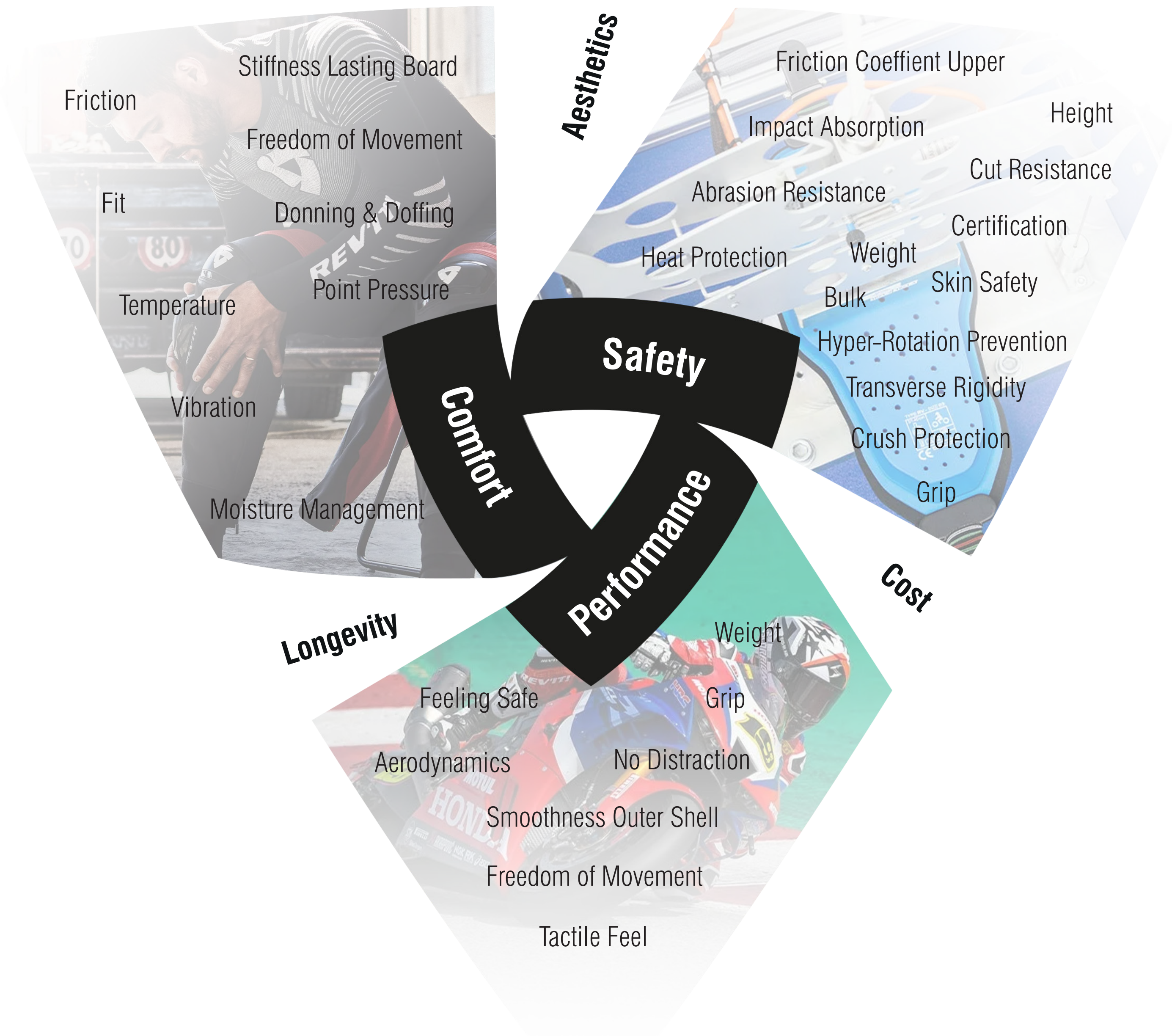


Figure 23. *The design drivers for the design of the REV'IT! MotoGP level road racing boot, derived from the analysis.*

13. BOOT REQUIREMENTS

Combining all the most relevant takeaways formulated in the analysis phase results in a concise list of requirements. These are the requirements the boot must comply with in order to create a boot that protects the rider, stimulates a great performance and is comfortable to wear. As a significant portion of the requirements comes from the NEN-EN 13634:2017 norm, which is a confidential norm, a list of additional requirements can be found in confidential Appendix 12.

General

1. The boots must comply with the technical standard NEN-EN 13634:2017 and score at least a protection level of CE Level 1 for each of the specific properties of the boot according to the standard | NEN, 2017.
2. The boots should meet the requirements of the FIM WORLD CHAMPIONSHIP GRAND PRIX REGULATIONS 2021, which are the regulations for the MotoGP Championship | FIM, 2021.
3. The boot must include the functionality of the following parts: outer sole, upper, grip panel, flex area, lasting board, sliders, toe slider, ankle brace, closure system, top gaiter, vents, inner lining, shift panel, shin protector, ankle protector, heel box and toe box | Chapter 10.
4. The boot's weight should not exceed 1168g for a size 43 | Chapter 9.
5. The boot must allow for aesthetic customisation to the preferences of the riders | Chapter 7.
6. In terms of aesthetics and functionality, the boot must fit the brand values of REV'IT!; performance, design and innovation | Chapter 6.
7. There should be Loctite on every screw of the boot to keep them in place even with the vibration of the motorcycle | Chapter 10.

Performance

8. The riders should not experience the boot interfering with their freedom of movement | Chapter 7.
9. The rider must experience the boot as safe; the safety of their feet should be no concern to them during the race | Chapter 7.
10. The tactile feel with the footpegs, shift and brake levers and bike should be considered sufficient by the riders | Chapters 7 & 10.

Safety

11. The level of protection and functionality should remain sufficient to survive two crashes per race | Chapter 11.
12. The boot should stay in place on the lower leg during any crash and in any position | FIM, 2021.
13. The boot should protect the lower limbs against abrasion, especially in the area surrounding the flex area | Chapter 11.

14. The boot should protect the lower limbs against impact, especially the heels, ankles, sides of the foot and toes | Chapter 11.
15. The boot should protect the lower limbs against punctures | NEN, 2017.
16. The boot should protect the lower limbs against burns | Chapter 10.
17. The boot should protect the lower limbs against cuts | NEN, 2017.
18. The boot's protection should result in a lower chance of fractures, sprains and strains in the lower leg caused by hyper-rotation of the ankle and foot joints compared to a situation with no boot | Chapter 10.
19. The boot should protect the lower limbs against the crushing weight of a MotoGP bike: at least 150 kg | FIM, 2021.
20. The boot should prevent the rider from slipping off the footpegs in any rider position | Chapter 10.
21. On the medial side of the foot, there should be no parts that could get caught on the bike or the track | Chapter 10.
22. It must be possible to cut the boot open in case the rider sustains an injury to the lower leg | Chapter 10.
23. At the maximum lean angle, the width of the boot may not be so large that the boot touches the asphalt | Chapter 10.
24. The boots may not cause a slide to turn into a tumble | Chapter 11.
25. Debris must be kept out of the boots, even during a crash | Chapter 10.
26. The materials used should be skin safe | NEN, 2017.
27. It must be possible to personalise the sizing and protection according to the preferences of the rider | Chapter 7.

Comfort

28. The outsoles must dampen the vibrations of the footpegs | Chapter 10.
29. There should be no points in the inner boot that exceed the pressure discomfort threshold of the foot | Chapter 10.
30. The temperature in the boot should not be indicated as uncomfortable by the rider | Chapter 8.
31. The inner liner should have a texture that is considered comfortable by the rider | Chapter 10.
32. The inner liner should be moisture-wicking | Chapter 10.

Wishes

1. The boot should allow for donning/doffing while injured | Chapter 7.
2. All sliders should be replaceable | Chapter 10.
3. All replaceable parts should be removable using one tool | Chapter 10.
4. The boots should not start to smell after a day of riding | Chapter 8.
5. There should be no squeaking sound when walking | Chapter 9.
6. The boot should take at most 25 seconds to put on | Chapter 9.

14. AREAS OF IMPROVEMENT

REV'IT! aims to pioneer progress in their industry and to problem-solve by engineering solutions to the challenges their users identify. Not only to outperform REV'IT!'s competition but, most of all, to improve the user experience of their riders. That is why identifying areas of improvement for the current boot solutions was the main focus of the performed research. The riders, consumers and experts mentioned many interesting potential directions. However, four were either mentioned frequently or indicated as a significant problem. An initial brainstorming session was performed for each problem to explore potential solutions (Appendix 8).

The Outer Sole

The outer soles of the boots that are currently on the market wear too much. Sometimes one session is enough to destroy the boot, mainly because of the pressure caused by the footpegs and the friction of the asphalt when the riders slide their foot over the asphalt before a corner. Riders differ in their riding style, foot positions and preferences regarding grip and flexibility. For this direction, the goal would be to research different materials, added sole features and potential customisation.

Injury Friendly Design

In a perfect world, the riders would be fully protected against any injury. Unfortunately, this is not the case yet. On top of that, the riders do not wait for their body to heal before they start racing again (Red Bull, 2016). Consequently, the riders have to put on gear that pushes into their swellings, rubs their burns and requires them to flex joints surrounded by damaged ligaments. Current boot designs do not offer any relief for this problem. So, researching the requirements stemming from it and exploring potential design solutions like an adaptable fit and optimising entry and exit for injury could result in a better user experience.

Hyper-Rotation Protection

Feeling safe in their gear and having as few injuries as possible is fundamental for the rider's focus. The riders are at a high risk of injury to their feet during a crash. Trauma due to hyper-rotation of the hindfoot is considered one of the more impactful ones (Alberto Naska EN, 2020). This problem led to the development of ankle support structures in their boots (De Wit, 2021). These systems provide ankle stability and limit injury but are far from perfectly protective.

Heat Protection

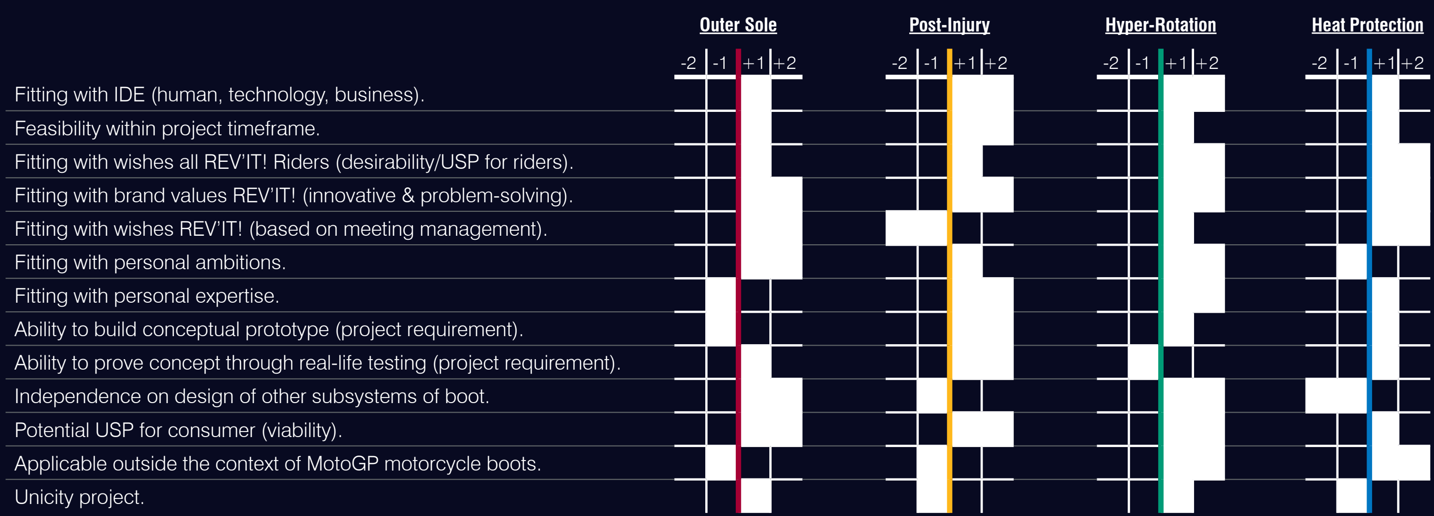
This picture is not the main reason the heat protection in boots is so important, but this is what it can feel like for the riders, even when their bike is not on fire. The exhausts can become up to 700 degrees, and heat can get trapped as the bikes are so streamlined, especially in the Moto3 (MotoGP, 2023). Despite insulation, it can become so hot that the riders burn their feet. Synthetic leather is not a good insulator, the current boots already come equipped with a heat-shielding layer, but this is insufficient.

15. FOCUS AREA

All areas of improvement could be the base for a unique selling point for REV'IT!'s racing boot that would fit the identity of an innovative problem-solver with an ear for user input. However, these are areas REV'IT! has limited to no experience with, unlike, for example, the design of lasting boards, ergonomic lasts, upper materials, inner linings, impact areas and sliders. For REV'IT!, getting up to the same level as their competitors for these mentioned parts of the boot requires fewer resources than developing in any of the areas of improvement.

Taking a deep dive into one of these areas and initiating a concept based on extensive research as a goal for this project would be of added value for REV'IT!. As the timespan of this project is limited, a choice was made for one area as a deep-dive would be of more value and more fitting with the project requirements than exploring all areas on a superficial level. The choice was made using the Harris Profile method (Van Boeijen et al., 2013) based on several initiated "wishes", see Table 2. This method requires these wishes to be ranked in terms of importance, with the most important ones being on top of the list. Every area of improvement was then rated for each of these wishes from -2 to +2. These ratings were based on the results of the Rider Session (Appendix 6), meetings with REV'IT!, brainstorm sessions, elaborations on the process per direction (Appendix 8), and personal reflection. To understand the outcome of the choice method, it is easiest to imagine that the white blocks are building blocks of a tower which is only supported by a hinge at the bottom of the coloured middle lines. Now visualise which "tower" would fall fastest to the positive side, rotating clockwise. This tower or area of improvement was the most fitting choice for the rest of this project, which was the one of the protection against injury caused by hyper-rotation of the hindfoot.

Table 2. *The Harris Profile that visually represents the strengths and weaknesses of the different choices for the direction of this project, with the most important wish on top and the least important one on the bottom.*



16. PROBLEM DEFINITION

"Limiting the damage caused by hyper-rotation of the joints of the lower limb of REV'IT!'s MotoGP riders during a crash with a lightweight, low-profile solution that does not cause any discomfort in terms of pressure or donning and doffing, and does not limit the riders in their freedom of movement and the tactile feel to a noticeable extend."

MotoGP-level riders are at a high risk of damaging their ligaments and bones due to hyper-rotation of the joints of their lower extremities during a crash. This is not only very painful, but ankle trauma is also considered one of the most detrimental lower limb injuries for the performance of the riders and so their careers. Riders have to miss races due to imbalance in their ankle, and continuous ligament problems have long-term effects like arthrosis and ankle instability (Kawalec, 2017).

This problem led to the recent development of ankle support structures in high-end road racing motorcycle boots. These systems provide ankle stability and limit the amount of injury, but ankle injuries are still a prevailing problem on the track. Even though the riders rate the ankle protection of their current boots with an 8.0 on average (Appendix 18), taking a look at the news page of the MotoGP and the Instagram of the Clinica Mobile (racing medical centre) tells a different story of ankle injury and lost races. According to Van den Goorbergh (2023), riders interpret their safety based on experience (also from colleagues), looks and how the boot feels. Feeling safe is important for better performance (Bautista, 2022). However, it can also result in risk compensation, the phenomenon of people taking increased risks when they feel protected by equipment (Gamble & Walker, 2016). This means that incorporating an ankle brace that does not protect well but provides an increased sense of safety could put the rider in extra harm's way. Making a brace that also decreases the risk of injury of riders is the right thing to do.

Besides this, riders rate the importance of an ankle brace with a 7.8 on average (Appendix 18), meaning it is considered a basic need at this level of riding. REV'IT! will have to come up with their own solution for their boot if they want to be considered a good alternative in this market. Getting from this point to a MotoGP-ready system requires in-depth research, ideation, testing and iteration. As the brand values of REV'IT! are design, performance and innovation, the final solution should match this. This means it should be designed with the user as a centre point, that there should be thought and proof behind claims, and that the final solution should not be traditional. This project's scope is limited to developing a concept design of the selected boot subsystem. In the design of this system, it is essential to consider the main design drivers: performance, protection, and comfort.

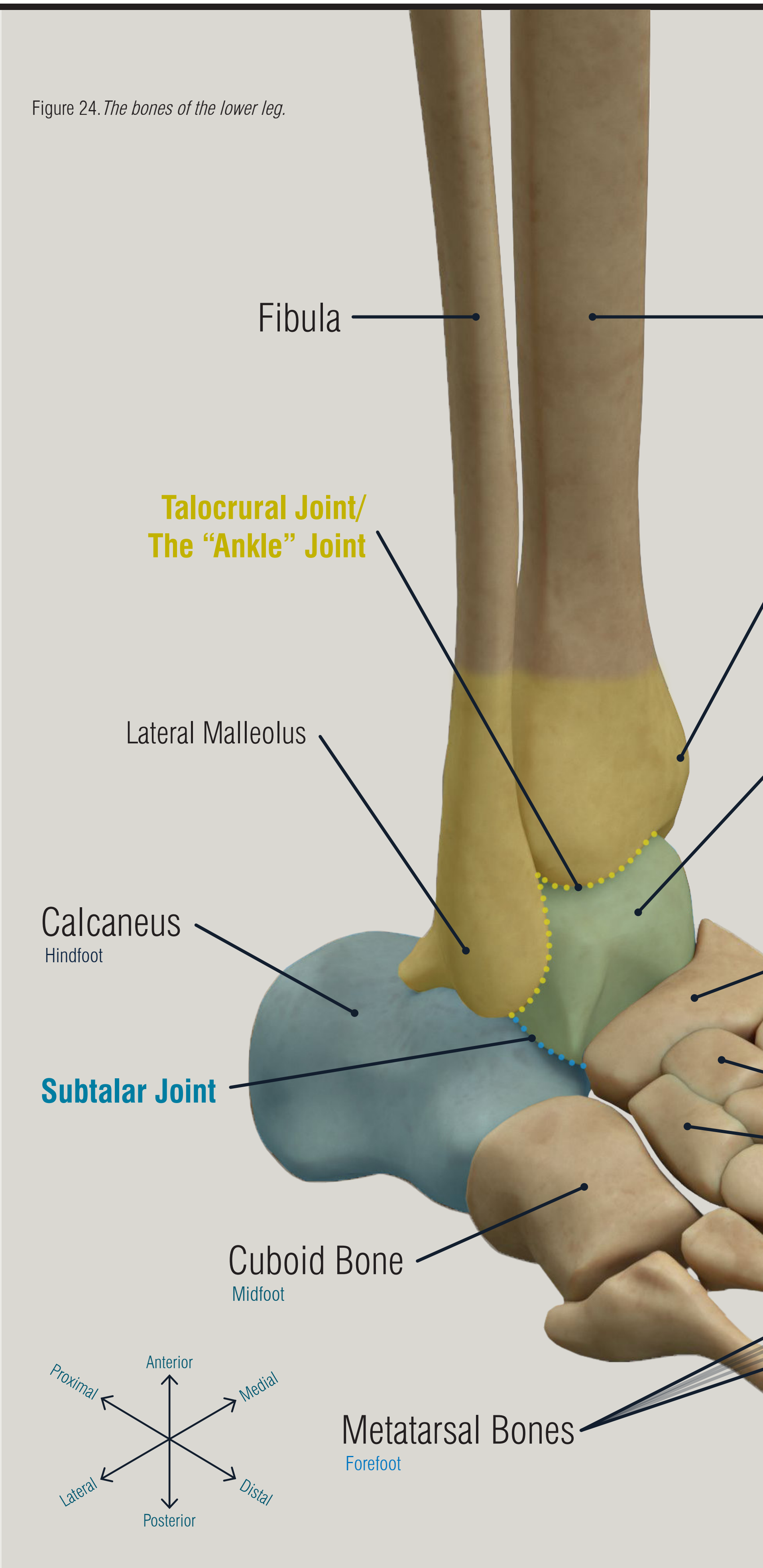
THE ANKLE BRACE

With the new problem statement comes a new narrowed focus on the boots' sub-part called the ankle brace. A key step in the development of this protective piece is comprehending what it is that even needs protecting, as the ankle is a complex system. This step is followed by a kinetic analysis that dives into the forces and deformations at play to calculate the required material properties. The findings of these additional analyses were added to the list of design drivers and requirements relevant for the ankle brace. This was the kick-off point for the design phase that resulted in the final concept. This section describes the final concept, the process at the core of this design and whether it works or not.

17. THE ANKLE

From experience, what part we refer to exactly when we talk about the ankle in daily conversation, can vary from person to person. Some refer to a joint, some to the lateral malleolus and some to the ligaments that surround the joints. This phenomenon is very understandable as "the ankle" is a rather complex and interesting system. So much so that the literature regarding the system and its movements and limits, is scarce, at times contradictory, and varying in results. A plethora of papers were reviewed for this chapter to find the best answers and most relevant data. When designing an ankle brace, knowing the anatomy, anthropometry, biomechanics and kinematics of the system is fundamental for multiple reasons. Knowing the measurements and understanding how the shape changes in different positions helps in designing a proper base shape that is rigid and flexible in the right places. The brace needs a sturdy base in order to be effective, yet natural movements should be allowed, and no pressure points should arise. This natural movement which is affected by the flexibility of the bracing system, is something the riders highly value in specific directions, see Appendix 6. Appendix 7 concluded that the riders use the entire range of motion of the lower limb when racing. Therefore, data is required to express this range of motion in numbers and design for maximum flexibility within this range. Naturally, the primary function of an ankle brace is to protect against hyper-rotation, usually at the expense of the range of motion. Pinpointing the detrimental rotation directions and knowing the rotational angles at which injury occurs is of great importance. That is why this chapter provides an overview of these elements.

Figure 24. *The bones of the lower leg.*



Bones

The foot consists of 26 bones (Kenhub, 2023a). The bones and their attached structures, like muscles, ligaments and tendons, define the shape of the lower limb. These bones are the framework that provides structure and support and allows for mobility. The location where two or more bones meet is called a joint. These joints are kept in place by their supporting structures and can be moved by either force applied by the muscles that, via tendons, are connected to the bones or by an external force. The bones allow these forces to transfer (Lee, 2001). The lower extremity divides into different clusters of bones; the lower leg (tibia and fibula), ankle (tibia, fibula and talus) and foot (calcaneus, cuboid, tarsels and metatarsals). The foot consists of the hind-, mid-, and forefoot (Salzar, Lievers, Bailey & Crandall, 2015).

REV'IT! Rider Injuries

Two of the three REV'IT! Riders that participated in the questionnaire regarding lower leg injuries broke a toe once, and one of them also twice a bone in the midfoot (Appendix 18).

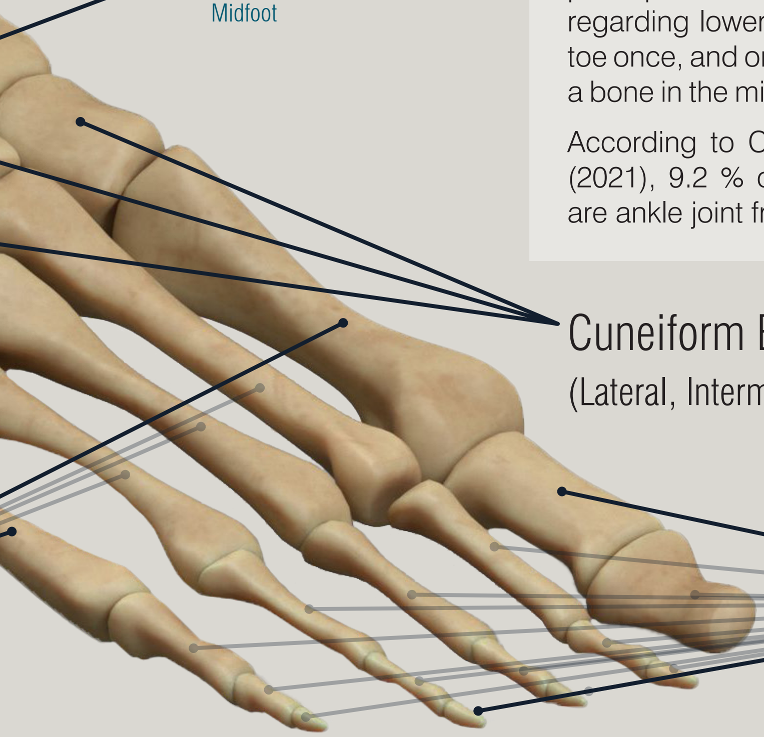
According to Campillo-Recia et al. (2021), 9.2 % of MotoGP fractures are ankle joint fractures.

Joints

The talocrural and subtalar joints are the ones that define the main articulations of the lower limb.The joint that is referred to as the "ankle" is the talocrural joint formed by the talus, tibia and fibula (Kawalec, 2017). The talus perfectly fits into the socket formed by the distal ends of the tibia and fibula, the medial and lateral malleolus, respectively. This structure resembles a mortise and tenon connection (Moore, Dalley & Agur, 2014). The anterior or front side of the talus is wider, which means that when the foot is in a flexed position, the ankle is more stable than when extended (Kawalec, 2017). The contact area between the talus and the calcaneus forms the subtalar/talocalcaneal joint (Catalyst University, 2020).

Synovial Joints

Both are synovial joints meaning the bones are connected via a fibrous joint capsule surrounding the articulating surfaces, allowing for greater mobility due to reduced friction within an allowed range defined by the joint capsule, ligaments and muscles. The bones do not touch directly, but the cavity between the bones is filled with synovial fluid. This fluid is produced and sealed off by the synovial membrane, part of the capsule that structurally connects the bones. This thin capsule alone is insufficient in stabilising the joint, hence the need for supporting ligaments (Crumbie, 2022; Dutton, 2021; Sendić, 2022).



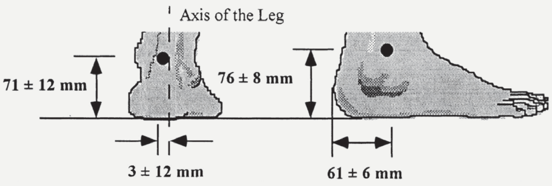


Figure 25. *Centers of rotation for xversion and flexion (Hall et al., 2018).*

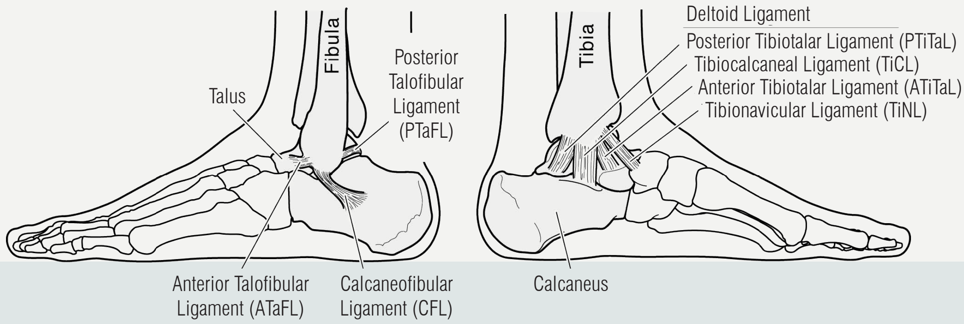


Figure 26. *The ligaments on the medial and lateral side of the foot (Funk et al., 2002).*

Rotational Axes

There are multiple theories about the mechanics of the joints. Some evidence suggests them to be hinge joints with oblique rotational axes (Procter & Paul, 1982; Sarrifian, 1993; Hicks, 1953), and some say they are multi-axial with varying axes of rotation depending on the axial load or compression of the joints and the position of the foot (Barnett & Napier, 1952; Scott & Winter, 1991). Officially neither of these joints can be said to rotate about a single fixed axis as they both contribute to a degree to all mentioned movements (Zhang, 2021). However, the talocrural joint contributes most to plantar and dorsiflexion and the subtalar joint most to in- and eversion. For xduction, both joints contribute an equal amount (Siegler, Chen & Schneck, 1988; Valderrabano et al., 2006). Understanding how these bones move internally clarifies why the foot's shape transforms as it does. However, for finding the right range of motion for the brace, solely looking at these joints' maximum range of motion paints only some of the picture and is less valuable than understanding how the foot articulates as a whole. Therefore, in practice, these joints are both considered hinge-type joints that move along a centre of rotation (Parenteau et al., 1995; Petit et al.; Hall et al., 2018), see Figure 25. All six degrees of freedom rotating around these points are shown in Figure 27.

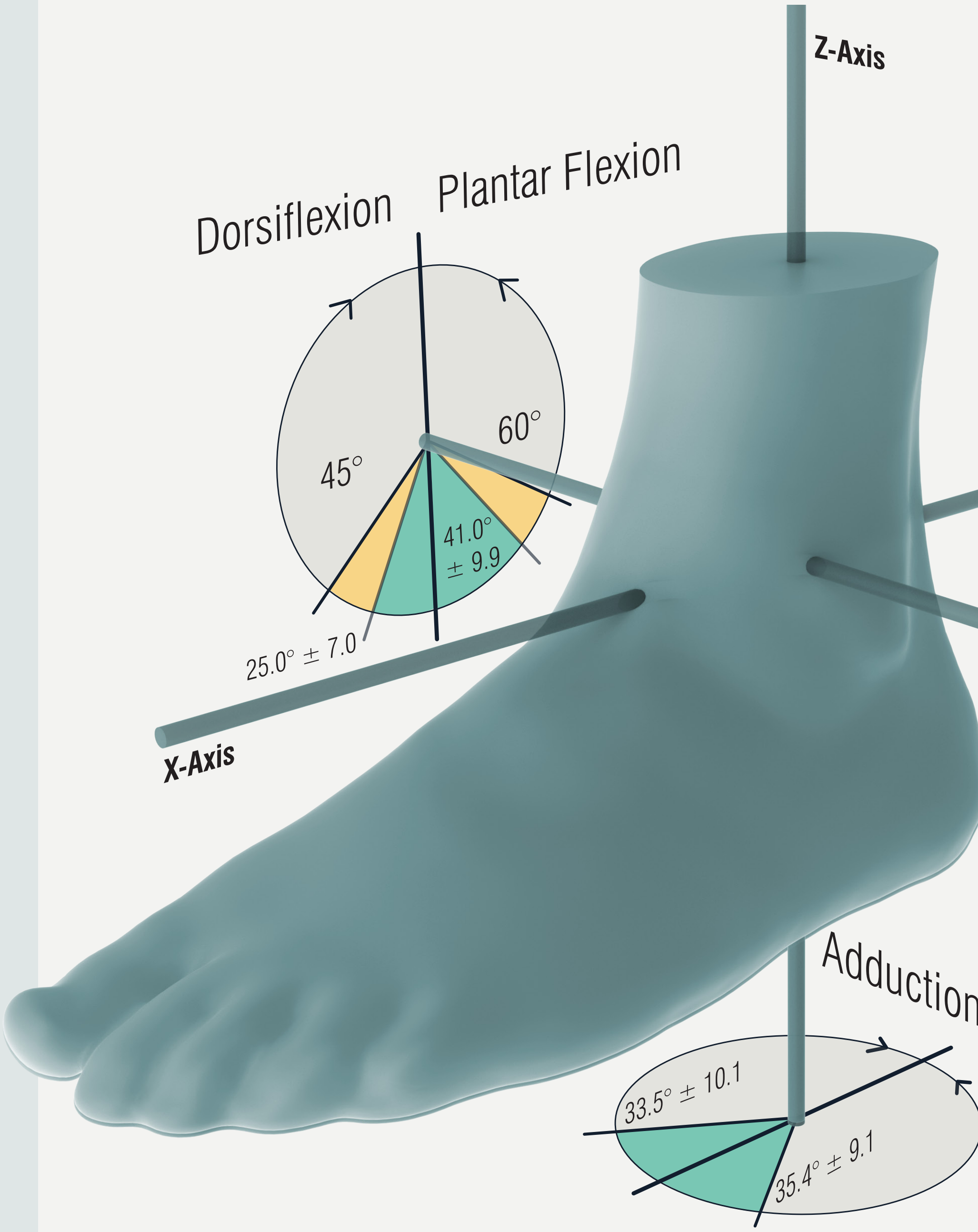


Figure 27. *The six degrees of freedom of the foot complex with the active range of motion of men be known injury angles (Alpinestars, n.d.; Funk et al., 2002; Crandall et al.,*

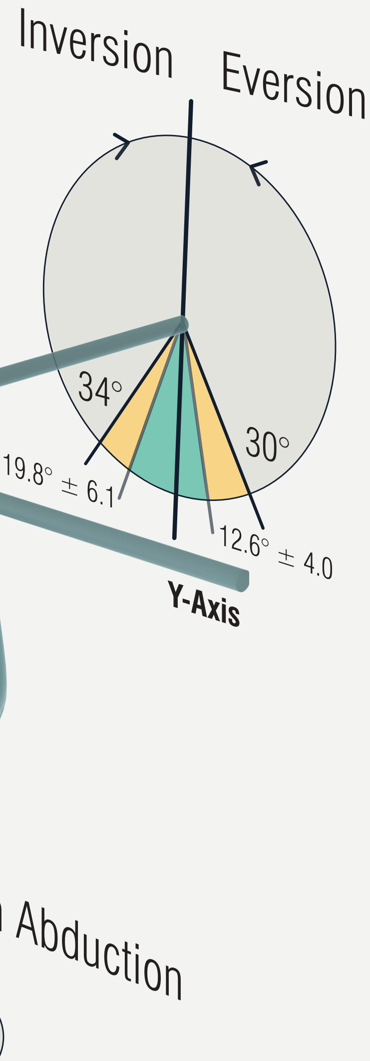
TU Delft

Table 3. *Yield forces and Young's Moduli of the ligaments (Siegler, Block & Schneck, 2015).*

Ligament	Yield Force (N)	Young's Modulus (MPa)
PTaFL	400.0	216.5
CFL	289.0	512.0
ATaFL	222.0	255.5
PTiTaL	405.0	99.54
TiCL	44.5	-
TiNL	107.0	320.7

Ligaments

Ligaments are the structures that connect bone to bone to stabilise joints. They are more flexible yet less strong than tendons (Bartel, Davy & Keaveny, 2006), making them more prone to damage. The interosseous, lateral, medial and posterior talocalcaneal ligaments support the subtalar joint. The ligamentous structures that support the talocrural joint are the lateral collateral ligament (LCL) and the stronger medial collateral ligament (MCL) or deltoid ligament. The medial ligaments stabilise the foot during eversion, while the lateral ligaments stabilise during inversion, still allowing for plantar and dorsiflexion. The lateral collateral ligament consists of the PTaF, CF and ATaF ligaments and the deltoid ligament of the PTiTa, TiC, ATiTa, and TiN ligaments with a few consisting of multiple layers (Drake et al., 2015; Moore et al., 2014; Sendić, 2022), see Figure 26. Table 3 shows that the PTaFL and PTiTaL are the strongest and the CFL and TiNL the stiffest ligaments. Unfortunately, no data is available for the ATiTaL. The weaker the ligament, the more likely it is to get damaged. The ligaments are most prone to damage during hyper-rotation without axial load. With axial load, the bones of the joints are likely to break as well (Funk et al., 2002). Injury, like overstretching and tearing, to the ligaments is called a sprain. A low ankle sprain is the most common ankle sprain (>90 % (Orthobullets, 2023)), which means the ligaments below the ankle joint are damaged. The most common ligament to sprain is the ATaFL, followed by the CFL. Their injury mechanisms are inversion combined with plantar flexion and dorsiflexion, respectively (Orthobullets, 2023). Damage in the structure between the tibia and fibula, the syndesmosis, is called a high ankle sprain and is far less common but more severe and most likely to occur in abduction (Nie et al., 2017; Wei, 2012). There are three grades of sprain depending on the severity of the injury: overstretching, partial tear, and complete tear. All injuries require rest, rehab (1 to 6 weeks), and complete tears surgery (Orthobullets, 2023).



tween 20 and 39 years old and the 1996).

Angles

All joint movements have a limit. The ligaments and bony structures create these limits. The limit that is reachable using muscles is defined as the active range of motion (aROM). The active range of motion of the target group, males between 20 and 39 years old, can be seen in Figure 27 and is indicated in green. Age, ethnicity and sex influence this ROM (Brockett & Chapman, 2016), and even the standard deviation within the target group shows that the range varies considerably. So, personalisation for the ankle brace is advised. Going beyond the active ROM is uncomfortable but does not result in injury until the next limit is reached, which is the injury angle. According to LMU (n.d.), most injuries result from in- and eversion and no relevant link was found between plantar and dorsiflexion injury mechanics. No data was available for ab- and adduction. The force resulting in the deformation of the ligaments and bones is what causes injury. The amount of axial preload on the joints significantly changes the maximum angle and force that can be reached. This makes sense as the bones touch each other when compressed, creating a stiffer and stronger construction (Stormont et al., 1985). The joints barely have any axial load when the rider flies through the air. Consequently, Figure 27 shows the angles for a scenario without axial load (Funk et al., 2002). Research regarding injury angles is scarce, often performed on older deceased test subjects and limited in sample size, but after reviewing all available research, these were the results that provided the best approximation for this scenario.

18. FROM CRASH KINETICS TO PROPERTIES

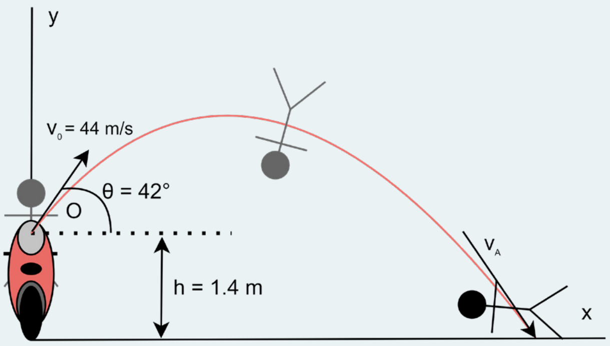


Figure 28. *The trajectory of a rider during a high-side crash with a horizontal landing on one foot.*

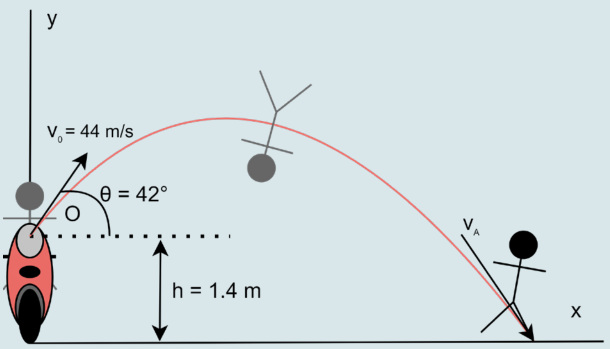


Figure 29. *The trajectory of a rider during a high-side crash with a vertical landing on one foot.*

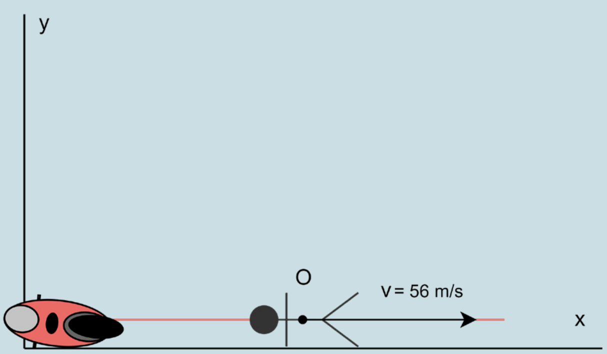


Figure 30. *The trajectory of a rider during a low-side crash where the rider slides over the asphalt and has the foot grip the asphalt.*

In our scenario we are dealing with a problem that involves force, velocity and displacement. We know the displacement that the ankle can undergo in degrees and we know the initial velocity that most high-side crashes and low-side crashes maximally occur at, namely 160 km/h (MotoGP, 2022f) and 200 km/h (Jessner & Mackinger, 2020). Other than that, very limited data is available on this topic, which is why this abstract approximation of the sitatuation was created. What we want to calculate is the amount of force that this puts on the ankle and consequently on the ankle brace. Calculating the forces requires the use of the equation of work and energy. Hibbeler (2013): "A force does work when it undergoes a displacement along its line of action." Examples of forces that do work are spring forces, weight, forces and couple moments that cause displacement. We are dealing with non-conservative forces as the work done depends upon the length of the path; the greater the joint angles the more work is done. The principle of Work and Energy is $T_1 + \sum U_{1-2} = T_2$. In other words, the initial kinetic energy (T_1) combined with the work done by all acting forces ($\sum U_{1-2}$) is equal to the final kinetic energy (T_2). Kinetic energy is generated by translational motion of the mass centre v_g and the rotational motion of the body, ω.

Crash Scenarios

To start three extreme crash scenarios were selected that would result in the most force applied to foot, going from bad to worst. Namely, a scenario where the rider is ejected from their motorcycle during a high-sider at 160 km/h at 42 degrees, where the mass centre of the rider is at 1.4 meters (MotoGP, 2022f; Lloyd, 2016) and the rider happens to land horizontally, on the medial side of his foot, see Figure 28. Another scenario occurs the same way but now the rider lands vertically on his feet (Figure 29). And in the final scenario the rider has a low-side crash that occurs at 200 km/h (Jessner & Mackinger, 2020). In this scenario the rider slides and immediately his foot grips the asphalt and is twisted at this speed (Figure 30).

Velocities

To understand the speed at which the ankle will be twisted in the high-side scenarios, the vertical and horizontal velocities at ground contact had to be calculated by approaching it as a free-flight projectile motion. This means that we consider the horizontal velocity to remain constant and that we take the influence of the constant downward acceleration caused by gravity into account for the vertical velocity. Getting launched at 160 km/h (44.4 m/s) results in a horizontal velocity of 119 km/h (33.0 m/s) and a vertical velocity of 85.9 km/h (23.9 m/s) (Appendix

15). Naturally, in real-life air drag influences these speeds, so this is just a theoretical approach to get an understanding. In the scenario of a low-sider, we consider no friction has been able to work yet, so the horizontal velocity is 200 km/h (55.6 m/s).

The Problem

The mass of the foot is 0.0145 times the body mass. For example, Petrucci, who weighs 77 kg, would have a foot that weighs about 1.1 kg and the rest of his body 75.9 kg. The kinetic energy of the body is dependent on the velocity and mass. More energy is required to decelerate the body than is required to decelerate the foot. This means the foot will start to twist before the rest of the body hits the ground. The entire body is moving at the same velocity, but when the foot touches the ground, it is quickly decelerated to 0 km/h. As the rest of the body is still moving at that velocity, the body will start pulling on the ankle joint and the reactive force of the asphalt will make the foot start to twist. To make it visually easier to understand we switch this around, however, and turn it into a situation where the asphalt will make the ankle go from -160 km/h to 0. Here we assume the leg to be fixated as otherwise too many variables would be at play to make a good force estimation. Normally friction would play a big role in this situation and the connection would be sliding plus the angle of the force would change along the course of the movement and the force changes as well. But this factors would make the calculations too complex.

The Displacement

The subtalar joint is represented as a hinge point that is fixated in the y- and x-direction but allows for rotational movement due to moment forces. According to Kjaersgaard-Andersen et al. (1988) the equation for the stiffness of the subtalar joint stiffness is $y = 0.0583 * x^2$. Based on those measurements combined with the average foot measurements stated in the previous chapter, the sizes indicated in the figures were given a value. As the subtalar joint was assumed to be a hinge joint, the side of the foot makes a circular motion with the distance between the joint and the side of the foot as the r of this circle. The straps were assumed to attach at the height of the head of the malleoli on both the medial and lateral side. These points remain steady during movement due to the tibia and fibula staying in place. With these parameters the horizontal and vertical displacement of the attachment points could be calculated and therefore the work performed by the brace. The displacement in the vertical direction was going from the active range of motion and the neutral position is on average 2.96 cm and from the active range of motion to the injury angle 2.2 cm for inversion.

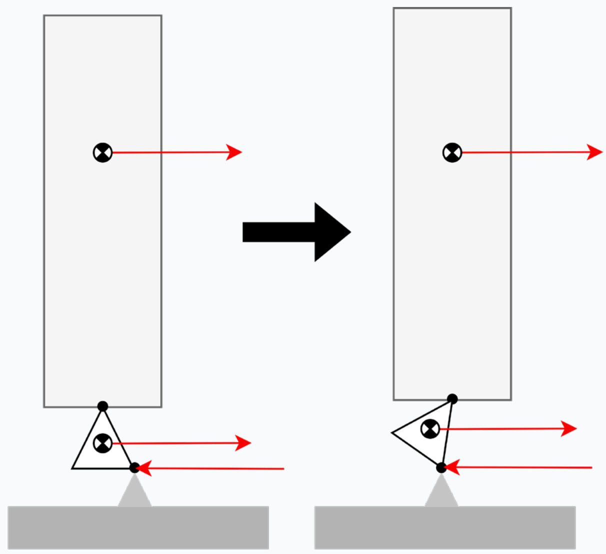


Figure 31. *The influence of a gripping point on the movement of the body and foot.*

The Forces

To calculate the forces at play Free-Body Diagrams were made showing the forces and the fixations, see Figure 32 and Figure 33. Due to the large mass of the body compared to the foot, the lower leg is considered secured in the x, y and rotational direction. For the equation of Work and Energy that applies in these scenarios, the work of the weight of the foot and the work of the brace and strings apply a constant force that works. The friction of the joint and the weight of the foot are left out of the equation. Meaning the kinetic energy of the foot minus the work of the constant forces is equal to the final kinetic energy, which is zero. The work of the strings is applied in under an angle, making it less efficient than the work of the brace, which is in line with the force.

The formula becomes:

$$T_1 + \sum U_{1-2} = T_2$$

$$(½ * m_{foot} * v_1^2) - (F_s * \cos(\theta_1) * (s_2 - s_1)) - (F_s * \cos(\theta_1) * (s_2 - s_1)) = ½ * m_{foot} * v_2^2$$

The Results

As v_2 is 0, T_2 is 0. Now the equation can be solved for F_s with a v_1 that is equal to vA_y for scenario 1 (23.9 m/s), vA_x for scenario 2 (33.0 m/s), and vA for scenario 3 (55.6 m/s). In these scenarios F_s is 10 kN, 20 kN and 36 kN for the case of inversion. This force will be distributed over the strings and the brace. The full version of the calculations can be found in Appendix 15.

Now What?

These forces are really high. Just because a material like Dyneema would be able to sustain the force of 10 kN does not mean the system will be able to generate such a high resultant force. This approach does not really result in a practical insight that can be used as a base for the design. It would be advised for REV'IT! to start using the sensors that they use in their airbag to measure the accelerations and forces that are applied to the boot during a crash to get a better understanding of the situation. For now, the conclusion was to get a string material as stiff as possible, an ankle brace that is as thick and wide made of stiff material with a big surface area. The approach from this point was to make a brace that is better than what is currently available and see how far it can be taken without compromising the design drivers. A test setup was designed to do real-life evaluations.

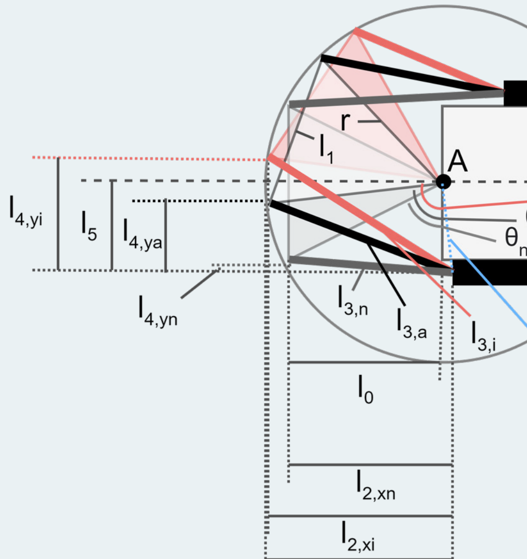


Figure 32. *The influence of inversion from neutral to the active injury angle on the length of the straps.*

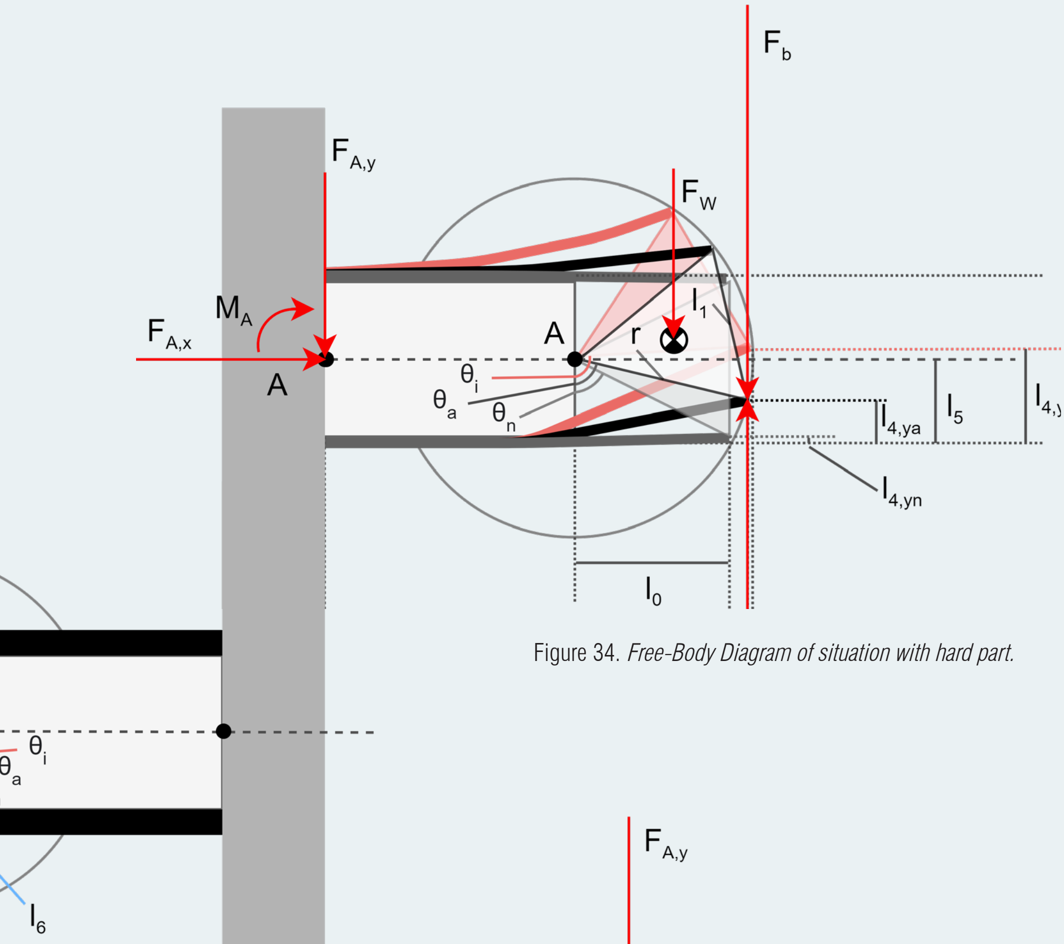


Figure 34. *Free-Body Diagram of situation with hard part.*

range of motion to the

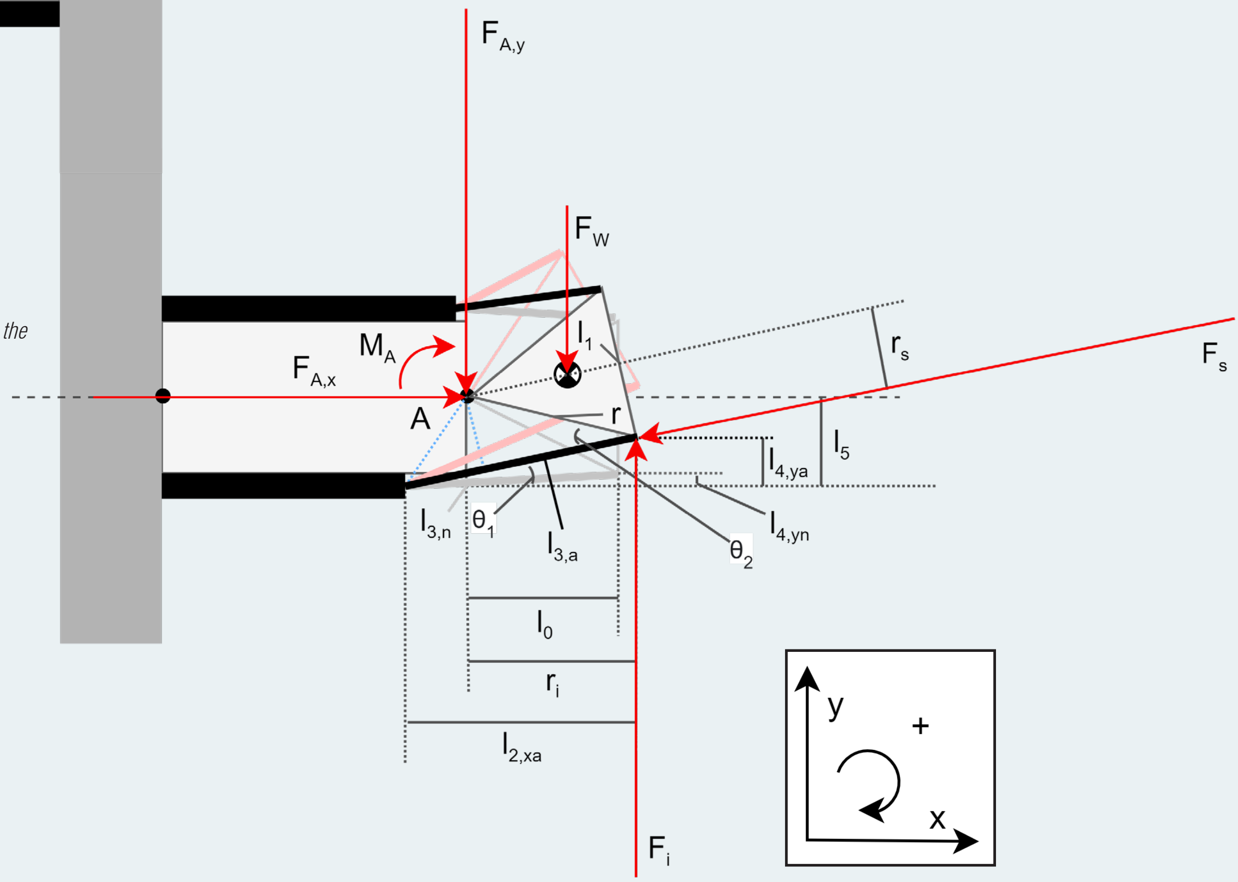


Figure 33. *Free-Body Diagram of situation with soleley straps.*

19. DESIGN DRIVERS

With the help of an online questionnaire, six professional riders were asked to give their opinions about ankle braces in boots and share their experiences. One of the questions was asked to get a better understanding of their ratings of the differerent design drivers that define the build-up of the ankle brace. They were asked to indicate where they would put the emphasis on a Likert scale from one to seven with one being the provided ankle protection and seven another selected design driver. The results were clear in that they generally value the level of protection as much as the other design drivers. The most influential ankle brace design drivers can be found in Figure 35.

Interestingly, the riders indicated that when choosing between an ankle protection system they do not feel at all yet offers proven protection and a system that feels sturdy and safe but is not proven to offer any protection, they choose the option somewhat in-between. The weight, freedom of movement while riding and tactile feel were considered slightly more important than other design drivers. In contrast, freedom of movement while walking and bulk were rated slightly less important (Figure 36). All results of this questionnaire can be found in Appendix 18.

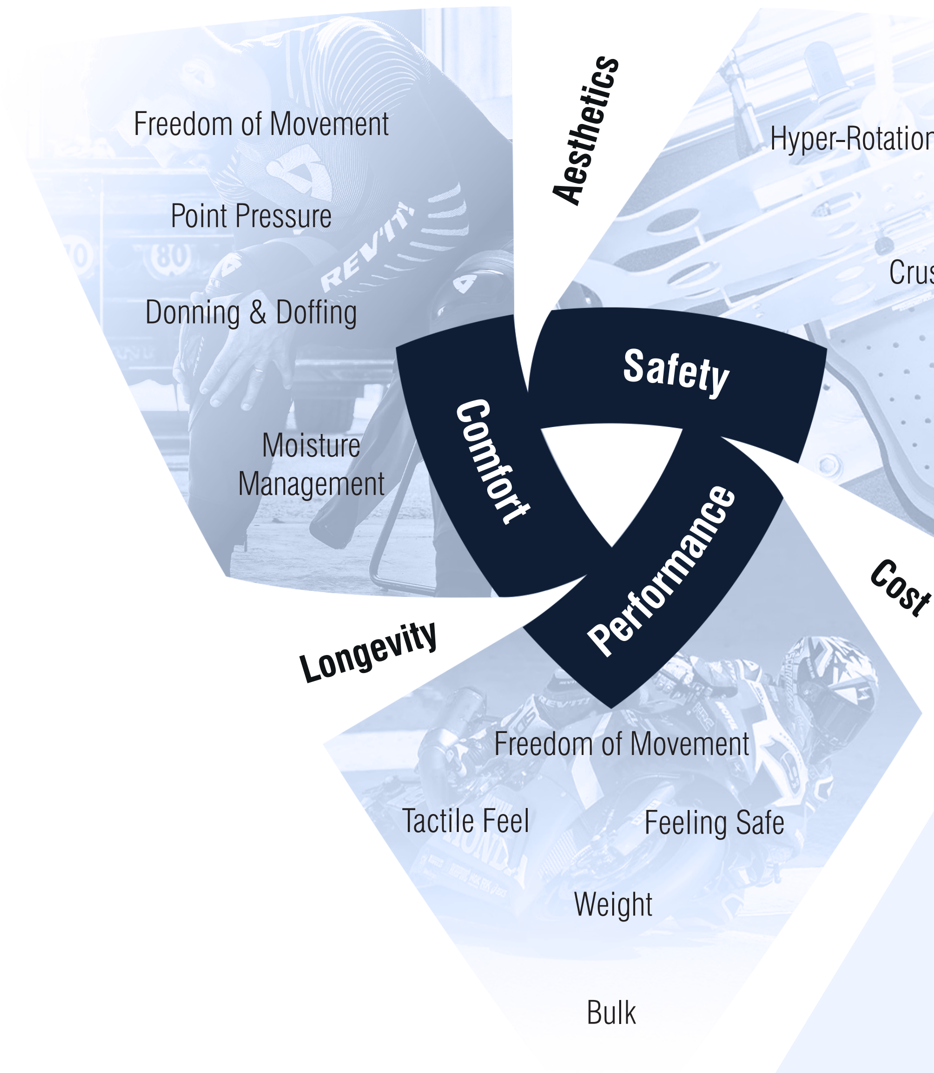


Figure 35. *The design drivers for the design of the ankle brace of the REV'IT! MotoGP level road racing boot.*

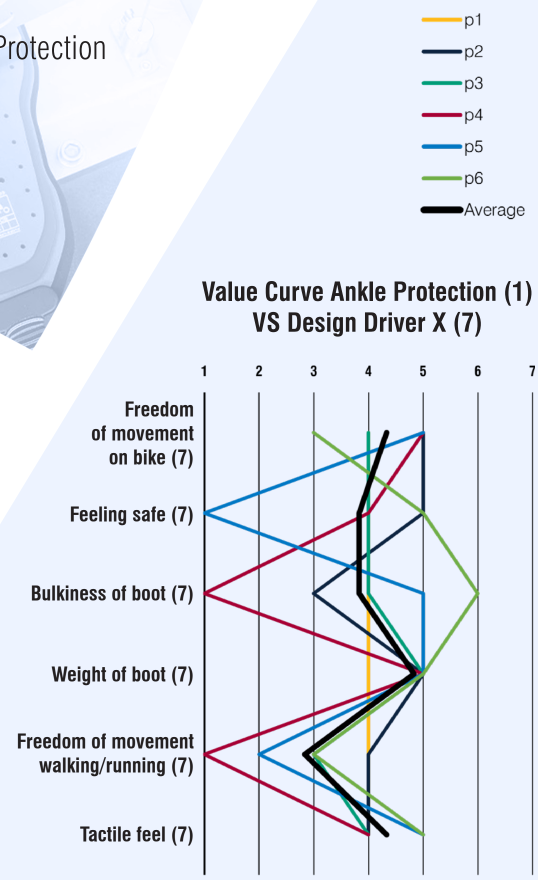


Figure 36. *Results Rider Questionnaire (Appendix 18).*

20. THE REQUIREMENTS

The formerly stated list of requirements applied to the entire boot, but defining the ones that apply to the ankle brace is an important first step in the concept generation process. Combining the prior list with research regarding the ankle and the findings of the questionnaire about the ankle brace filled in by professional riders resulted in the following requirements:

Safety

1. The ankle brace should provide more protection against injury caused by hyper-rotation of the joints of the hindfoot in both high-side and low-side crashes than the currently available options, meaning more force should be required to bend it towards an injury angle | Chapter 16 & 17.
2. The inner boot and brace should stay on the lower leg during a crash, and while riding; thus a securing system must be in place | Chapter 10.
3. It must be possible to cut the entire boot open and easily remove the brace if the rider sustains an injury to the lower leg | Chapter 11.
4. The ankle brace must allow for personalisation based on the anatomy and preferences of the rider | Chapter 17.

Performance

5. Riders should not experience the brace interfering with their freedom of movement, meaning it should allow for the aROM | Chapter 7 & 17.
6. The rider must rate the perceived provided safety by the ankle brace with at least an 8 on a scale of 10 | Appendix 18.
7. The rider should not consider the tactile feel of the boot to be compromised by the ankle brace | Chapter 10.
8. The protection and functionality should remain sufficient enough after a first crash to continue riding and survive a second crash | Chapter 11.

Comfort

9. There should be no points in the inner boot that exceed the pressure discomfort threshold of the foot caused by the brace | Chapter 10.
10. The ankle brace should not have a noticeable effect on the temperature and moisture management of the overall boot and make the boot thermally uncomfortable | Chapter 8.

Wishes

1. The ankle brace should allow painless donning and doffing when the rider is injured | Chapter 7.
2. The brace should not squeak when walking | Chapter 9.
3. The inner boot should weigh no more than 364 g | Chapter 9.
4. The inner boot with brace should take up max 15 seconds of the total donning/doffing time | Chapter 9.

21. THE REV'IT! ANKLE BRACE

FINAL PROTOTYPE


Upper
3D Printed
Hard Part
Lower
3D Printed
Hard Part
REV'IT!

FINAL MODEL

Racing Suit
Dyneema® Strings
Lacing System
Inner Boot
Connective Strap

3D Printed Hard-Part

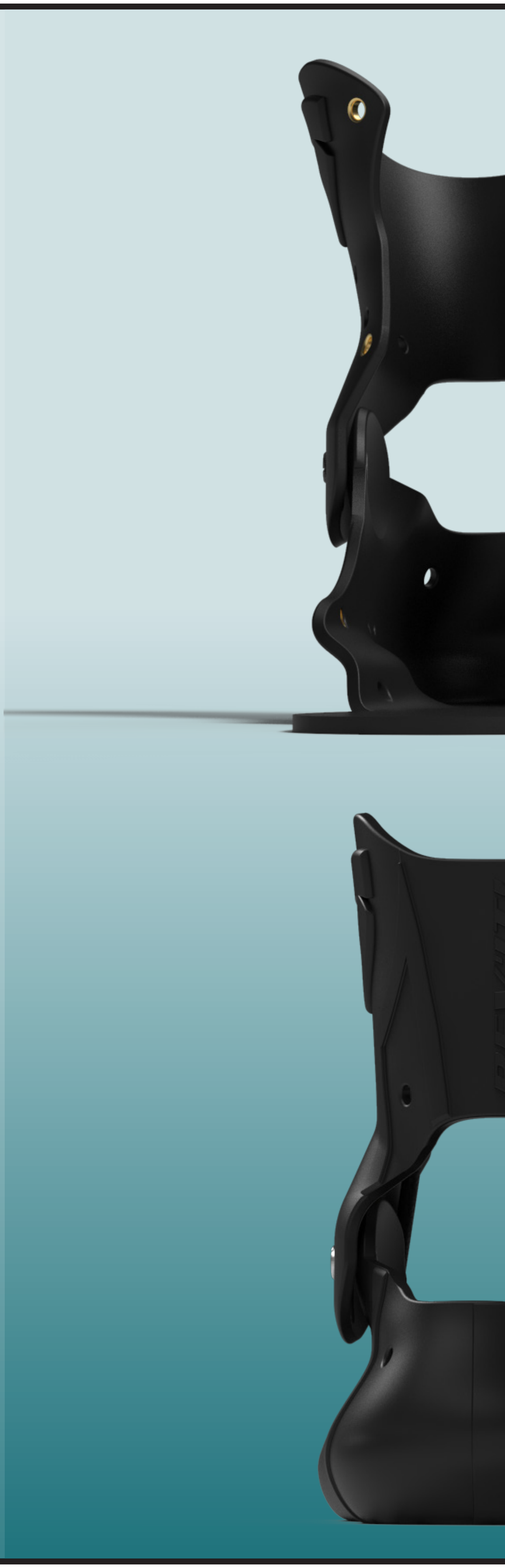
The hard part is the skeleton of the brace. It is a 4 mm thick piece with a pivot point that encloses the inner boot and allows for the active range of motion, both xflexion and xversion-wise. It is what the strings are attached to and what keeps the system upright.

Shape

The design of the hard part is created based on an offset of the 3D scan of the user. Compared to a standardised shape, the advantage is that it has protection in the right places, distributes the forces more evenly over the leg, and is much more comfortable to wear as it uses the riders' exact measurements. Using this technique means that the variety of iterations did not result in a design with fixed dimensions but instead, dimensions that should be tailored to the specific user. However, some basic principles were applied. For example, the pressure was applied only to pressure-tolerant areas (Creaeliu, 2022). The areas that were avoided are the medial and lateral malleoli, Achilles tendon, navicular tuberosity and heads of the I and V metatarsals. The areas used to fixate the hard part and thus distribute forces over are the calcaneus, longitudinal arch, transversal arch and the area above the malleoli. This was evaluated and improved based on user tests described in the coming evaluation chapter. The hard parts form a tube-like structure that resists bending. The wider this "tube", the more resistance it provides, and the better it protects. The surface of this part should be as big as possible, as a greater surface area means better force transmission and force distribution, which is a more comfortable experience for the rider. Naturally, compromises have to be made. Too big of a surface would interfere with the freedom of movement and tactile feel. Therefore, the right parts were cut out to allow for: the bending of the forefoot by removing material until the start of the forefoot, dorsiflexion by removing material in the back, an aROM by replacing part of the surface with a pivot point and entry and exit by removing material at the front side. The exact design and its parameters can be found in the CAD model in Appendix 21.

Manufacturing

Choosing the manufacturing method significantly impacts the product characteristics, price and design. Since the use case is the MotoGP, only a low quantity of braces should be produced, making it interesting with the mentioned advantages to 3D print the hard parts per rider. This low quantity leads to the preference for additive manufacturing (AM) rather than the alternative subtractive and formative techniques. AM not only



provides the lowest cost but also allows for more complexity in the design (3D Hubs, n.d.a.). By adding material layer by layer, more complex shapes can be created, such as closed hollow structures or parts with overhanging back sections.

Various techniques were considered. However, vat photo polymerisation and material jetting would result in a very brittle model prone to degradation caused by UV light. Moreover, material extrusion is low-cost but results in too vulnerable parts that respond differently depending on the direction of the force (3D Hubs, n.d. a.). This makes them all unfit. Based on the insights of Vanstiphout and Van Steen (2023), the choice was made to go for powder bed fusion.

As with any of the mentioned AM methods, the material is cured layer by layer. Two types of powder bed fusion can be distinguished: Multi Jet Fusion (MJF) and Selective Laser Sintering (SLS). A layer of powder particles is extruded and cured by a high-energy source in combination with an agent for MJF or a laser source for SLS. Both techniques lead to similar results: a high level of detail, strength properties better than all techniques mentioned above and the potential for post-processing to make the product even more durable. The difference, however, is in the price, aesthetics and slightly different mechanical properties (3D Hubs, n.d. a.). MJF would be the best alternative in this case.

Material

The first requirement for the material of the hard parts is its stiffness. Although TPA and TPU would be good options for shock absorption, they are excluded from the options as the material would bend under the magnitude of the applied forces. Due to the nature of the context of the design being a high-impact motor crash, PA11 was chosen as the final material. The impact resistance, elongation, chemical resistance and weight are very appealing and, in this case, the best option (HP, 2019). In order to increase the characteristics even more, the parts are vapour fused. This post-processing technique uses a vapourised solvent to smoothen the surface. This technique also creates a hydrophobic surface and improves the elongation at break and tear resistance of the part (Fictiv, 2022).

Pivot Point

The pivot point is designed to fully allow for the complete active range of motion without limitation. The location of the pivot point was chosen to lie at the centre of rotation of the talocrural joint for optimal plantar and dorsiflexion, see Chapter 17. An optimised ball-like surface area with enough space between the upper and lower part's hinge area contributes to this smooth hinging. As REV'IT! might want to do something with one of the design principles of the pivot point, it is not shown or discussed in detail in this report.

Lacing System

There is a variety of possibilities when it comes to the fixation of the brace to the user's lower leg. However, many of these take up a significant amount of space which would make the product bulky. Bulkiness on its turn results in a decreased range of motion and tactile feel of the rider.

After using velcro straps in the first iteration, it was found that the function of fixating the hard parts, could be added to the already in place laces of the inner boot. The iterations following this finding researched the optimal placement of the holes for lacing up the hard parts.

It appears that the most comfortable way of lacing is by adding four holes to the upper part and two to the lower part. The distance between de distal and proximal locations in the upper part is maximised in order to distribute pressure and avoid pressure points at the edges of the part. The lower part is laced up as much to the front of the foot as possible because of the hinge which keeps the part in its place at the heel. The laces are positioned in such a manner that it does not interfere with the restricting strings.

Additionally, the holes are foreseen with a metal insert or grommet as it is important to have a smooth hole so that the laces slide through effortlessly in order to efficiently tighten the boot and it adds to the aesthetics of the system.

The goal was to prevent the ankle from moving towards injury angles. As stated, the hard part acts as a skeleton to which the strings are connected. These strings act like an outer layer for the “tube” and significantly increase the bending stiffness of the system. For an optimal riding experience, the brace should allow the active range motion but should, from that point, start to limit to prevent reaching the injury angle defined in Chapter fixme. The strings can be made in a variable length and therefore be personalised to the active range of motion of the rider and their preference. The tighter the rope, the more stiffness the system provides, but if the rider is hyperflexible, likely more FOM is required.

Location

The location of the strings was initially inspired by the ligamentous structures surrounding the ankle joint (Appendix Fixme). In this way, the straps serve as an enhancement of the natural structures that are designed by the body. Because of the shape of the hard part, it is impossible to exactly copy how the ligaments are attached, and thus an approximate position was used. The user and compression test results confirm that the final location allows for the active range of motion while restricting movement beyond this point.

Attachment

The straps are looped through a hole in the upper and lower hard parts. The loop increases the force that can be applied to the strap and engenders a slim attachment to the hard part. No additional material or structure needs to be added to the hard part, making it bulkier and creating a risk for pressure points. The edges of the holes are rounded off so that the strap can move along easily

Dyneema

with the ankle movements. Additionally, the holes are positioned far enough from the edge of the hard part to better withstand the large forces applied to it during a crash. Using only one small round hole per part for each string creates the smooth movement that is required for the anterior and posterior strings. The strings in the middle will undergo fewer such movements and thus are connected with two holes creating a more stable support. This is also why a string was chosen and not a strap for the anterior and posterior ones. A strap would start to buckle in all positions and create bulk, increasing the risk of pressure points.

The strings are connected by a thick tubular strap in the case of the middle strings to keep them in place. For the other strings, the thin elastic strap keeps the strings slightly under tension and in place, not interfering with the FOM while keeping the design tidy.

® Strings

Material

Dyneema® was chosen as the fibre material making up the string, as this is 15 times stronger than steel and, therefore, the strongest one available. On top of that, it is lightweight and resistant to water and UV, making it ideal for a boot that needs to remain lightweight and is exposed to sweat and sunlight (Aviant, 2023). A thickness of 3 mm was chosen, which is the thinnest Dyneema® rope available. Yet, it is not too thin, which could damage the hard part due to greater pressure. The breakage force of a single 3 mm string is 1.414 kg (Touwbestellen.nl, 2023). The ends of the strings are connected by pulling both ends into the core of each other and stitching them together. This creates a smooth and low-profile connection which is sturdy and reliable.

22. CONCEPT EVOLUTION

The final concept did not just appear out of thin air. It started as a simple prototype made of tape and strings and, in 10 steps, turned into a full-scale functional model. At the start, the iterative steps were bigger than the final ones, but every one of them contributed to a better design. Luckily, many mistakes were made throughout the process, resulting in insights that could be turned into improvements. The evaluations resulting in iterations were focused on protection, freedom of movement, comfort, donning/doffing and aesthetics. This chapter provides an overview of this process.

Concept 1

This was the result of the on paper ideation process (Appendix 14). An upper and lower shape were made from a 3D scan of the lower leg. These were the base for the straps to be attached to. Initially, the idea was to knit straps out of Kevlar yarn and lace them through the hard parts to allow stretch until the aROM, yet not buckle, and then stiffen (Appendix 13). The velcro kept the hard parts in place to test how the straps would behave. Without the inner boot, the hard parts were so comfortable that it was possible to forget it was there, but with the inner boot, it was too tight.

Initial Fundamental Prototype

With the making of this spitting model, the idea of using supportive strings or straps mimicking the ligamentous structures of the ankle was born. This would be a lightweight, small-profile solution that could support in any flexion position. The optimal placement and length of the strings were investigated to allow for the full range of motion flexion-wise and tighten when inverting and everting in any position from plantar to dorsiflexion (Appendix 16).

Concept 2

As knitting Kevlar yarn was an extremely tedious process, taking tw one strap, an alternative was sought after; using thin ropes. This pr from tangling up while knitting and significantly speeds up the proces for this, a three times stronger fibre was found: Dyneema. A new made using this material. The extremities of the straps were now a the edges of the hard parts, to allow for more evenly distributed for part itself was also adapted. Bending Concept 1 towards the inj force would make the pieces covering the malleoli dig into the sk this concept, these pieces were cut off above these bony parts, res comfortable fit. The parts were also scaled up to better fit around th

Concept 3

Putting Concept 2 in the compression test setup (Appendix 22) was no success. The straps might have been very strong, but the brace would not stay in place, despite efforts to strap it down. It resulted in resultant forces higher than solely wearing an inner boot but no higher than just 40 N. Also, it would not get back into position after bending the ankle, both being far from ideal. At the time, REV'IT! was working on a preliminary ankle brace design. 3D Printing this design, going back to the calculations and ankle research, and accidentally buying a too-thick rope of Dyneema, something clicked. The previous idea used the foot joints as a basis, which would have been okay with lower forces. However, this extremer scenario could still injure the bone structures internally or dislocate the joint. The advantage of a pivoting hard part is that it acts like a wide tube around the foot with high resistance to bending as it compresses on one side and extends on the opposite side. Furthermore, putting the optimal pivot point in the right place allows free movement flexion-wise, and the system returns to the right position after bending. However, this structure on its own also did not do well in the compressive test (Appendix 22). So, what if these ideas were combined? The hard part would serve as a structural core, keeping the parts in place and already providing bending resistance. The strings would, with very little effect on the bulk and weight, create a super stiff outer layer for the tube in any flexion position and significantly increase the resistance against bending, while also providing flexion protection. This idea was then combined into a rough prototype.

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ngled, following
ce and the hard
ury angles with
kin. Therefore in
sulting in a more
e inner boot.

Concept 4

The principles of Concept 3 were combined with the 3D scan-based hard part design. The hard parts were reshaped, also 2 mm thick and a pivoting point inspired by REV'IT!'s version was implemented and made to allow for 12.6 ° eversion and 19.8 ° inversion. The goal was to find the right string attachment locations. The concept was user evaluated based on what still allowed for enough freedom of movement while providing rotational resistance in all positions. All strings on both sides were made of one rope to adjust the tension depending on the rider's FOM preference. However, this was not smooth, and the compressive test results were worse compared to Concept 5 with six separate strings due to more settling in the rope, though the principle would be interesting to explore further. Furthermore, the REV'IT logo was added for branding and aesthetic reasons, and the velcro was replaced by a lacing system that kept both the hard parts and inner boot in place.

Concept 5

As said, this concept is an adaptation of Concept 4 but with all strings comprising separate pieces of rope. For this design, different options for the design of the strings were considered: running over the outside of the hard part by looping it back through a second hole or on the inside, looping the strings or knotting it to the hard parts with its outer ends, and a single string for the neutral position or a rectangular shape? The choice was made to limit the number of holes for the integrity of the material of the hard part, as having the strings more on the inside did not cause any discomfort. Furthermore, the looped variant of the strings was chosen, as knots or other connections added more bulk in the wrong places, on top of the fact that this is a stronger connection. Additionally, the rectangular outwards-facing strings shape in the middle added more stability when inverting in a neutral position compared to a single string. It allowed for more rotational resistance in the ranges between the neutral and outer flexion positions. This was worth the extra holes. Last, the lacing system was updated to distribute the forces more evenly.

Concept 6

There were some pressure points at the top, near the malleoli and at the sides of the foot of Conept 5. Therefore, the lower hard part shape was adjusted to have less sharp corners and bigger surfaces. The upper shape got a wider opening at the top and a less forward protruding surface in the middle. Also, the heel covering part was made higher, making the tube-like structure stiffer and the heel better protected. The height was made so that it would not dig into the skin in plantar flexion. Furthermore, this concept was a test to see if a triangular string shape would add any value in terms of stability. It barely did, and adding another set of holes to the hard part is not worth it. On top of this, the pivot point was optimised to become a rounder, more ball-like connection between the two parts to make it a smoother connection and so having less interference with flexion. As the strings looked messy and the ones in the middle got caught sometimes, some trials were done to keep all strings in place.

Concept 8

Making the hard parts
even stiffer. The 2 millin
be more forgiving if th
double the thickness t
increased thickness. Th
the tactile feel of the bo
but if the riders report r
and bulk, making it thi
final topology of the h
the takeaways from Co
stopper and lock were
having to knot the lac
looking variant for keep

TU Delft

Concept 7

This concept was made with the use of the hard part of Concept 6, but the strap topology was changed based on the insights from this concept and user tested in terms of freedom of motion and experienced support. This concept was again compression tested and the results were impressive as can be seen in the next chapter.

Concept 9

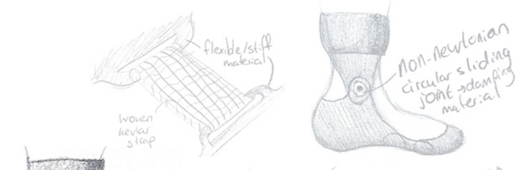
The thicker shape of Concept 7 made the upper part a little tight. So, this part was offset from the leg by an extra millimetre. Besides this, the pivot point was no longer turning optimally. Therefore, the contact shape was adjusted in this design, and a bigger distance was created between the lower and upper half, which had a big impact. Furthermore, the inner boot was adjusted to a size 38 by hand to fit the rest of the model. And finally, the goal was to make the model more aesthetically pleasing by making the brace black, making the red connection strap look more professional, making the holes rounder, and adding grommets to the holes of the lacing system. To take this a step further, tests were done with a white pencil and marker to see if adding lines would improve the look.

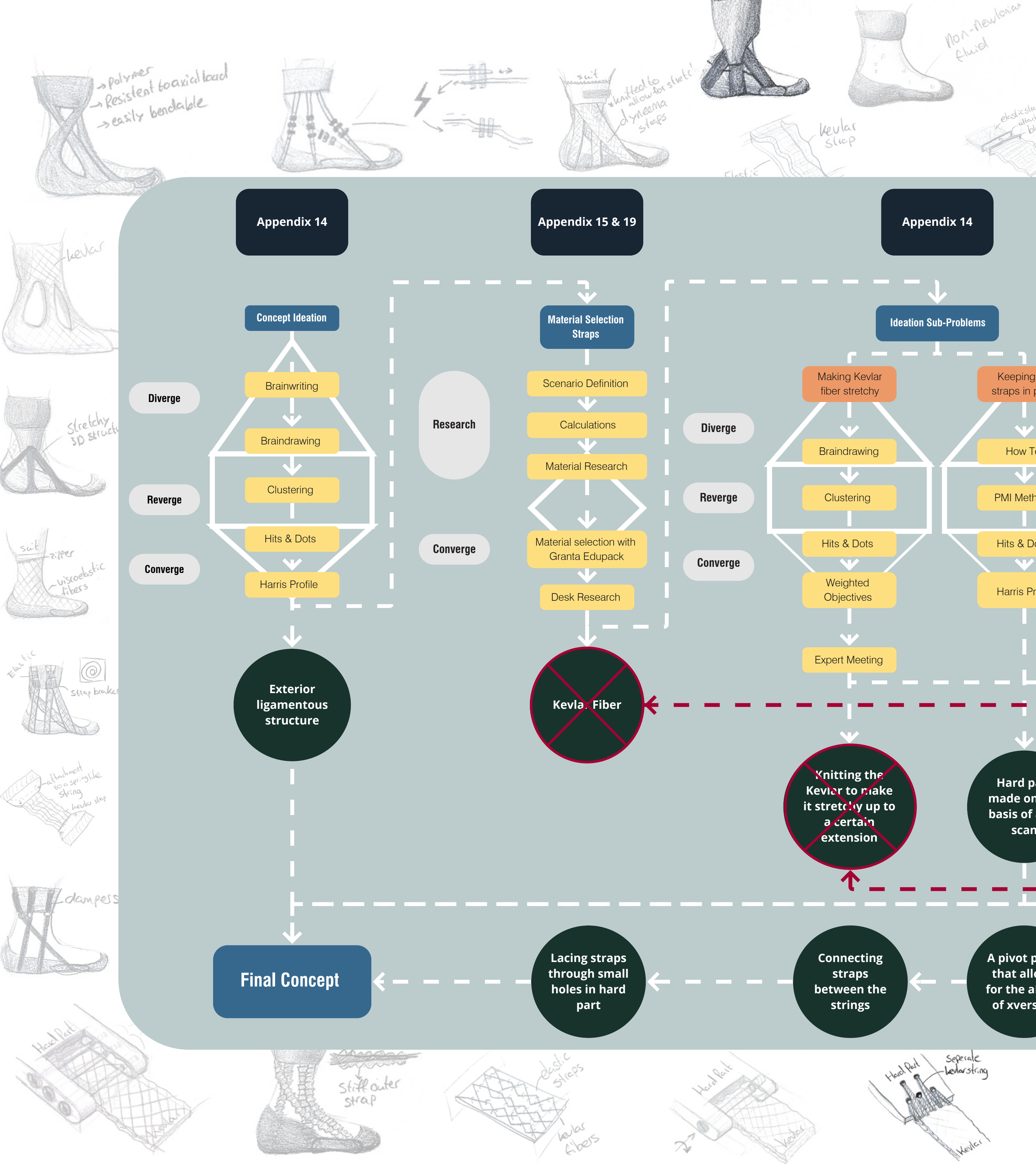
thicker would make the tube-like structure metre structure was still flexible, so it would he shape was incorrect. It was decided to to 4 millimetre to see the influence of this his turned out pretty well. How this influences oot will have to be field tested at some point, no downsides in terms of weight, tactile feel cker would be an option. Furthermore, the oles for the strings was defined based on oncept 7, and finishing touches like a cord e implemented in the lacing system to not es and make it look better. Also, a better- bing the middle straps together was tried.

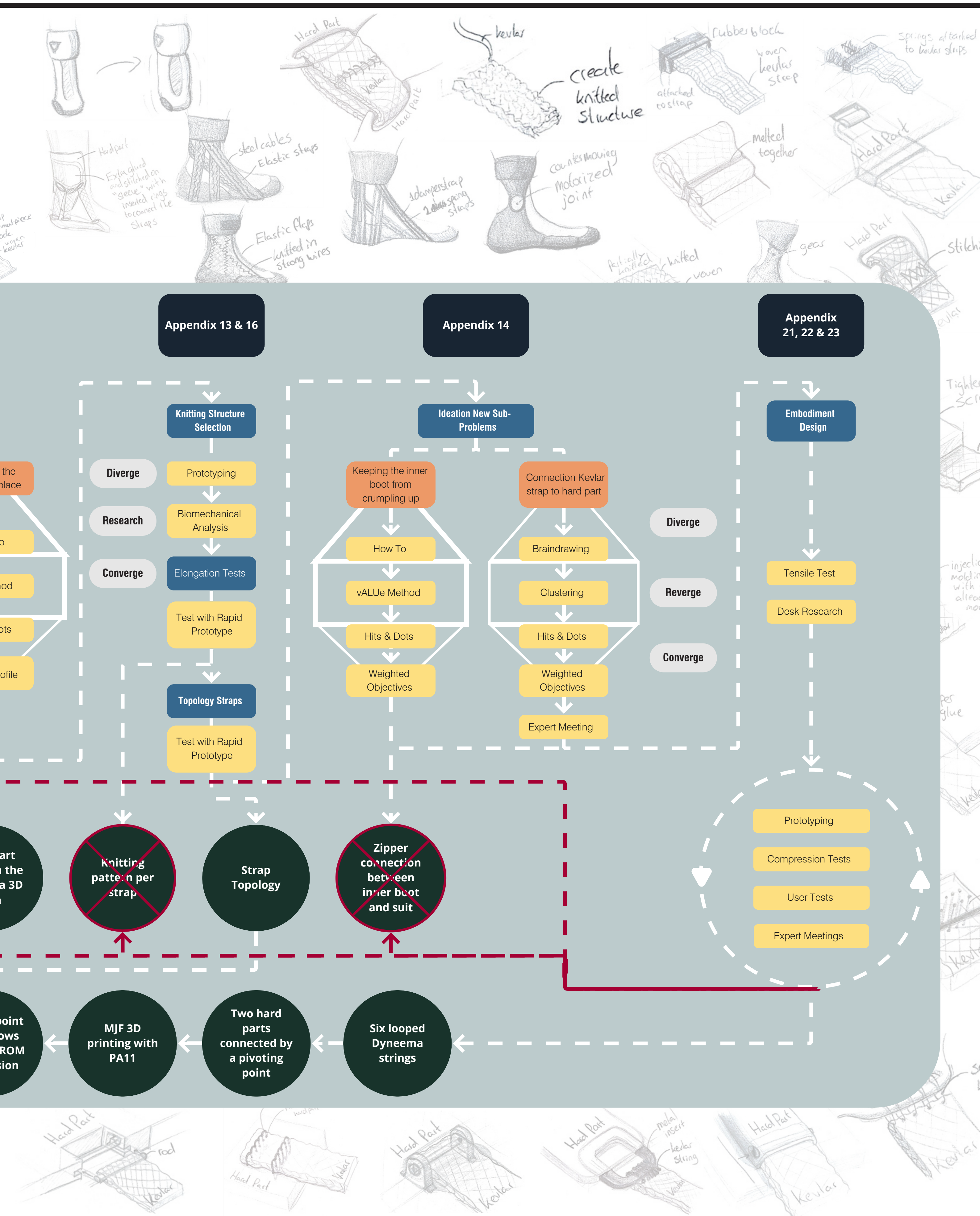
Concept 10

This is the final concept. The final colours were selected on the basis of the colour study of Appendix 24, and the line designs tried out on Concept 9 were implemented in the form of protruding surfaces. This concept was 3D printed using the method of Multi Jet Fusion instead of regular FDM printing to give it a more refined look and to have better material properties in all directions. Also, the connective straps between the strings were updated and refined in order to look better, be more easily producible and not interfere with the freedom of movement. The one in the middle is a tube made out of stitched-together webbing straps stitched through the strings, and the other bands are made from very thin and flexible elastic bands.

23. THE IDEATION PROCESS







Appendix 13 & 16
Appendix 14
Appendix 21, 22 & 23
Knitting Structure Selection
Diverge
Prototyping
Research
Biomechanical Analysis
Converge
Elongation Tests
Test with Rapid Prototype
Topology Straps
Test with Rapid Prototype
Ideation New Sub-Problems
Keeping the inner boot from crumpling up
How To
vALUe Method
Hits & Dots
Weighted Objectives
Connection Kevlar strap to hard part
Braindrawing
Clustering
Hits & Dots
Weighted Objectives
Expert Meeting
Diverge
Reverge
Converge
Embodiment Design
Tensile Test
Desk Research
Prototyping
Compression Tests
User Tests
Expert Meetings
Knitting pattern per strap
Strap Topology
Zipper connection between inner boot and suit
MJF 3D printing with PA11
Two hard parts connected by a pivoting point
Six looped Dyneema strings
create knitted structure

24. EVALUATE: DOES IT WORK?

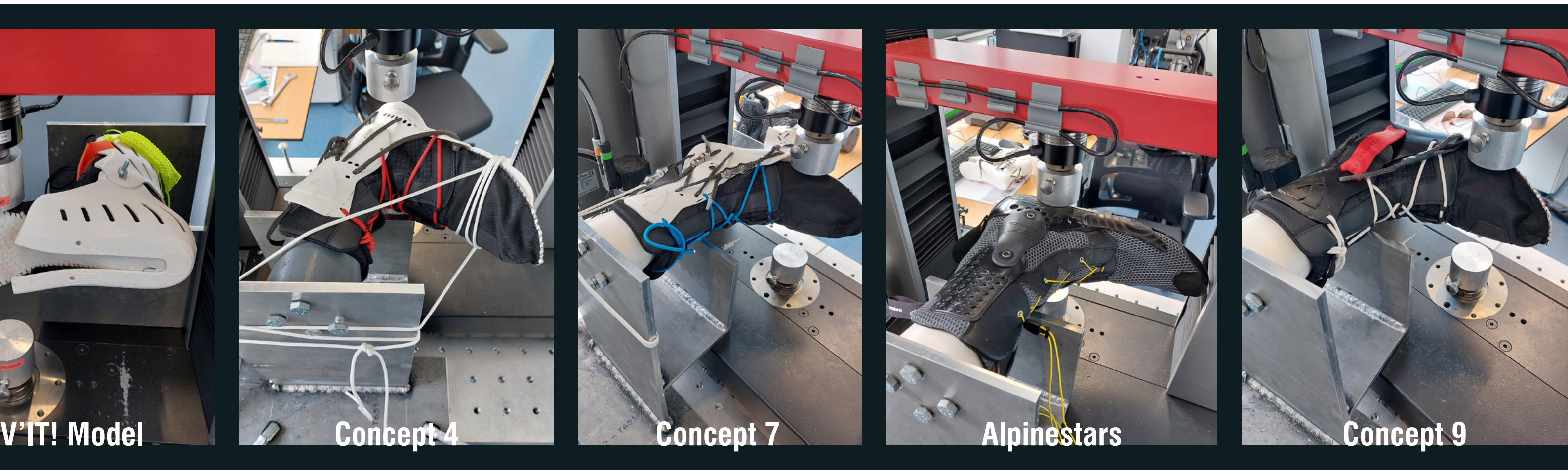
What this question means depends on whom you ask. One rider might say it works when it takes a second off their lap times, the other when he has a little more peace of mind before the race, and another when he does not injure his ankle during a crash. Van den Goorbergh (2023) indicated the latter as the main way riders evaluate if gear provides protection.

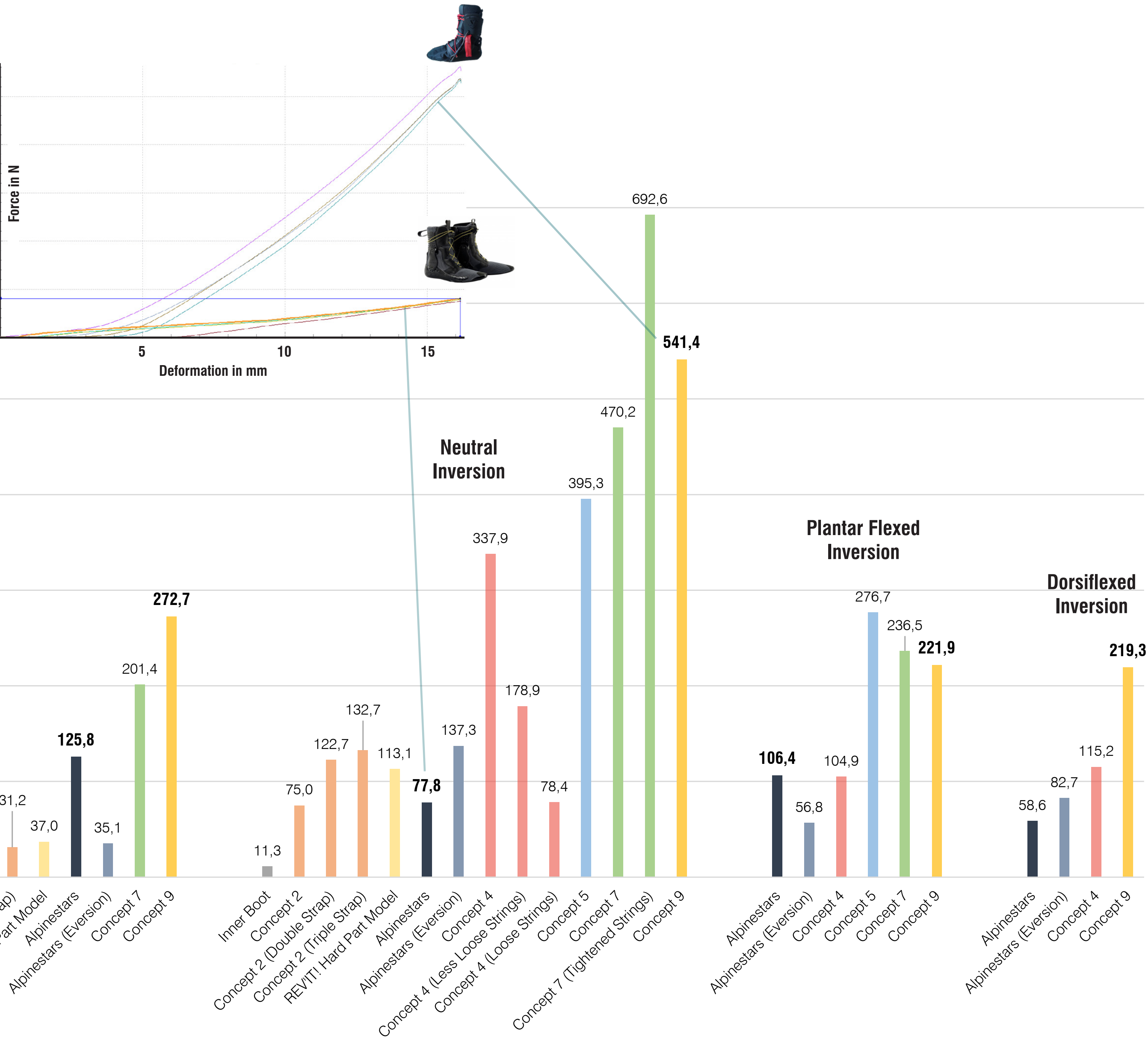
The EN13634 standard does not state a way to evaluate the efficacy of the ankle brace. Alpinestars is currently the only one trying to express this level of protection in numbers (Den Dekker, 2021). They put a pivoting lower leg model into a compression testing machine and saw how much force was required to rotate the foot, providing a sense of the stiffness. The machine measured this rotation as the distance the compressor was moved downwards. Inspired by the test setup they used, a setup was designed for the Faculty of Industrial Design Engineering testing facility: the 10 kN Zwick. The Zwick does not have a tool to perform this specific test, so it was designed and handmade in the workshop. The foot model inside the prototype was a 3D print of the lower leg scan that pivoted around two axes: one that mimics the movement of xflexion and one xversion (see Appendix 22). This way, the most injury-prone position could be simulated: plantarflexed inversion. This model had limitations based on the angles defined in Chapter 17. For xflexion, the limit was the aROM and for xversion, the injury angle, as the latter is the one of interest for finding the resultant force required to rotate it. This model was used to calibrate the machine and define the travel distance to reach the injury angle in all positions unrestrictively. Going beyond this point would give a skewed perspective, as the force would be generated by the foot model and not by the brace. The machine was forced to stop at that point.

All concept models with significant structural adaptations were put to the test. As Alpinestars is considered the best, their inner boot was also tested to compare results. The tests were done in different positions: neutral with the compressor on the middle of the foot and the forefoot (Abduction) and strapped into a plantar and dorsiflexed position. Most tests were done in an inverted position. The goal was to see how the concepts compared to each other. In principle, eversion occurs similarly. The difference, however, is that the aROM and injury angle are slightly smaller, meaning on that side, the stiffness should be even greater and the strings tighter on that side.

The results can be seen in Figure 37. Some data was left out due to it being unusable. It shows that with every iterative step, the concept became better. Only Concept 7 once exceeded the final version when the strings were tightened so that the joint in the hard part no longer allowed for xversion. In Concept 9, the strings were a little looser to provide more FOM. With the same looseness of the strings, Concept 9 performed slightly better, which is interesting as Concept 9 is 4 mm thick and Concept 7 is 2 mm. The curves show that the model allows for a certain range of motion with limited resistance and, after that point, becomes stiffer, which is the ideal behaviour. Finally and most importantly, it can be concluded that the new brace design requires 2.2, 7.0, 2.1, and 3.7 times more force to push the towards the inversion injury angle in a neutral (with the compressor on the forefoot and middle of the foot), plantar flexed and dorsiflexed position, respectively, compared to the brace of Alpinestars. Meaning the goal was achieved. The full research can be found in Appendix 22.

Figure 37. *Results of the 10 kN co*
required to bend the leg towards t





mpression tests performed on the inner boot, the initial hard part model of REV'IT!, the Alpinestars Supertech R V1 inner boot and concept 2, 4, 5, 7 and 9 showing the force in N he inversion injury angle.

Design Drivers, Requirements & Wishes

The best way to evaluate the concept is by holding it against the list of requirements and seeing how it fits with the design drivers (Chapters 19 & 20). Per requirement and wish, the concept was reviewed seeing whether or not they were being met (Table 4 & Table 5). Based on that outcome, recommended next steps were formulated. These are either steps for evaluating if the requirement is being met or steps for optimising or improving the design. The concept met all testable requirements. The rest will still need to be evaluated once the full boot design is ready and the ankle brace is implemented. Then the riders can evaluate it in a real-life test setting, and further optimisation can be done. In Figure 38, an overview is presented of how the ankle brace scores on the applicable design drivers compared to the best alternative of Alpinestars, based on own insight, test results and the rider interview (Appendix 20 & Appendix 22). The design drivers where the brace is relatively lacking should be the base for further iteration.

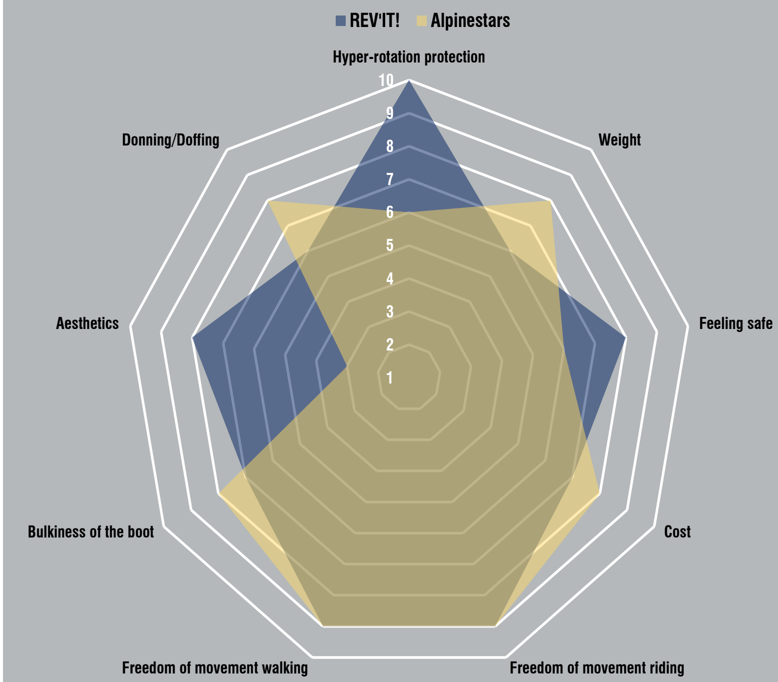


Figure 38. *Design driver review of the new ankle brace concept of REV'IT! and the ankle brace of the Alpinestars Supertech R V1, evaluated on a scale from 1 to 10.*

Table 4. *Performance of concept design according to requirements.*

#	Requirement	Status		Suggested Next Step
1	The ankle brace should provide more protection against injury caused by hyper-rotation of the joints of the hindfoot in both high-side and low-side crashes than the currently available options, meaning more force should be required to bend it towards an injury angle.	✓	The case (Figure 37)	Epidemiology study analysing effect and further optimisation of the FOM vs protection balance
2	The inner boot and brace should stay on the lower leg during a crash, and while riding; thus a securing system must be in place.	?	Very likely	Laboratory test (pull force)
3	It must be possible to cut the entire boot open and easily remove the brace if the rider sustains an injury to the lower leg.	✓	The case	Further optimisation with medics
4	The ankle brace must allow for personalisation based on the anatomy and preferences of the rider.	✓	The case	Optimise the fitting process
5	Riders should not experience the brace interfering with their freedom of movement, meaning it should allow for the aROM.	?	Very likely	User test in training session
6	The rider should not consider the tactile feel of the boot to be compromised by the ankle brace.	?	Uncertain	User test in training session
7	The protection and functionality should remain sufficient enough after a first crash to continue riding and survive a second crash.	?	Likely	Impact tests
8	There should be no points in the inner boot that exceed the pressure discomfort threshold of the foot caused by the brace.	✓	Under off-bike conditions	User test in training session
9	The ankle brace should not have a noticeable effect on the temperature and moisture management of the overall boot and make the boot thermally uncomfortable.	✓	Under off-bike conditions	User test in training session

Table 5. *Performance of concept design according to wishes.*

#	Wish	Status		Suggested Next Step
1	The ankle brace should allow painless donning and doffing when the rider is injured.	X	Very unlikely	Further optimisation for frontal entry and exit
2	The brace should not squeak when walking	✓	The case	
3	The inner boot should weigh no more than 364 g	X	Current weight: 444 g	Shape topology optimisation
4	The inner boot with brace should take up max 15 seconds of the total donning/doffing time	X	Current time: 20 seconds	Optimisation of lacing system

User Test

As the riders are really busy and getting in contact with them was a challenge, all user tests were done by me. The design was built around a 3D scan of my foot, so the boot also only really fits me. Naturally, I am not a MotoGP rider and generally, this approach would not necessarily be advised as user insight is highly valuable. However, with the previous analysis results and user insights in mind, and personal riding experience, a good approximation could be made of what would be required. The advantage of this situation was that the iterative process was quick due to being able to directly translate own experience into improvements. Every time a new variant of the concept was finished, the user test included wearing it for two hours and walking and running around and jumping from time to time to experience the comfort of the brace and define potential pressure points. This evaluation also included making all the movements identified in the foot position analysis (Appendix 7). Furthermore, rotational force would be applied through body weight to feel the level of support and experience if this situation would result in other pressure points. As a final user test for this project, all rider positions were simulated on a motorcycle to confirm that all movements could be made. See figures on the left.

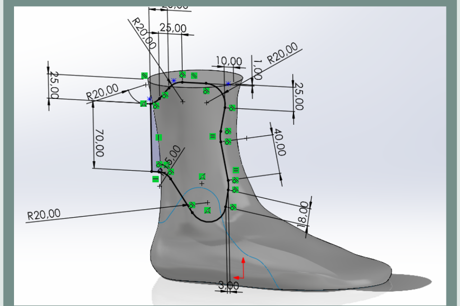
From this point, it is recommended to start doing user tests with riders and not wait until the entire boot design is finished. Not only to improve the design but also because Van den Goorbergh (2023) indicated to highly value that he was being heard as a rider in the form of interviews and co-creation. In his eyes, this is what makes REV'IT! unique and such a quality brand. Therefore, putting more effort into these types of rider interactions would be strongly recommended to keep the riders on board.

25. NEW RIDER JOURNEY

Measuring & 3D scanning rider

3D scanning rider's feet in all positions

Turn scans into brace base shape



Designing personalised hard part

3D printing

Testing in training setting

Everything provided by REV'IT! is tailor-made for the MotoGP riders, and according to Van den Goorbergh, REV'IT! does this very well (Appendix 20). This requires the manufacturers to measure the riders from head to toe. Once that is done, the riders receive their new test gear during the training season to try everything on and see what still needs to be adjusted. Then everything is communicated back to REV'IT!, and they get the final version before the start of the season (Schamp, 2021: Appendix 9). Since 2021, they have also been experimenting with 3D scanning the riders. But there is interest in implementing this technology for these kinds of applications. The racing boot will have to fit somewhere into this process, and it would be the perfect opportunity to start with this.

As concluded in Chapter 17, feet come in different shapes and sizes, and the way they move differs too. 3D scanning the lower extremities would be an excellent way to create a boot that fits their riders like a glove. Protection can be placed in the right spot, pressure points can be avoided, and for the ankle brace, this means better protection with a personalised freedom of movement. Having the surface of the hard parts smoothly follow the outlines of the leg of the rider keeps them in place better and allows for more evenly distributed forces. Therefore, the following new fitting journey would be advised for the riders. As part of the yearly fitting routine, they now do not only get their measurements taken, but they will also step into the 3D foot scanner for a few minutes. They will put on their racing socks for an accurate representation (Schamp, 2021). Then the rider is instructed to make all required movements for the different scans: inversion (neutral, plantar flexed and dorsiflexed), eversion (neutral, plantar flexed and dorsiflexed), plantar flexion and dorsiflexion.

Based on this scan that includes all the relevant degrees of their active range of motion, product developers of REV'IT! can start creating the customised 3D hard parts. They can also provide the manufacturer with instructions on the length of the Dyneema strings, which can be measured using all available foot scans. Then the model will be 3D printed, together with the boot assembled, and the new boots will be handed over to the rider to test during training. Is everything okay? Then this boot version will be used for the rest of the season unless something comes up midseason. If not, then iterations will be done to get it just right for the rider to have a good racing season.

26. COST ESTIMATION

For the boots of the riders, REV'IT! only pays for production costs, and provide them for free. To get an idea of what these costs would be like, an overview was made of the expenses for the production of the final prototype (Table 6). Naturally, these are mainly consumer prices including VAT and the assembly costs (working hours) are omitted, but it provides an insight. The target group is small, and a few parts have to be custom-made per rider, meaning that the price per piece is likely to remain this high. The most expensive part is the 3D print, while the other materials come down to a few euros. A way for REV'IT! to bring down the cost price is starting a partnership with a manufacturer who is looking for possibilities to get their 3D printers filled up to keep the quality of the powder high.

Naturally, moving from the MotoGP variant to the consumer version is a different story. Then the market price becomes relevant. But, for consumers, it is not worth the effort and costs to get the hard parts personalised and 3D printed. REV'IT! will likely create a few standard sizes for the hard parts based on the ergonomic last, reducing their costs significantly.

Bill of Materials Ankle Brace

Part	Amount	Price per Item (€)	Total Price (€)
PA11 MJF 3D printed hard parts - upper and lower part	1	160.60 (lower) & 124.04 (upper)	298.87
Dyneema ® rope Q1 - 3 mm	1.42 m	1.10/m	1.56
M4/6 x 8 mm Tubular Rivet - Flat Head	2x	7.08/10x	1.42
M4 x 6mm Button Socket Screw (with Loctite)	2x	5.32/100x	0.12
Laces (Paracord 550 Type 3) - 4 mm	1.7m	0.40/m	0.68
Polyester sewing thread	5 m	3.50/100m	0.18
Heavy webbing - 25 mm	0.4 m	0.87/m	0.35
Elastic band - 20 mm	0.5 m	0.95/m	0.47
Cord lock - 4 mm	1x	0.40	0.40
Eyelet/grommet - 5 mm	6x	0.03	0.17
Zipper pull/Cord End - 3 mm	1x	0.89	0.89
Loctite & Glue	1x	0.05	0.05
		Total	**305.16**

Table 6. *Bill of Materials including cost prices (Appendix 25; Schroeven-express.nl, 2023a-b; Paracord:2023, 2023a-d, Huissteden.nl, 2023; Touwbestellen.nl, 2023, Ritomshop, 2023).*


BARDAHL
ADDITIVES & OILS
X-lite
AKRAPOVIC

REFLECTION

This project is only a starting point for further development. What comes next is up to REV'IT! and other product developers. This section reflects and looks back on the project in the form of summarizing conclusions, recommendations for next steps and a personal reflection of the graduation process as a whole.

27. CONCLUSION

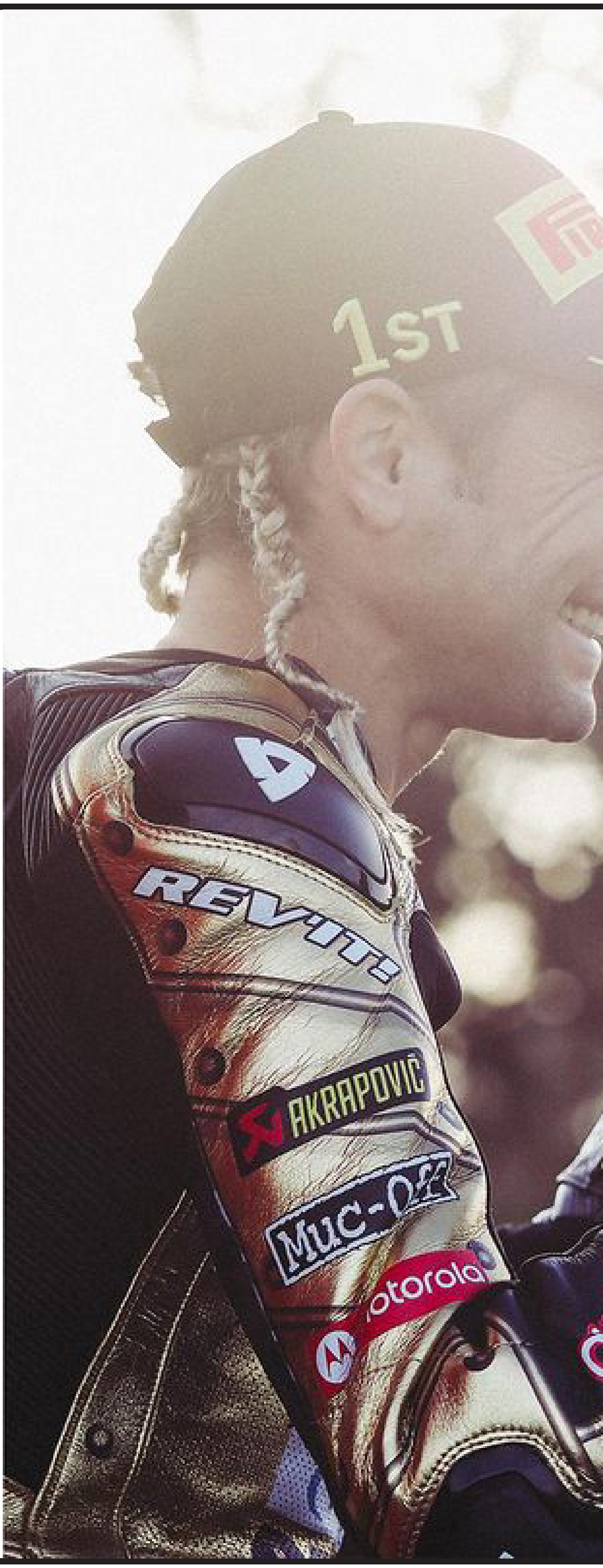
The goal of this project was to analyse what goes into a MotoGP racing boot and what the requirements are, to identify areas of improvement and to create a concept validated in a laboratory setting using a prototype. It was found that a MotoGP racing boot comes equipped with multiple protective parts, of which many are evaluated before bringing the boot to market.

This appeared not to be true for the ankle brace, although this is one of the most important parts of a MotoGP racing boot that contributes to the well-being of the riders. It was therefore identified that finding a better solution for the protection of the lower extremity against hyper-rotation than what is currently available to the riders was the most fitting and desired direction for the project. This goal was achieved with the final concept presented in this project.

Viability

Racing boots for MotoGP riders are a niche market meaning that the riders have limited options available when looking for the boot that optimises their performance. This, on the other hand, also means that there is a lot of room for improvement and that the market is not saturated. REV'IT! can distinguish their racing boot from the competitor's boots by improving safety while still optimising performance. That can be done by implementing an ankle brace that is proven to be effective based on test data and still allows the necessary range of motion in order to ensure optimal movement and tactile feel of the rider's lower extremities.

Not only does this achieve that riders are less likely to suffer an ankle injury which benefits their performance, but it also improves their long-term well-being. Many ankle problems only develop over the years in the form of arthrosis and instability, which could potentially be delayed by better protecting the ankle in the first place. TRL4 was reached with the final prototype of this project, and if it were further developed and implemented as mentioned in the recommendations, the concept would have a chance of success.



Feasibility

Both the unsaturated market and the physical prototype prove that the ankle brace would be feasible to produce and that riders would wear it. Because of the small user group, it is beneficial to use a personalised design and production technique, meaning 3D printing. If we really look into the technical manufacturing and assembly aspect of the prototype, there is still room for improvement regarding the convenience with which the boot should be assembled. For sure, if REV'IT! were to aim for implementation in different areas than the MotoGP, this would be of great relevance. Due to the pace in which REV'IT! aims to realise their first racing boot, it is not likely that the ankle brace would be part of this design. However, MotoGP riders stated in their interviews that they do have high expectations of REV'IT!'s first boot due to the way they perceive REV'IT! as a high-quality brand.

People expect at least as good a product as Alpinestars' boot and maybe even better, even including novelty, as they correlate innovation with REV'IT! as a brand. During the interviews, it was learned that the riders prefer REV'IT! mainly due to the personal contact, pleasant treatment and high-quality products. According to Van den Goorbergh (2023), the personal aspect is something other brands do not provide. I would therefore recommend to not compromise on quality by putting a boot early to market but rather focus on a REV'IT! worthy boot.

Desirability

The outcome is a protective low-profile solution that is very robust for its weight. And although this might be a very desirable product on paper, that does not guarantee the same outcome in reality.

From past implementations, it can be learned that riders and people, in general, are often hesitant towards new developments, regardless of how beneficial they seem to be based on testing data. It should therefore be the aim to let the riders experience for themselves that the ankle brace is what they did not know they needed. The same happened in the past with, for example, the airbag system, which riders thought they would never use but do not want to ride without anymore (Van den Goorbergh, 2023). It is important to immerse the riders in the story and the thought process behind the ankle brace for increased safety, medical problem solving and performance. This builds trust and also opens a conversation for the future. A better ankle brace is something several riders indicated they wanted to see improvements on, which is also what the research showed.

28. RECOMMENDATIONS

This is where the stick gets handed over as the project comes to an end. Further elaboration upon this subject, in collaboration with many more people, could bring this working prototype towards a market-ready product. To support this process, several recommendations are listed below that could be used as a starting point in taking the next steps.

Further Development

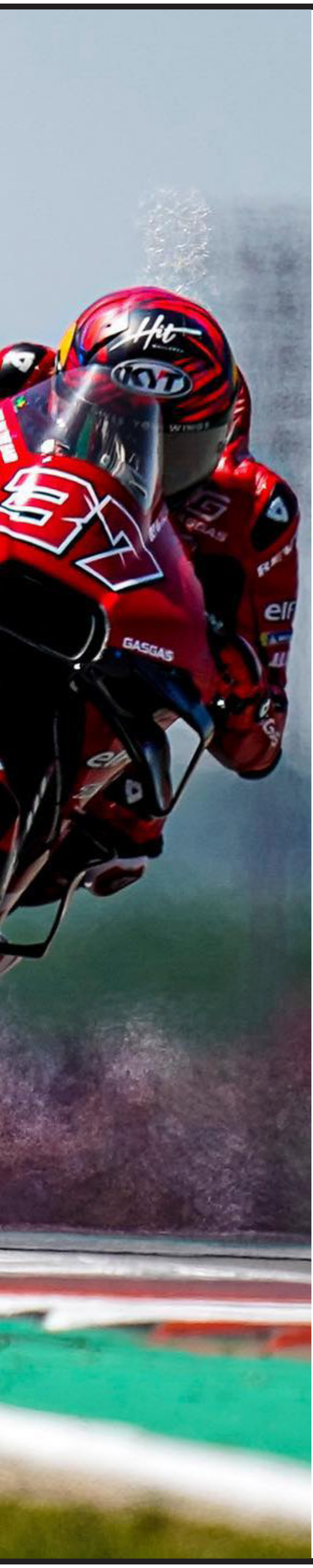
Looking at the list of requirements and wishes, there are still some aspects that could not be evaluated in a real-life situation with the actual users. The first recommendation would therefore be to continue the development of the overall boot and see how everything fits together before further developing the ankle brace. This would result in a better understanding of the wiggle room left when optimising and designing the final ankle brace. The logical next step would then be to start optimising the ankle brace for force transfer using less material with shape topology optimisation. The goal in this phase would be to reduce weight and size while increasing the provided stiffness even more.

When the entire boot is developed, testing the interaction between the ankle brace and the user becomes possible, though it would be advised to include the riders as soon as possible. A second recommendation is to analyse the impact of the ankle brace on the soft tissue and surrounding bodily complexes. This is, for a large part, related to the stiffness of the material and ankle brace structure.

In case the brace material is too stiff, it could, on the one hand, cause pressure points on the soft tissues and, on the other hand, break rather than bend under high impacts during the crash. This would increase the risk of damaging the soft tissue of the user.

In case the ankle brace structure is too stiff or rigid, this could potentially bring more damage to surrounding bodily complexes. Naturally, the ankle has been the focal point of this research, but it is, of course, part of a very complex system. It would be advised to dive deeper into the impact of a stiffened ankle joint on the knee and the hip joints. It is not expected to be an issue as the ankle only absorbs little energy by deforming and breaking before the impact protectors get in contact with the ground and transfer the forces. Regardless, complex simulation software and talking to experts could provide more insight into this assumption.

Often for protective gear, a protocol is in place that states it should be replaced when an impact has occurred in order to guarantee full protection, such as, for example a cycling helmet. As this would mean a total replacement of the ankle brace or even a racing boot each time the rider makes a slide, the third recommendation would be to research the longevity of the ankle brace. A testing robot arm could be used to run the boot through a large number of cycles and perhaps crashes as well. This would result in a recommendation of when replacement is necessary.



Optimisation Development

Although this project has resulted in a working prototype that proves the concept effective, optimisation before implementing it in a racing boot is advised. A few recommendations are listed which could be tackled. However, these recommendations are based on an ideal scenario meaning that depending on the time and budget of REV'IT!, some might be prioritised above others.

The current lacing and Dyneema® strap systems work effectively in the current prototype. However, to improve the assembling processes and time, revising these systems could potentially have the largest positive impact. It would be recommended to research how the Dyneema® straps could be attached more rapidly without sacrificing the effectiveness and slim size of the current construction. Additionally, a tightening system, such as the BOA® laces, would be an ideal replacement for the current lacing system. This would speed up the process for the rider to put the boot on and off, as it currently takes about 20 seconds.

Another optimisation would be to dive deeper into the design drivers considering the optimal ROM that should be allowed comfortably by the ankle brace. Many riders have stated that, above all, a racing boot's range of motion and tactile feel are very important, sometimes even above safety. It could become REV'IT! 's goal to prove that safety perfectly exists alongside increased performance. Further elaborative research can provide more insights into the optimal supported ROM and the variety among riders, as they stated. This could result in a system where a professional or the rider themselves can change the setting of the ankle brace to allow or restrict specific ranges.

Additional Development

In general, it would be interesting to research alternative innovative ideas. However, these usually come with a high price in terms of budget and time necessary to accomplish such a development. Nevertheless, recommendations are provided in case someone seeks to do so. One recommendation could be to research non-Newtonian materials to see if one could respond according to their deformation rate. This way, you could make a cuff design that is flexible while riding and making normal movement, but stiffens and protects once the deformation happens too rapidly.

Another recommendation would be to investigate the impact of impact protectors on hyper-rotation protection. Absorbing part of the energy prior to when the foot starts to rotate would be ideal. Distributing the forces over a larger area near the centre of rotation would reduce the momentum of the force on the ankle joint. Eventually, in an ideal world, the MotoGP could start researching the impact of the riders' gear on their safety and evaluating the actual effects of using better protective gear on injury rates to be able to increase rider safety.

Implementation

The product, as displayed in this project, is tailored to the MotoGP riders and cannot be mass-produced due to the basis of a personal 3D scan. This version would therefore be a way to market REV'IT! and receive positive feedback and promotion from the riders. However, other potential implementations could be medical recovery, motocross and other high-risk sports. Further research should be done on this topic. Additionally, it might be interesting to research whether this ankle brace can be redesigned to a prefabricated version for the general public, as less extreme impacts are to be expected in this user group. An off-the-shelf version could potentially provide the safety necessary for daily use, whereas a personal version based on a 3D scan would be the premium version.

29. PERSONAL REFLECTION

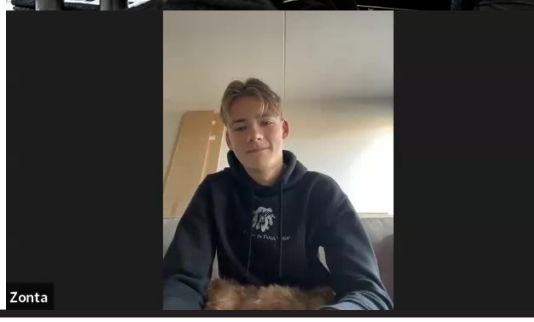
This project has been quite a challenge, both cognitively and mentally. I have seen low lows, but what I will most likely remember looking back is how cool it was to do this project for REV'IT! and work with MotoGP riders. I am very grateful for this opportunity. Also because I got to meet so many nice and knowledgeable people through this project. My goal was to learn as much as I could still, while I was still studying. Some people taught me how to knit both by hand and machine, some how to use a compression machine, some how to grind off welding seams, others how to 3D print carbon fibre, or how to use the CNC for milling the edges of an aluminium plate or how to use the 3D foot scanner, or how to improve my visualisations skills. The list goes on and on, and that is what I value most from this project.

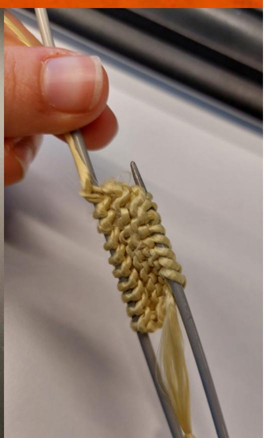
I set up a few goals at the beginning of the year and always kept them at the back of my mind. I wanted to improve my project management skills, use tools from the Ergonomics Lab, apply ideation methodologies, talk to experts and most of all, focus on visual communication as my Bachelor End Project was just a simple Word document. I reached all the goals I set for myself, which is satisfying. Naturally, there is much room for improvement, but I look forward to the next steps.

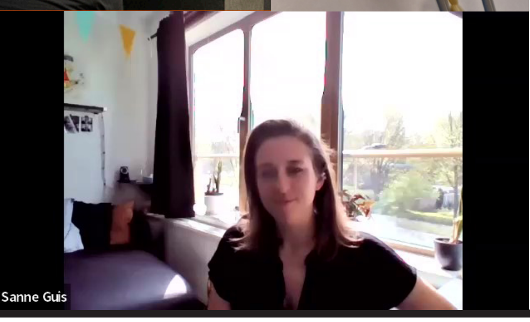
My greatest external challenge in this project was communication. Most everyone was hard to reach, busy and not really looking to spend time on my project, both outside the faculty and in the faculty and REV'IT!. But I did not give up and found some hidden gems that helped me out a lot, which I appreciate very much.

My greatest internal challenge was project management and the management of my mental health due to stress. The project was very broad and vague, and it was not always going in the right direction, which are key elements for me to get overwhelmingly stressed out. Therefore, I started listening to audiobooks about procrastination, habits, getting things done, time management and non-violent communication during my commutes. I felt I needed to get a hold of it and saw this as the opportune moment to work on it and try things out. This affected me greatly, as with small steps, I tried to have more time for myself, for my loved ones and divide my attention between my work and studies. Of course, this definitely had ups and down. For example, I still spent the final week of my project locked up in a room, barely eating and sleeping. But I feel like I can take away valuable learnings from this process and that otherwise, this could have been the case for a month instead of a week.

What helps is that, in the end, I came up with a design that seems to work. There was a point where I was not too fond of the project, as I knew my ideas were bad, and I was not seeing it change anytime soon. I am glad I got the opportunity to push through that phase and turn this project into something I can feel proud of. Overall I would summarise this project as a challenging, tough, but cool learning opportunity. Therefore, I look back on a successful project.







30. LIST OF APPENDICES

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31. REFERENCES

1. _AtSpeed. (2020). *Dainese Axial D1 Boot Review.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=_F82baJr9Xg

2. Alberto Naska EN. (2019). *ROOKIE RIDER VS MOTOGP RIDER: WHAT'S DIFFERENT? Naska VS Jonas Folger @ Cremona - Yamaha R.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=V8Osi_tAYi0

3. Alberto Naska EN. (2020). *BREAKING IN HALF A DAINESE BOOT - Racing Is Life 2020 Ep.5.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=K-PGbHHGZxM

4. Alex Castillo. (2017). *Jack Miller explains how to use the foot-pegs in MotoGP.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=rOafxmMHvUA&list=PLXHb1nVbXUWWlG9BXtiHoudW7PuLYY20r&index=15&t=42s

5. Alpinestars. (n.d.). *About us.* Retrieved March 2, 2022, from https://www.alpinestars.com/pages/about-alpinestars

6. Alpinestars. (n.d.). *PPE for lower leg protection.* Retrieved from REV'IT!.

7. Autosport. (2019). *Marquez's Thailand MotoGP crash analysed - 4.*81s and a 26g landing. Retrieved March 2, 2022, from https://www.autosport.com/motogp/news/marquezs-thailand-motogp-crash-analysed-481s-and-a-26g-landing-4987787/4987787/

8. Barnett, C., & Napier, J.C. (1952). *The axis of rotation at the ankle joint in man. Its influence upon the form of the talus and the mobility of the fibula* J Anat, 86. Retrieved June 7, 2022, from https://scholar.google.com/scholar_lookup?title=The%20axis%20of%20rotation%20at%20the%20ankle%20joint%20in%20man.%20Its%20influence%20upon%20the%20form%20of%20the%20talus%20and%20the%20mobility%20of%20the%20fibula&publication_year=1952&author=C.%20Barnett&author=J.%20Napier

9. Bartel, D.L., Davy, D.T., & Keaveny, T.M. (2006) *Orthopeadic Biomechanics P. Pearson Prentice Hall. I*SBN 0130089095

10. Bedolla, J., Santelli, J., Sabra, J., Cabanas, J.G., Ziebell, C., & Olvey, S. (2016). *Elite Motorcycle Racing: Crash Types and Injury Patterns in the MotoGP Class.* American Journal of Emergency Medicine, 34 *(9), 1872-1875.* Retrieved March 2, 2022, from http://www.journals.elsevier.com/american-journal-of-emergency-medicine/ doi: 10.1016/j.ajem.2016.07.005

11. Betterguards. (n.d.). *The BetterGuard.* Retrieved March 2, 2022, from https://betterguards.de/en/products/the-betterguard-sprunggelenkbandage

12. Brockett, C.L., & Chapman, G.J. (2016). *Biomechanics of the ankle,* Orthopaedics and Trauma, 30 *(3)*, 232-238. Retrieved June 7, 2022, from https://www.sciencedirect.com/science/article/pii/S1877132716300483

13. Campillo-Recio, D., Comas-Aguilar, M., *Barrera-Ochoa, S., Caceres-Palou, E.*, Charte, A., & Mir-Bullo, X. (2021). Accidents and injuries in elite MotoGP motorcycle riders. *Journal of clinical orthopaedics and trauma*, 18, 25–29. https://doi.org/10.1016/j.jcot.2021.04.006

14. Catalyst University (2020). *The Subtalar Joint | Anatomy, Basic Movements, & Ligaments.* https://www.youtube.com/watch?v=1FSbEHliTaY

15. Champion Helmets. (2018a). *Dainese Axial D1 & D1 Air Review - ChampionHelmets.com.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=dhoY0BOb8mU

16. Champion Helmets. (2018b). *Dainese Axial D1 Motorlaarzen - ChampionHelmets*.com. [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=Z1ky7mKrcOM

17. Champion Helmets. (2019). *Sidi Rex Laarzen Review - ChampionHelmets.com.* [Video]. Retrieved January 6, 2021, from https://www.youtube.com/watch?v=PbZhcAFzYvI

18. CMG Staff. (2020). *Dainese buys up TCX.* Retrieved October 18, 2021, from https://canadamotoguide.com/2020/10/05/dainese-buys-up-tcx/

19. Count Greffi. (2020a). *SIDI Rex Boots - The King of Protective Motorcycle Boots, Period.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=riXwgw0HIPI

20. Count Greffi. (2020b). *Dainese Axial Pro In Boots - Protection & Mobility to the Max, Crash Tested by Me and Rossi Approved.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=W2dvc3j_MPA&t=1s

21. Count Greffi. (2021). *SIDI Rex Air - The Perforated King of Protective Boots.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=e1uiH1CF9uo

22. Crandall, J., Portier, L., Petit, P., Hall, G., Klopp, G., Bass, C., Hurwitz, S., Trosseille, X., Tarriere, C., Pilkey, W., Lavaste, F., & Lassau, M. (1996). *Biomechanical response and physical properties of the leg, foot, and ankle.* Paper 962424, Society of Automotive Engineering.

23. Crumbie, L. (2022). *Types of joints: Arthrology.* Retrieved June 7, 2022, from https://www.kenhub.com/en/library/anatomy/arthrology

24. Dainese, L. (2002). *WO0221954A1.* European Patent Office.

25. Dainese. (n.d.). *About us.* Retrieved March 2, 2022, from https://www.dainese.com/nl/en/dainese/about-us.html

26. De Wit, K. (2021). *Interview Product Manager MKC Moto.*

27. DemoneRosso: The Dainese Journal. (2021a). *How the knee slider was born, from Kenny Roberts to Kevin Schwantz.* Retrieved October 18, 2021, from https://demonerosso.dainese.com/the-evolution-of-the-knee-slider

28. DemoneRosso: The Dainese Journal. (2021b). *Axial Distortion Control*

System, offering maximum protection and control on track and road for 20 years. Retrieved March 2, 2022, from https://demonerosso.dainese.com/motogp-in-your-boots

29. DemoneRosso: The Dainese Journal. (2022). *Cutting-edge technologies and products, from world championship riders to all enthusiasts.* Retrieved October 18, 2021, from https://demonerosso.dainese.com/you-too-can-buy-motogp-equipment
30. digitaltrends. (2019). *The technologies your car inherited from race cars.* Retrieved March 2, 2022, from https://www.digitaltrends.com/cars/racing-tech-in-your-current-car/
31. Drake, R.L., *Vogl, A.W.*, Mitchell., A.W.M (2015). Gray's Anatomy for Students (third ed.), Churchill Livingstone, Philadelphia. https://scholar.google.com/scholar?q=Grays%20Anatomy%20for%20Students
32. DriveMag Riders. (2020). *2020 Motogp Top Speed Yamahas As Fast As Honda At The Qatar Tests.* Retrieved March 2, 2023, from https://riders.drivemag.com/news/2020-motogp-top-speed-yamaha-s-as-fast-as-honda-at-the-qatar-tests/ trusts.
33. DrivingGeeks. (2022). *What cc Does MotoGP Use?.* Retrieved March 2, 2023, from https://www.drivinggeeks.com/motogp-cc/
34. DuPont. (2017). *KEVLAR® ARAMID FIBER TECHNICAL GUIDE.*Retrieved March 2, 2023, from https://www.dupont.com/content/dam/dupont/amer/us/en/safety/public/documents/en/Kevlar_Technical_Guide_0319.pdf
35. Dutton, M. (n.d.). *The Musculoskeletal System. In: Dutton M. eds. Dutton's Orthopaedic Examination, Evaluation, and Intervention.* (5e) McGraw-Hill. Retrieved June 7, 2022, from https://accessphysiotherapy-mhmedical-com.libaccess.lib.mcmaster.ca/x?bookid=2707&sectionid=224662311
36. Federation Internationale De Motocyclisme. (2021). *FIM WORLD CHAMPIONSHIP GRAND PRIX REGULATIONS 2021.* Retrieved March 2, 2022, from https://www.fim-moto.com/fileadmin/user_upload/Documents/2021/2021_FIM_Grand_Prix_World_Championship_Regulations-updated_4_November.pdf
37. Fictiv. (2023). *Preventing 3D Printing Heat Creep: Solutions and Causes.* Retrieved June 7, 2022, from https://www.fictiv.com/articles/preventing-3d-printing-heat-creep-solutions-and-causes
38. Fong, D.T., *Hong, Y., Chan, L.* Yung, P.S., & Chan, K. (2007). A Systematic Review on Ankle Injury and Ankle Sprain in Sports.
39. Friedrich Paulsen, F., & Waschke, J. (2013). *Sobotta Atlas of Human Anatomy, Vol.1, 15th ed., English; General Anatomy and Musculoskeletal System.* ISBN: 9780702052514
40. Funk, J.R., Srinivasan, S.C.M., Crandall, J.R., Khaewpong, N., Eppinger, R.H., Jaffredo, A.S., Potier, P., & Petit, P.Y. (2002). *The effects of axial preload and dorsiflexion on the tolerance of the ankle/subtalar joint to dynamic inversion and eversion.* Stapp Car Crash J, 46, 245–265.
41. Gamble, T., & Walker, I. (2016). *Wearing a Bicycle Helmet Can Increase Risk Taking and Sensation Seeking in Adults.* Psychological Science, 27(2), 289–294. Retrieved June 7, 2022, from https://doi.org/10.1177/0956797615620784
42. GetGeared. (2017). *Motorcycle Boots: The Ultimate Guide To Buying Motorcycle Boots.* Retrieved March 2, 2022, from https://inspire.getgeared.co.uk/motorcycle-boots-ultimate-guide/
43. Golano, J., Vega, G., de Leeuw, P.A., Malagelada, F., Manzanares, M.C., Gotzens, V., & van Dijk C.N. (2016). *Anatomy of the ankle ligaments: a pictorial essay.* Knee Surg. Sports Traumatol. Arthrosc. 24, 944-956.
44. Goonetilleke, R.S. (2013). *The Science of Footwear.* (1st ed.). CRC Press. ISBN 9781138077843
45. GPone. (2018). *MotoGP, The 'Perfect' Champion: 1.70m Tall and 64 kg.* Retrieved March 2, 2023, from https://www.gpone.com/en/2018/06/26/motogp/the-perfect-champion-1-70m-tall-and-64-kg.html
46. Heijne, K., & Van der Meer, H. *(2019). Road Map for Creative Problem Solving Techniques.* Boom.
47. Hertzberg, H. T. E. (1972). The human buttock in sitting: Pressures, patterns, and palliatives. *American Automobile Transactions, 72*, 39-47. https://doi.org/10.4271/720005
48. Hibbeler, R. C. (2013). *Engineering Mechanics: Dynamics (Thirtheenth Edition).* Singapore: Pearson Prentice Hall. ISBN: 9780132911276.
49. Hicks, J. (1953).*The mechanics of the foot: I.* The joints J Anat, 87 (4), 345. Retrieved June 7, 2022, from https://www.scopus.com/inward/record.url?eid=2-s2.0-0005512099&partnerID=10&rel=R3.0.0
50. Huissteden.nl. (2023). *Gutermann super sterk naaigaren - 000 zwart.* Retrieved June 7, 2022, from https://www.huissteden.nl/gutermann-supersterk-naaigaren-kl-000
51. Jeffers, R. F., Tan, H. B., Nicolopoulos, C., Kamath, R., & Giannoudis, P. V. (2004). Prevalence and patterns of foot injuries following motorcycle trauma. *Journal of orthopaedic trauma*, 18(2), 87–91. https://doi.org/10.1097/00005131-200402000-00005
52. Jessner, W., & Mackinger, T. (2020). *Here's Why Motogp Riders Survive Such High Speed Crashes: Three reasons why riders usually walk away from even the most spectacular crashes.* Retrieved March 2, 2023, from https://www.redbull.com/int-en/theredbulletin/how-to-survive-a-motogp-crash
53. Josh Herrin. (2019). *Pro Racer Explains Proper Foot Positioning! (Track Day Tips #2).* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=b77E4Bl2hD4&list=PLXHb1nVbXUWWIG9BXtiHoudW7PuLYY20r&index=16
54. JUST 4 FUN. (2017). *GEAR SHIFT CHANGE IN MOTO GP LIKE A BOSS.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/_watch?v=HzlocNrlfHw&list=PLXHb1nVbXUWWIG9BXtiHoudW7PuLYY20r&index=12
55. Kawalec, J.S. (2017). *12 - Mechanical testing of foot and ankle implants.* Mechanical Testing of Orthopaedic Implants, Woodhead Publishing, 231-253, Retrieved June 7, 2022, from https://www.sciencedirect.com/science/article/pii/B9780081002865000123
56. KENHUB. (2023). *Main bones of the lower limb.* Retrieved March 2, 2022,

from https://www.kenhub.com/en/study/main-bones-found-on-lower-limb

57. Kjaersgaard-Anderson, P., Wethelund, J.O., Helmig, P., & Soballe, K. (1988). The stabilizing effect of the ligamentous structures in the sinus and canalis tarsi on 18 Leg, Foot, and Ankle Injury Biomechanics movements in the hindfoot. Am J Sports Med 16(5): 512–516.

58. Lee, C. (2001). *The Bone Organ System: Form and Function.* Science Direct. Academic Press, 3–20. doi:10.1016/B978-012470862-4/50002-7

59. Life at Lean. (2018). *Road vs Race Shift: The Differences, and Which is Better?.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=qko4JQlHsCg&list=PLXHb1nVbXUWWlG9BXtiHoudW7PuLYY20r&index=17

60. Lin, M., & Kraus, J.F. (2009). A review of risk factors and patterns of motorcycle injuries. *Accident Analysis & Prevention,* 41(4), 710-722. https://doi.org/10.1016/j.aap.2009.03.010.

61. Lloyd, J. D. (2016). *Biomechanics of Solo Motorcycle Accidents.* Retrieved March 2, 2023, from https://drbiomechanics.com/motorcycle-accident-reconstruction-2/

62. Mazzarolo, G. (2002). *WO02052969A1.* European Patent Office.

63. Mazzarolo, G. (2009). *WO2009028001A1.* European Patent Office.

64. Mazzarolo, G., & Vanin, D. (2014). *WO2014049535A1.* European Patent Office.

65. Mike on Bikes. (2020). *10 Ways MotoGP Racers MASTER the Corners.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=ZyRCFIT5ztA&list=PLXHb1nVbXUWWlG9BXtiHoudW7PuLYY20r&index=14&t=15s

66. MKC Moto. (2019). *Dainese Axial D1 motorschoen review - MotorKledingCenter.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=oavolncOxvI

67. Moore, K.L., Dalley, A.F., Agur, A.M.R. (2014). *Moore Clinically Oriented Anatomy (seventh ed.)*, Lippincott Williams and Wilkins, Philadelphia, PA https://scholar.google.com/scholar_lookup?title=Moore%20Clinically%20Oriented%20Anatomy&publication_year=2014&author=K.L.%20Moore&author=A.F.%20Dalley&author=A.M.R.%20Agur

68. MotoGeo. (2021). *Alpinestars Supertech R Boot Review / @MotoGeo.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=5vSegTcY9Xk

69. MotoGP Podcast. (2020). *Mission Winnow presents: Powering Innovation - Ep3: Defying gravity.* [Podcast]. Retrieved March 2, 2022, from https://open.spotify.com/episode/3Zt6zVHU5R7oSXs0ednPuR?si=5b639d7ffed2456b

70. MotoGP. (2020). *Top 10 Crashes of the Decade.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=pR-bCYGszww&list=PLXHb1nVbXUWWlG9BXtiHoudW7PuLYY20r&index=23&t=5s

71. MotoGP. (2020b). *Motorcycle race suits and more: Tech Talk with Simon Crafar.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=3pHGsQw6R4I&t=477s

72. MotoGP. (2021). *Behind The Stars & Stripes: The Next Generation - S2 E4.* [Video]. Retrieved March 2, 2022, from https://www.motogp.com/en/video_gallery/2021/12/15/behind-the-stars-stripes-season-2/403583?n=403561

73. MotoGP. (2021b). *MotoGP™ Explained: Championship and race weekend format.* [Video]. Retrieved March 2, 2022, from https://www.motogp.com/en/video_gallery/2021/09/06/motogp-explained-series/389802?n=369959

74. MotoGP. (2021b). *MotoGP™ explained: What makes a Grand Prix circuit great?.* [Video]. Retrieved March 2, 2022, from https://www.motogp.com/en/video_gallery/2021/09/06/motogp-explained-series/389802?n=378606

75. MotoGP. (2022a). *Best photos: Moto2™ & Moto3™ Portimao Test.* Retrieved March 2, 2022, from https://www.motogp.com/en/gallery/2022/02/20/best-photos-moto2-moto3-portimao-test/407158

76. MotoGP. (2022b). *Meet the Moto3™ rookies.* Retrieved March 2, 2022, from https://www.youtube.com/watch?v=noSHtIY-zwQ

77. MotoGP. (2022c). *Sepang Test Day 2 - best photos.* Retrieved March 2, 2022, from https://www.motogp.com/en/gallery/2022/02/06/sepang-test-day-2-best-photos/405472

78. MotoGP. (2022d). *Sepang Test Day 1 - best photos.* https://www.motogp.com/en/gallery/2022/02/05/sepang-test-day-1-best-photos/405232

79. MotoGP. (2022e). *Pertamina Grand Prix of Indonesia 2022: Schedule.* Retrieved March 2, 2022, from https://www.motogp.com/en/event/Indonesia#schedule

80. MotoGP. (2022f). *Marc Marquez' MotoGP™ Warm Up Crash | 2022 #IndonesianGP.* [Video]. Retrieved March 2, 2023, from https://www.youtube.com/watch?v=jRyFhZ6Oe3k

81. MotoGP. (n.d.). *Moto3.* Retrieved March 2, 2023, from https://www.motogp.com/en/riders/Moto3

82. MotoGP.com. (2020). *Moto2™ and Moto3™ break Qatar top speed records.* Retrieved March 2, 2023, from https://www.motogp.com/en/news/2020/03/06/moto2-and-moto3-break-qatar-top-speed-records/326795

83. Motorcycle Gear Hub. (n.d.-a). *BEST SPORT MOTORCYCLE BOOTS GUIDE (UPDATED REVIEWS!).* Retrieved March 2, 2022, from https://www.mcgearhub.com/motorcycle-boots/best-sport-riding-boots-guide-updated-reviews/

84. Motorcycle Gear Hub. (n.d.-b). *BEST SUMMER MOTORCYCLE BOOTS GUIDE (UPDATED REVIEWS!).* Retrieved March 2, 2022, from https://www.mcgearhub.com/motorcycle-boots/best-summer-riding-bootsguide-updated-reviews/

85. Motorsport. (2022). *Eerste vrouwelijke wereldkampioen Carrasco terug in Moto3.* Retrieved March 2, 2022, from https://nl.motorsport.com/moto3/news/eerste-vrouwelijke-wereldkampioen-ana-carrasco-terug-moto3/7767043/ https://www.revzilla.com/motorcycle/revit-xena-3-womens-race-suit

86. Nie, B., Forman, J.L., Mait, A.R., Donlon, J., Panzer, M.B., & Kent, R.W. (2017). *Searching for the "sweet spot": the foot rotation and parallel engagement of ankle ligaments in maximising injury tolerance.* Biomech Model Mechanobiol. 16, 1937–1945.

DOI 10.1007/s10237-017-0929-z

87. Orthobullets. (2023). *Ankle Sprain.* Retrieved June 7, 2022, from https://www.orthobullets.com/foot-and-ankle/7028/ankle-sprain

88. OT World. (2022). *Vortrag wiss. Studie/ technischer Beitrag [8453] Abstract [2858].* Downloaded March 2, 2023, from https://www.ot-world.com/files/otworld/congress/102858.pdf

89. Paracord. (2023a). *ITW Nexus Aerohead.* Retrieved June 7, 2022, from https://www.paracord.co.uk/paracord-accessory/cord-end-stoppers/cord-locks/itw-nexus-aerohead

90. Paracord. (2023b). *Cord Lock 20-25 Black.* Retrieved June 7, 2022, from https://www.paracord.co.uk/ https://www.paracord.co.uk/paracord-accessory/cord-end-stoppers/cord-locks/cord-lock-20-25-black

91. Paracord. (2023c). *25 mm Heavey Webbing.* Retrieved June 7, 2022, from https://www.paracord.co.uk/https://www.paracord.co.uk/black-25mm-heavy-webbing

92. Paracord. (2023d). *Imperial Red Paracord Type III.* Retrieved June 7, 2022, from https://www.paracord.co.uk/https://www.paracord.co.uk/paracord/paracord-550/550-solid-colors/original-nylon/imperial-red-paracord-type-iii

93. Parenteau, C.S., & Viano, D.C. (1995). *A New Method to Determine the Biomechanical Properties of Human and Dummy Joints.* Proc. International IRCOBI Conference on the Biomechanics of Impact, 183-196.

94. Patterson, S. (2022). *MotoGP: The 'More Fair' Rule Example Motogp Must Follow.* Retrieved March 2, 2023, from https://the-race.com/motogp/the-more-fair-rule-example-motogp-must-follow/

95. Peek, C., Braver, E.R., Shen, H., & Kraus, J.F. (1994). Lower extremity injuries from motorcycle crashes: A common cause of preventable injury. *Journal of Trauma - Injury, Infection and Critical Care, 37*(3), 358-364. doi:10.1097/00005373-199409000-00004

96. Petit, P., Portier, L., Foret-Bruno, J.Y., Trosseille, X., Parenteau, C., Coltat, J.C., Tarrière, C., & Lassau, J.P. (1996). *Quasistatic characterisation of the human foot-ankle joints in a simulated tensed state and updated accidentological data.* In: Proceedings of the international research council on the biomechanics of impact. Dublin, Ireland, 363–376.

97. Plaude, L. (2022). *Expert meeting textile expert faculty Industrial Design Engineering.*

98. Pramac. (2017). *MotoGp tutorial - Gear, brake, ride!.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=bRj2OBcuQSU&list=PLXHb1nVbXUWWlG9BXtiHoudW7PuLYY20r&index=13

99. Procter, P., & Paul, J.P. (1982). *Ankle Joint Biomechanics.* J. Biomechanics. 15(9), 627-634.

100. Red Bull. (2016). *Incredible MotoGP comebacks.* Retrieved March 2, 2022, from https://www.redbull.com/id-id/incredible-motogp-comebacks

101. RevZilla. (2011). *A Sidi Vortice Boots Review at RevZilla.com.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=MrxVSVI-l9A&t=126s

102. RevZilla. (2015). *Alpinestars Supertech-R Boots Review at RevZilla.* com. [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=iMPPp5GD2jM&t=4s

103. RevZilla. (2017). *TCX RT-Race Pro Boots Review at RevZilla.com.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=hs5QuaoegKI

104. RevZilla. (2018). *Forma Ice Pro Boots Review at RevZilla.com.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=SMkuOCi2LUw

105. RevZilla. (2019a). *Dainese Axial D1 Boots Review.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=Uxjo9RDEyJA

106. RevZilla. (2019b). *SIDI Rex Boots Review.* [Video]. Retrieved January 6, 2021, from https://www.youtube.com/watch?v=OJ8x-WfaPzI

107. RevZilla. (2021). *Alpinestars Supertech R Boots Review.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=NKYJFU_jz4Q&t=4s

108. RevZilla. (2022a). *Alpinestars Supertech R Vented Boots.* Retrieved January 6, 2021, from https://www.revzilla.com/motorcycle/alpinestars-supertech-r-vented-boots

109. RevZilla. (2022b). *Alpinestars Supertech R Boots.* Retrieved January 6, 2021, from https://www.revzilla.com/motorcycle/alpinestars-supertech-r-boots

110. RevZilla. (2022c). *SIDI Rex Air Boots.* Retrieved March 2, 2022, from https://www.revzilla.com/motorcycle/sidi-rex-air-boots

111. RevZilla. (2022d). *SIDI Rex Boots.* Retrieved March 2, 2022, from https://www.revzilla.com/motorcycle/sidi-rex-boots

112. RevZilla. (2022e). *TCX RT-Race Pro Air Boots.* Retrieved March 2, 2022, from https://www.revzilla.com/motorcycle/tcx-rt-race-pro-air-boots

113. RevZilla. (2022f). *Dainese Axial D1 Air Boots.* Retrieved March 2, 2022, from https://www.revzilla.com/motorcycle/dainese-axial-d1-air-boots

114. RevZilla. (2022g). *Forma Ice Pro Flow Boots.* Retrieved March 2, 2022, from https://www.revzilla.com/motorcycle/forma-ice-pro-flow-boots

115. RevZilla. (2022h). *Dainese Axial D1 Boots.* Retrieved March 2, 2022, from https://www.revzilla.com/motorcycle/dainese-axial-d1-boots

116. RevZilla. (2022i). *Forma Ice Pro Boots.* Retrieved March 2, 2022, from https://www.revzilla.com/motorcycle/forma-ice-pro-boots

117. REV'IT! [@revit]. (2022e). *REV'IT!.* [Facebook Page]. Facebook. Retrieved January 6, 2021, from https://www.facebook.com/revit

118. REV'IT! [revit_official]. (2022c). *REV'IT!.* [Instagram page]. Instagram. Retrieved January 6, 2021, https://www.instagram.com/revit_official/

119. REV'IT!. (2014). *Álvaro Bautista: Interview part 2.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=diKMkhO9vic&list=UUICZYvvNxCRgVlz4ofv77Sw&index=72

120. REV'IT!. (2018). *2018 Corporate Presentation.* Downloaded from the personal server of REV'IT!

121. REV'IT!. (2019a). *REV'IT! Personeelsmap.* Retrieved form REV'IT!'s personal server.

122. REV'IT!. (2019b). *REV'IT! Innovation Vision (V5).* Retrieved form REV'IT!'s personal server.

123. REV'IT!. (2021). *REV'IT! Rider Alvaro Bautista.* Retrieved October 18, 2021, from https://www.revitsport.com/nl_nl/blog/wsbk-rijder-alvaro-bautista

124. REV'IT!. (2021a). *Our History.* Retrieved October 18, 2021, from https://www.revitsport.com/us_en/about-revit/history

125. REV'IT!. (2021b). *Behind the brand: The guiding forces behind REV'IT!.* Retrieved October 18, 2021, from https://www.revitsport.com/us_en/about-revit/mission-vision-brand-values

126. REV'IT!. (2021c). *Het Sand 4 H2O Ladies Outfit Overzicht: De Kracht van Geslacht.* Retrieved December 10, 2021, from https://www.revitsport.com/nl_nl/ontdek/ridertype/motorkleding-adventure-travel/vrouwen-motorkleding-sand-4

127. REV'IT!. (2021c). *Our Story: Making big promises yet overdelivering.* https://www.revitsport.com/us_en/about-revit/our-story

128. REV'IT!. (2022). *Homepage.* Retrieved January 6, 2021, from https://www.revitsport.com/nl_nl/

129. REV'IT!. (2022b). *REV'IT!.* [LinkedIn Page]. LinkedIn. Retrieved January 6, 2021, from https://www.linkedin.com/company/rev'it-sport-international/

130. REV'IT!. (2022d). *REV'IT!.* [YouTube Page]. YouTube. Retrieved January 6, 2021, from https://www.youtube.com/user/REVITsport

131. REV'IT!. (2022e). *De Nieuwe Lichting REV'IT! Riders.* Retrieved March 2, 2022, from https://www.revitsport.com/nl_nl/blog/revit-rijders-motogp-wsbk

132. REV'IT!. (n.d.). *REV_IT_Brand_RIDER JOURNEY.* Downloaded from the personal server of REV'IT!

133. Ritomshop. (2023). *Nestelringen goudkleurig gat Ø 5 mm 100 st.* Retrieved June 7, 2022, from https://www.ritomshop.nl/nestelringen/nestelringen-goudkleurig-gat-4.5-mm

134. RSFinch. (2020). *Alpinestars Supertech R black/red/yellow fluo UNBOXING + test ride.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=_cFkLTOWp18

135. Salzar, R.S., *Lievers, W.B.*, Bailey, A.M., & Crandall, J.R. (n.d.). Leg, Foot, and Ankle Injury Biomechanics.

136. Sarrafian, S.K. (1993). *Biomechanics of the subtalar joint complex Clin Orthop Relat Res.* 290,17-26 Retrieved June 7, 2022, from https://www.scopus.com/inward/record.url?eid=2-s2.0-0027280669&partnerID=10&rel=R3.0.0

137. Schamp, M. (2021). *Interview REV'IT! Racing Service Coordinator.*

138. Schroeven-express.nl. (2023a). *Metalen schroeven Zeshoekig hol M4X6 volledige draad klasse 10.9 sleutel van 2.5 Wit verzinkt staal.* Retrieved June 7, 2022, from https://www.schroeven-express.nl/metalen-schroeven-bhc-zeshoekig-hol-volledige-draad-109-zeshoekig-hol/36742-150393-metalen-schroeven-zeshoekig-hol-m4x6-volledige-draad-klasse-109-sleutel-van-25-wit-verzinkt-staal-3663072100039.html#/84-conditionnement-100_eenheden

139. Schroeven-express.nl. (2023a). *Moer binder bolkop split M4/6 6X8 kopdiameter 9 A4 RVS.* Retrieved June 7, 2022, from https://www.schroeven-express.nl/moer-binder-bolkop-split-a4-rvs/27875-115376-moer-binder-bolkop-split-m4-6-6x8-kopdiameter-9-a4-rvs-3663072187511.html#/81-conditionnement-10_eenheden

140. Scott, S. H., & Winter, D. A. (1991). *Talocrural And Talocalcaneal Joint Kinematics And Kinetics During The Stance Phase Of Walking.* J. Biomechanxs. 24(8), 743-752.

141. Sendić, G. (2022). *Ankle Joint.* https://www.kenhub.com/en/library/anatomy/the-ankle-joint

142. Sidi. (n.d.). *LA NOSTRA STORIA.* Retrieved March 2, 2022, from https://www.sidi.com/en/content/16-our-story

143. SidiSport. (2018). *SIDI REX.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=rzrd9DsPzpE

144. Siegler, S., Block, J., & Schneck, C.D. (1988). *The Mechanical Characteristics of the Collateral Ligaments of the Human Ankle Joint.* Retrieved June 7, 2022, from https://sci-hub.se/10.1177/107110078800800502

145. Siegler, S., Chen, J., & Schneck, C. D. (1988). *The Three-Dimensional Kinematics and Flexibility Characteristics of the Human Ankle and Subtalar Joints—Part I: Kinematics.* Journal of Biomechanical Engineering, 110(4), 364. doi:10.1115/1.3108455

146. Silly Side Down. (2017). *Forma Ice Pro Boots Review.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=YyXGSCyaval

147. Simonsen E. B. (2014). *Contributions to the understanding of gait control.* Danish medical journal, 61(4), B4823.

148. Sportbike Track Gear. (2015). *Forma Ice Pro Boot Review from SportbikeTrackGear.*com. [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=wlIJLseGDjA

149. Sportbike Track Gear. (2017). *2017 High End Race and Sport Boot Buying Guide from Sportbiketrackgear.com.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=bsfRxUkQZko&t=1501s

150. Sportbike Track Gear. (2019a). *TCX RT-Race Boots Ride Review | Sportbike Track Gear.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=_BfHzgrLL30

151. Sportbike Track Gear. (2019b). *TCX RT-Race Pro Air Boots Ride Review | Sportbike Track Gear.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=kC0nR-wKYjo

152. Sportbike Track Gear. (2019c). *Alpinestars Supertech R Boots Crash Damage Review | Sportbike Track Gear.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=GxCDgqd4OSY

153. Sportbike Track Gear. (2021). *Alpinestars Supertech R V2 Boot Review | Sportbike Track Gear.* [Video]. Retrieved March 2, 2022, from https://www.youtube.com/watch?v=JzvYRZ1Omrw

154. Tomida, Y., Hirata, H., Fukuda, A., Tsujii, M., Kato, K., Fujisawa, K., &

Uchida, A. (2005). Injuries in elite motorcycle racing in Japan. *British journal of sports medicine. 39*(8). 508-511. DOI:10.1136/bjsm.2004.013722

155. Touwbestellen.nl. *(2023). Dyneema touw Q1 BLACK.* Retrieved June 7, 2022, from https://www.touwbestellen.nl/product/q1-black/

156. Valderrabano, V., Hintermann, B, . Horisberger, B., & Fung, T.S. (2006). *Ligamentous posttraumatic ankle osteoarthritis.* Am J Sports Med, 34, 612-620. Retrieved June 7, 2022, from https://journals.sagepub.com/doi/10.1177/0363546505281813

157. Van Boeijen, A., Daalhuizen, J., Zijlstra, J., & Van der Schoor, R. (2013). *Delft Design Guide.* Amsterdam: BIS Publishers.

158. Van Roon, M. (2021). *Interview REV'IT! senior footwear designer.*

159. Visordown. (2020). *THE DAINESE GROUP HAS ACQUIRED THE TCX BOOT BRAND!.* Retrieved March 2, 2022, from https://www.visordown.com/news/product-news/dainese-group-has-acquired-tcx-boot-brand

160. Wei, F., Post, J.M., Braman, J.E., Meyer, E.G., Powell, J.W. and Haut, R.C. (2012). *Eversion during external rotation of the human cadaver foot produces high ankle sprains.* J. Orthop. Res, 30, 1423-1429. https://doi.org/10.1002/jor.22085

161. Wu, D., Hours, M., Ndiaye, A., Coquillat, A., & Martin, J. (2019). Effectiveness of protective clothing for motorized 2-wheeler riders. *Traffic Injury Prevention, 20*(2), 196-203. doi:10.1080/15389588.2018.1545090

162. Yamaha Racing. (2021). *What is MotoGP?.* Retrieved March 2, 2022, from https://www.yamaha-racing.com/motogp/about/

163. Yoganandan, N., Nahum, A. M., Melvin, J. W. (2015). *Accidental Injury: Biomechanics and Prevention (Third Edition).* Springer. DOI 10.1007/978-1-4939-1732-7

164. Zasa, M., Paolo, S., Polo, R., Pogliacomi, F., Commessatti, M., Ceccarelli, F., & Indelli, P. F. (2016). Epidemiology of injuries in the 2014 MotoGP World Championship: The “Clinica Mobile” experience. *Sports Orthopaedics and Traumatology, 32*(3), 298-294. https://doi.org/10.1016/j.orthtr.2016.05.001.

165. Zhang, Y. (2021). *Computational modelling of biomechanics and biotribology for an artificial ankle joint.* In Woodhead Publishing Series in Biomaterials, Computational Modelling of Biomechanics and Biotribology in the Musculoskeletal System (2), Woodhead Publishing, Pages 499-515. Retrieved June 7, 2022, from https://www.sciencedirect.com/science/article/pii/B9780128195314000195