KSS-BIKE

DEVELOPMENT OF A TRIAL BICYCLE WITH SUSPENSION FOR CROSS-TRAINING MOTORCYCLISTS

Master Graduation Project 2019
Integrated Product Design

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EXECUTIVE SUMMARY

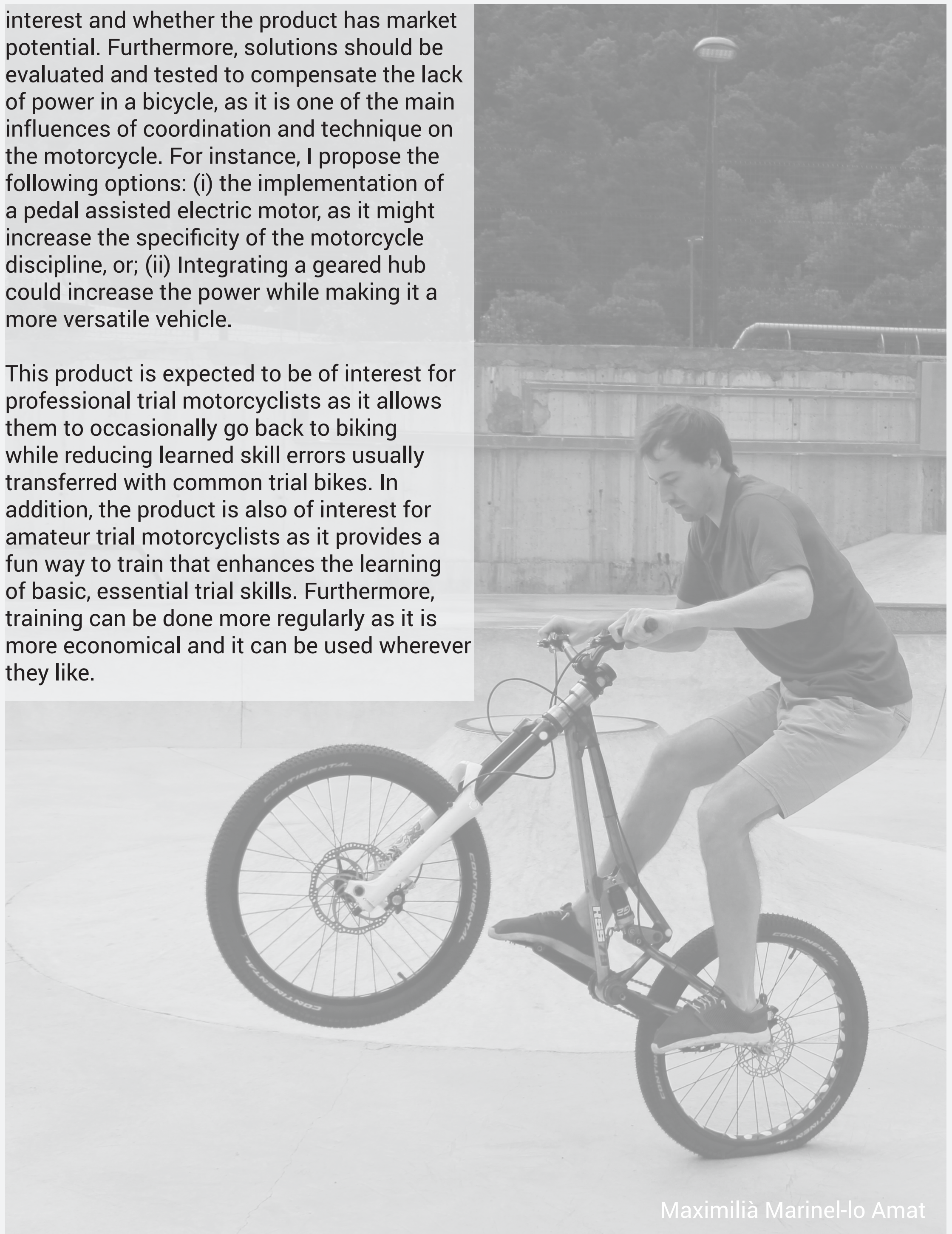
Trials is a subdiscipline of mountain biking that has a small yet passionate community. There are two variants of this sport: one practiced with a specific trials bicycle and one with a trials motorcycle. Though these two disciplines have the same basic requirements, there are clear distinctions in the technical sports gestures that the respective athletes employ. This is due to some fundamental differences in the vehicles used, one critical difference being that the trial motorcycle has a suspension system while the trial bicycle does not. This leads to incompatibility between the sports at a high level as cross-training can cause learned skill errors, where athletes adopt bad habits from practicing the other discipline. This is particularly problematic for trial motorcyclists, as there are various benefits from training with a bicycle, namely: bicycles provide a more complete workout for trial riders, bicycles are easier to maintain, laws restrict the use of motorcycles in certain areas, and the fact that many trial riders begin their trial experiences on a bicycle.

This is the opportunity that Xavi Casas, a professional in both motorcycle and bike trial, has identified and has asked me to help him explore. The research question we aim to answer is: “Will the integration of a suspension system in a trial bicycle allow it to mimic more closely the usability of a motorcycle trial, in order to be suitable for cross-training of trial athletes?”

To answer this question, I employ the Stanford d-school’s Design Thinking approach and various methods from the Delft Design Guide. The first stage involves making a deep-dive into the topic and empathizing with trial athletes from both disciplines and at different competency levels. Next, the empathy findings are applied to establish clear, human-centered needs and insights, and a meaningful challenge is defined: To design a trial bicycle that integrates the main gestural and postural qualities from the trial motorcycle discipline, resulting in a minimum viable product (MVP) which can serve as a point of departure for further development. This is followed by the ideation phase where suspension design possibilities are generated, analyzed, and iterated, to determine the final design characteristics in a design freeze. This design has been further developed and brought into the real world through a functional prototype, created in collaboration with a metal manufacturer specialized in building motorcycle frames (Derivados Del Motor S.L.). Finally, the prototype has been tested by users in the target group and both subjective and objective feedback has been gathered in order to evaluate the MVP and refine the solution.

From the evaluation of the MVP, it can be concluded that when performing an essential trial move, the new design enables sports gestures that are common in the motorcycle trial discipline but not in bicycle trial. This confirms that a trial bike with suspension is more suitable for cross-training motorcyclists than a conventional trial bicycle. Still, the actuation of the suspensions is much more delicate than on the motorcycle, which is presumably due to the lack of stiffness and power that a bicycle has in comparison with a motorcycle. As a result, four suggestions for further development are given based on these new insights. First, more user tests should be conducted with a wider variety of obstacles that require different essential moves, and giving the athlete more time to become acquainted with the product. Second, in-depth marketing research should be carried out to measure customer interest and whether the product has market potential. Furthermore, solutions should be evaluated and tested to compensate the lack of power in a bicycle, as it is one of the main influences of coordination and technique on the motorcycle. For instance, I propose the following options: (i) the implementation of a pedal assisted electric motor, as it might increase the specificity of the motorcycle discipline, or; (ii) Integrating a geared hub could increase the power while making it a more versatile vehicle.

This product is expected to be of interest for professional trial motorcyclists as it allows them to occasionally go back to biking while reducing learned skill errors usually transferred with common trial bikes. In addition, the product is also of interest for amateur trial motorcyclists as it provides a fun way to train that enhances the learning of basic, essential trial skills. Furthermore, training can be done more regularly as it is more economical and it can be used wherever they like.



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01 INTRODUCTION

Agreements made between student, supervisory team and client about the objectives and approach of the project. This includes an overview on the context, research approach, and structure of the report.

The brand Montesa becomes 50 years old (Smith Cota, 1968)

CONTEXT

Trial riding is a sports discipline that has two main variants; it can either be performed by bicycle or by motorcycle (see figure 1). In this sport, the rider attempts to pass through an obstacle course without setting foot to the ground. It is an extreme test of bike handling skills over all kinds of obstacles, both natural and man-made. (Thomas, Miny, Jidovtseff, 2018). Trials currently has a small yet strong interest and is followed worldwide, though it is still primarily a European sport (Tarnas, Wielinski, De la Fuente, Arguelles, 2011).

The discipline performed on a bicycle (Bike Trial) and the one performed on a motorcycle (Motorcycle Trial) are similar in many ways as the main requirements are similar. However, the fact that the sports are conducted with fairly different vehicles, results in the athletes having to perform in relatively different ways.

Results from world championship in bike and motorcycle trial show that the countries dominating both disciplines are generally the same ones. In fact, many of the motorcycle trial riders were initiated in the world of trial with the bicycle. This proves that both sports remain closely related (Tarnas et al., 2011).

It is quite common for athletes who do trials to practice or have practiced both disciplines. This is ideal for beginners, however, it is a common belief among riders that it causes a problem for intermediate and professionals who specialize in one of the two disciplines, as it will cause them to adopt bad habits.

Figure 1. Xavi Casas and Toni Bou face to face, 2007

PROBLEM DEFINITION

Training with a trial bicycle provides a more complete workout for trial riders compared to training with a motor trial (See Appendix C). Hence, trial motorcycle riders often need to complement their training with additional gym exercises, whereas trial bicycle riders do not. Moreover, training by bicycle has additional benefits, such as it being easier to maintain, laws restricting the use of motorcycles in certain areas, and the fact that many trial riders begin their trial experiences on a bicycle (See Appendix C). For these reasons, many trial motorcyclists would like to train with a trial bicycle rather than a trial motorcycle (Trials bicycle for cross-training, 2015). The practice of improving an athlete's performance in one specific sports discipline by training in a (variety of) different sport(s) is called cross-training and is a widely used technique in competitive sports (Tanaka, 1994).

Although the bicycle is a great tool for cross-training athletes, at a high level it evokes learning skills that are acceptable on the bike but erroneous on the motorcycle, according to professional trial rider Xavi Casas (See Appendix C). Although they are both two-wheeled vehicles, there are a number of differences between the trial bike and motorcycle that impact the usability of the vehicle. This results in what is known as a learned skill error. The impact of learned errors in sport is that, despite quality coaching and prolonged training, there is often a poor transfer of learning (Hanin, Hanina, 2009, p.55).

This problem with learned errors in cross-training indicates that there is an opportunity to create a new design in trial bike that is suitable for cross-training while maintaining the benefits of a bicycle. This is the opportunity that Xavi Casas, who has been a professional in trial since 1993 and who has previous experience in setting up businesses in trial bicycles, aims to fill.

Casas approached me to help him with the design of this new hybrid trial bicycle. His vision is to add suspensions to the traditional trial bicycle so that it can be used for cross-training purposes. **Therefore, the research question I aim to answer with this project, is whether the integration of a suspension system in a trial bicycle will allow it to mimic more closely the usability of a motorcycle trial, in order to be suitable for cross-training of trial athletes.**

Until now the main efforts in trial bicycle development have been dedicated to weight reduction (Coxworth, 2013; Patterson, 2014). However, as of yet no one has gone through the process of adding certain elements for motorcycle training purposes. Thus, this research aims to add value by studying the potential of the trial bicycle as a training device that can be used for trial cyclists and motorcyclists alike. This project contributes to the research and development of sports equipment, in particular into the fields of cycling and motorsports.

Hypothesis:
The integration of a suspension on a trial bicycle can transform the usability of the bicycle to mimic that of a trial motorcycle, and so prevent the transfer of learned skill errors.

APPROACH

The process of development is based mainly on the Design Thinking Bootleg of Stanford University's d-school (Doorley, Holcomb, Klebahn, Segovia, & Utley, 2018). The main goal of the project is to test the client's hypothesis and reach a suitable design that is able to solve the problem he has identified, resulting in a working prototype. As the client is an expert in the field and already has a specific problem in mind that he wants to explore, the goal of this project is more focused on solving the problem than on identifying it. Design Thinking proposes a human-centered approach to problem solving, which matches well with the design goal. Furthermore, this approach adds value to this project by emphasizing the importance of prototyping and testing innovations out in the real world. Throughout the five modules of the Design Thinking process (figure 2), a series of proven design procedures are used, which are taken from the Design Thinking Bootleg (Doorely et al., 2018) and the Delft Design Guide (Van Boeijen et al., 2014).

In order to discover the underlying problems the users face, I begin by conducting in-depth research into the Trials discipline. To do this, background research will be performed including an analysis of shape, components and interactions of multiple two wheeled vehicles. Furthermore, interviews with trial riders will be conducted to gain further insights on their perception of both trial disciplines, and to gain a better understanding of their training routine and the fundamental issues they face. The problem will then be defined by focusing on who this solution is designed for and the exact problem that will be tackled.

In order to answer the research question, it will then be determined whether the client's envisioned solution is appropriate. Next, various design options will be explored. An extended study of the integration of suspension systems on a bicycle will be carried out to gain in-depth knowledge of the kinematics, the different types of system and the influence of these on riding experience.

These will then be evaluated and a design freeze will be chosen for the Minimum Viable Product (MVP). In order to make a selection of the most suitable suspension systems, a range of desired kinematic values and a list of other requirements will be generated. Some suspension systems will be further selected and developed into concepts for the final design. Ultimately, only one concept will be chosen (design freeze) to be further developed and built in to a functional prototype for proper testing.

Finally, the prototype will be built in collaboration with a professional motorcycle frame manufacturer. The usability of the prototype will be tested by performing certain essential trial moves with the prototype and video analyzing the performance. This will then be compared with the interaction of a trial bicycle and trial motorcycle performing the same moves to compare whether the usability of the prototype is more similar to a trial motorcycle, as is expected. This video analysis in combination with feedback from trial riders will help determine and evaluate the new design. Video recording is a proven measure to improve technique and evaluate sport gear performance (Hanin, Korjus, Jouste, Baxter, 2013).

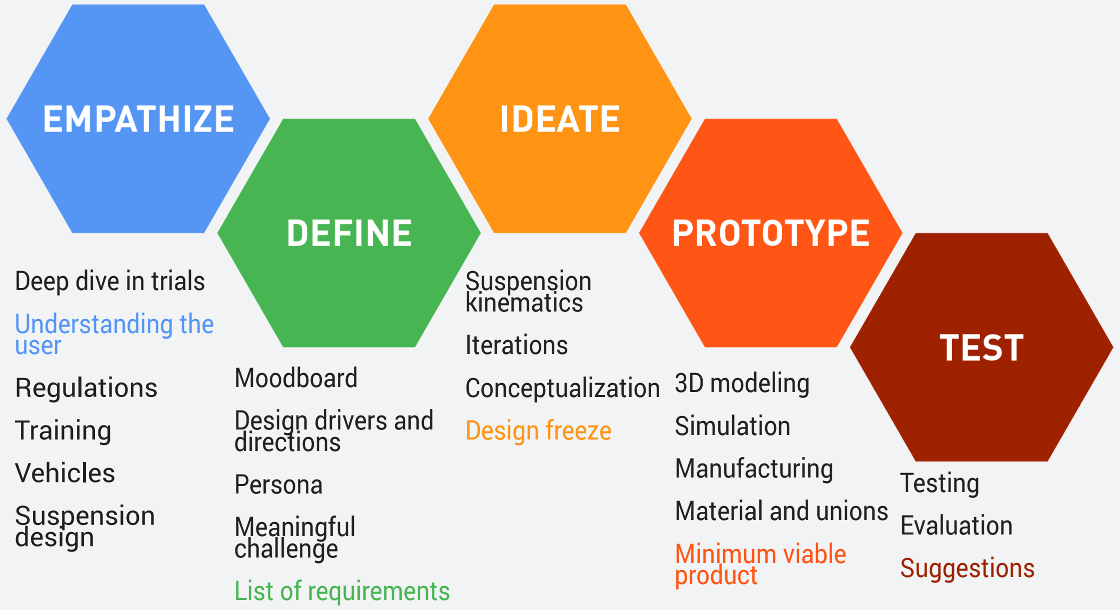


Figure 2. Design Thinking Process of Stanford University's d-school, 2018

02 EMPATHIZE

Deep dive into the design context through observation, engagement, and immersion to detect opportunities, gain useful insights, and empathize with their needs.

Europe's largest Trial-Bike-Park opened in Ainet (Wibmer, 2015)

WHAT IS TRIAL?

Trials is an exhilarating sport as it involves maintaining control over the bike in extreme situations (Figure 3). It is generally practiced individually and the goal is to overcome diverse obstacles within a limited amount of time and without touching the ground with any part of the body (BikeTrial International Union, n.d.). The obstacles can be either natural or artificial and are grouped into tracks. Touching the ground or taking too much time results in penalty points that are accumulated. If a participant makes their way through the section without touching the ground with their foot, they earn a score of 0. The competitor that gets the lowest overall score wins the competition.

Both trial disciplines, the one performed on bicycle and on a motorcycle, have the same or very similar competition rules and the skills required are similar (Tarnas, 2011). Balance, precision, and coordination are essential for a correct performance. However, due to a different interaction of the vehicle, performing a trial move properly with a motorbike requires distinct techniques than if it is done on a bicycle, says professional trial rider Xavi Casas (Appendix C).

Figure 3. Sequence photo indoor, 2017

BICYCLE TRIAL

Bike trials is an officially recognized discipline by the Union Cycliste Internationale (UCI). It is considered to be one of the most technically difficult cycling sports practiced, because it is a problem-solving discipline that requires riders to be astute in the art of anticipation. Supreme balance and exact coordination play an important role (Union Cycliste Internationale, n.d.).

Trial competitions are mainly conducted outdoors using the natural terrain such as rocks and hills. However, it is also quite common to practice indoors or in a more artificial setting where the terrain is built using any sort of structure such as pallets, containers, tubes, etc (BikeTrial International Union, n.d.). In addition to this, it is important to mention the existence of street trial, this is a variant that does not have a specific competition setting. It is used in a more urban environment and the obstacles are performed in a slightly more dynamic way than regular bike trial (Union Cycliste Internationale, n.d.).

Trial is followed worldwide, but it is still mainly an European sport. The countries where it is practiced the most are Spain, France, England, and Germany. This discipline targets mainly young athletes that range in age from 8 to 30 years old and the average age in which athletes achieve best results is at the age of 24 (Tarnas, 2011).

MOTORCYCLE TRIAL

As a trial discipline, motorcycle trial is also about perfection. Like bike trial, it is not based on speed but rather on building up extreme skills in elements such as anticipation, balance, and exact coordination. The regulations of the sport are stated FIM (Fédération Internationale de Motocyclisme).

The sport initiated in Scotland just before 1910 with the use of what were back then conventional motorcycles (Murray, n.d.). It was not until the 1960's that Trials was recognized as a sport and some manufacturers began developing specialized bikes for this activity (Murray, n.d.). Currently, the sport is most popular in the United Kingdom and Spain, though there are participants around the globe (Murray, n.d.). This discipline is practiced by a wide-range of ages, from young up to middle aged athletes participating.

Trial motorcycles are distinct from other sport motorbikes in that they are extremely lightweight, lack seating as they are designed to be ridden standing up, they have strong brakes, and they have suspension travel that is shorter relative to off road motorcycles (What is Motorcycle Trials, n.d.).

USER INSIGHTS

Sports gear is developed with the main focus of providing support to athletes along the practice of a particular discipline. The athlete is the main user and therefore, in order for a product to stand out, it must have some particular distinguishable benefit to them.

In this case, the main users are motorcycle trial riders. To understand the needs and problems these users face, a user research has been performed to gain deeper knowledge about this particular group. The intention of the research consists of understanding the typical career trajectory of motorcycle trial riders, what are their training habits, understand what type of complications they tend to experience, and how they perceive bicycles for training.

In order to engage with the user and gain a deeper understanding of them, methods from the Design Thinking Bootleg (Doorely et al., 2018) have been employed. To begin with, four subjects were interviewed in order to engage with the users. During these interviews, more in-depth knowledge about their interests and struggles were encountered. Furthermore, user observation was carried out to view the behaviour of the user in the context of their daily lives (Doorley et al., 2018).

Figure 4. Trial riders in line at the Arinsal competition, 2019 .

INTERVIEWS

To get to know the target user, interviews were conducted on four trial riders, each with a fairly different involvement in the sport. Two separate groups were interviewed, the first one being amateur motorcycle trial riders, and the second one being professional motorcycle trial riders. Questions where mainly addressed to understand the perception of trial riders in both the bicycle and motorcycle discipline, understand their motivations and training routines, and also encounter any struggle they might experience.

Interviews were conducted individually along a face-to-face or on the phone meeting of approximately 30 minutes. A series of prepared open questions were proposed to the athletes and the responses where voice recorded in spanish or catalan, furthermore these responses where summed up and translated into english on written notes (Find the questionnaire and notes from the interviews in Appendix C).

Intermediate

MARC CATAFAL

25 YEARS OLD

Spanish graphic designer living in the city of Sabadell. Marc has been riding a trial motorcycle since he was 8 years old. He tends to go motorcycling in the weekends and he often attends competitions. Although he did own a trial bike when he was little, Marc´s experience is mostly with the motorcycle.

ERIC GARCIA

22 YEARS OLD

Andorran computer engineering student. Eric started training trials at the age of 13 with a trial bicycle and began attending many spanish competitions at the age of 15. Simultaneously, he also did motorcycle trial. Currently, he only practices motorcycle trial and does so during the summer months.

Professional

XAVI CASAS

40 YEARS OLD

Spanish professional motorcycle trial rider. His greatest achievements are on bike trial with a world cup in 2005 and multiple world records. In his career he has often alternated between bicycle and motorcycle trial, however, nowadays he is training motorcycle trials. He also has entrepreneurial experience developing trial components for bicycles.

JORDI PASCUET

39 YEARS OLD

Spanish professional motorcycle trial rider. He was European champion in 1998 and also participated in the trial world cups for 10 years. Furthermore, he also obtained two Guinness world records. Jordi´s trial career has always been focused on the motorcycle, although he did begin training with a trial bicycle at a very young age.

Discussions

1 Is it beneficial for trial motorcyclists to initiate trial with the bicycle?

All four participants agreed that it is beneficial, mainly for the technique transfer. Jordi Pascuet says most good, young motorcycle riders come from the bike discipline and that is very noticeable as the overall technical level of the sport has truly evolved in the recent years. Furthermore, Casas says that most of the world motorcycle world champions did bicycle trial in the early stages of their career. These statements where supported by Eric Garcia who says “I noticed that it was much easier for me to learn static moves on the motorcycle than for many of my peers, I believe this is due to previous experience on the bicycle”.

2 What are the main distinctions between the practice of bicycle trial and motorcycle trial?

Xavi Casas and Jordi Pascuet agree that the motorbike requires much more coordination as there are more elements to control. According to Casas “It takes many more years of practice to become a good trial rider on the motorbike than on the bicycle because there are more elements to control”. Furthermore, the motor obviously plays an important role as the way both vehicles are powered is very different and “for motorcycle trial riders it is really important to know how to use the inertias", says Pascuet. Eric Garcia explains that "on the bicycle all the efforts to move the bike are made by the rider, whereas on the motorbike it is more of a combination of motor and the rider's moves".

3 Could you describe your training habits?

For this question, there is a noticable difference between the answers given by professional and intermediate trial riders. From the interviews, it has been found that professional riders focus on training mainly sport specific, so they spend most of their time training on the motorcycle. Jordi Pacuet says "the sport is so technical and coordination plays such an important role, that most of the training is directly on the motorcycle. In addition, we usually do some cardio and some weight-lifting". Pascuet and Casas insist that during the preparatory season, they train four to six days per week for about three hours.

Intermediate riders on the other hand say their training is more sporadic, such as on week-ends or whenever they have free time. Marc Catafal says, "I work in the city and whenever I want to ride my trial motorcycle I have to go somewhere far away because in the nearby environments it is forbidden to ride on the motorcycle. Plus, overall it is quite an expensive sport, so I can't train so regularly".

4 During training periods do you avoid using the bicycle?

From the interviews, it seems that for professional motorcycle trial riders it is a big deal to alternate vehicles. They say that your body gets really used and adjusted to one type of ride and that alternating creates confusion. Casas says that "Most professional trial riders don't have a second motorcycle because, even if they are the exact same model, two motorcycles never work exactly the same". Pascuet says that many of the riders he knows started on the bike but that most of them rarely continue to practice both sports. On the other hand, intermediate riders don't think it is a big deal to alternate training on the bike and on the motorcycle.

Insights

01 **Most of the professional motorcycle trial riders are initiated with the bicycle discipline.**

02 **Professional trial motorcyclists avoid using trial bicycles because it generates confusion on their technique. For intermediate riders, alternation between trial bike and motorcycle is not a problem.**

03 **Motorcycle trial requires coordination between many more elements than bicycle trial. For this reason, most of the training for professionals is sport and vehicle specific.**

04 **Intermediate motorcyclist have more difficulties training due to available time, costs, and traffic regulations.**

05 **Trial motorcyclists have difficulties learning basic moves directly on the motorcycle.**

OBSERVATIONS

To gain a deeper understanding of the target user's behavior while performing trials, further research has been conducted. As previously described, trial bicycles do not have suspension systems, whereas trial motorcycles do. Professional trial rider Xavi Casas (Appendix C) believes the absence of a suspension on the trial bicycle is one of the main factors that makes the trial movements on the bike so different from how it is done on a motorcycle.

To proceed with the discovery phase, further research has been conducted on how the front and rear suspension system are used while performing trials on a motorcycle based on observation of online videos. In these videos, skilled motorcycle trial riders perform specific moves, so it can be observed more or less when the suspensions are actuated. Furthermore, the trial training centre of North America provides us with detailed online articles where some essential trial moves are described by professional trial riders.

Observation and analysis are carried out on the three essential trial moves. These consist of a series of manoeuvres used to overpass the many kinds of obstacles a trial rider might encounter. Three main trial essential moves have been identified (Figure 5), which are: (a) jumping gaps, (b) rocking and (c)climbing large obstacles (NonStop off road academy coaching manual, Nelson, 2015).

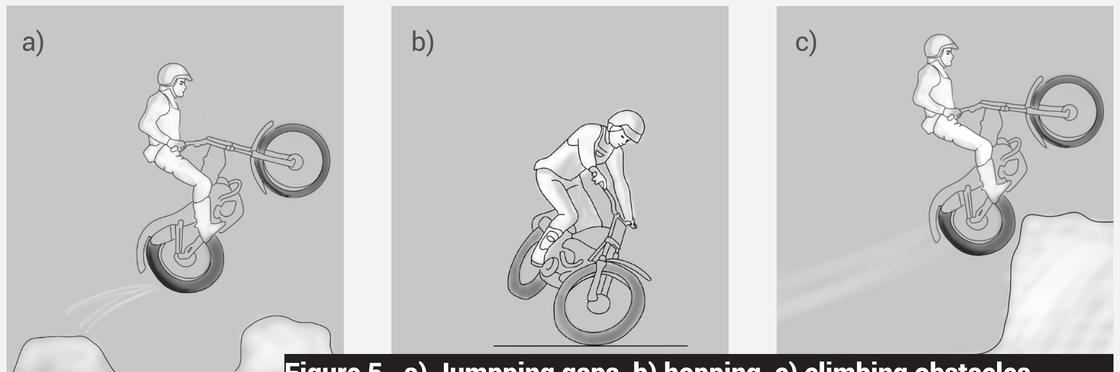


Figure 5. a) Jumpping gaps, b) hopping, c) climbing obstacles

ESSENTIAL MOVES

1 JUMPING GAPS

This move consists of standing statically on the back wheel of the vehicle and jumping from one origin location to a new location, repeatedly if needed (Figure 6). It is an ideal move for jumping long distances with precision (Trials Training Center, 2005). Bruce LeRiche, an instructor from Trials Training Center, says: “The basic idea to the bunny hop over a gap is to use the suspension and clutch along with weight shifts of your body to jump the bike toward a front wheel landing”(Trials Training Center, 2005, para. 2).

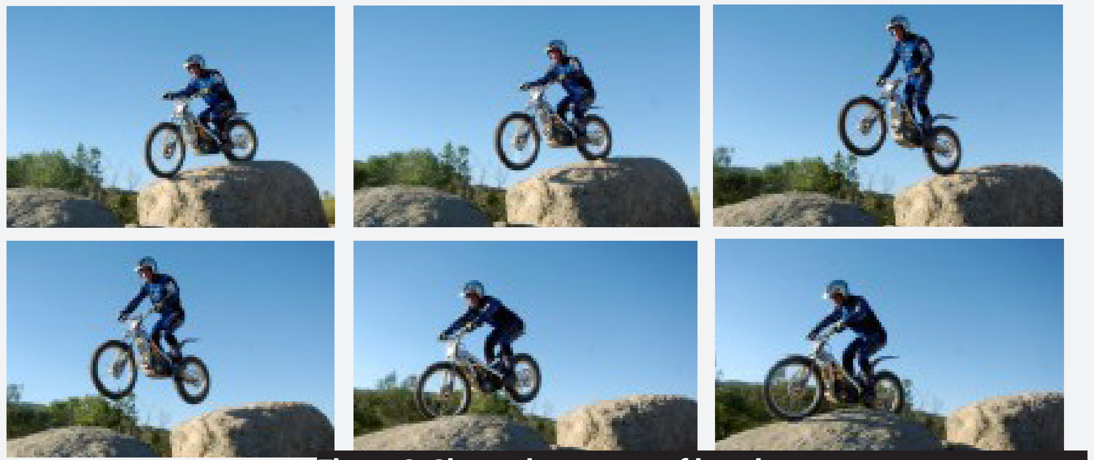


Figure 6. Shows the process of jumping gaps.

2 ROCKING / HOPPING

Rocking consists of pivoting over either the front (Figure 7.b) or rear (Figure 7.a) wheel of the bike for balance and for turning (see Figure 7). It is a move mainly used to position the bike in the best location before performing the next move, and it is essential when moving around tight spaces. This move consists of braking and leaning the body towards the wheel that the rider wants to pivot on, and then lifting the opposite wheel while swinging it towards the selected side (Trial Training Center, 2004a).

Figure 7. Wheel hopping. a) Front wheel b) Rear wheel.

3 CLIMBING OBSTACLES

This move is used to climb larger obstacles, therefore it requires more power than the previous ones. It consists of getting distance from the obstacle and arriving towards it by lifting the front wheel and jumping high to reach the top of the obstacle, preferably with the back wheel. An interesting observation is that when performing this move, motorcyclists try finding a kicker (Figure 8) such as a rock or solid bump, used to help compress the suspension (Trial Training Center, 2004b).

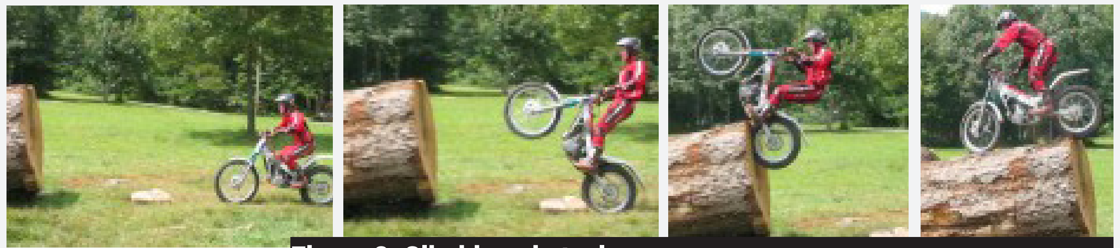


Figure 8. Climbing obstacles.

INFLUENCE OF THE SUSPENSION

It has been observed that, on the motorcycle, coordinating the use of the suspension is a key element while performing any particular move. In the step by step description of the moves provided by the Trial Training Center online tutorials (Trial Training Center, 2004a, 2004b, 2005), it is explained exactly at which point during the move each suspension must be compressed. Furthermore, motorcyclists need to actuate the suspension and then wait for the rebound before performing the next moves, according to CrossTraining Enduro (“Learn to Ride Trials”, 2004). Most riders struggle with the timing when using the suspension and as a consequence the motorcycle does not react the way they expect (“Learn to Ride Trials”, 2004).

The essential moves conducted on the motorcycle have been compared to the same or similar moves performed on the bicycle, through video observation and the support of the descriptions provided by Chris Akrigg in an online article (Dodd, 2009). As expected, the description of these moves does not mention how to coordinate with the suspensions, as trial bicycles do not have suspensions. Furthermore, Eric Garcia (Appendix I) active trial rider in both motorcycle and bicycle trial says that “when performing on the bicycle, the rider is the one that absorbs all the impacts by flexing legs and arms, a trick we use is to not inflate the wheels too hard so they absorb shocks a bit”. Overall, it has been noticed that performing a trial move with the motorcycle requires one additional step than it does with the bicycle.

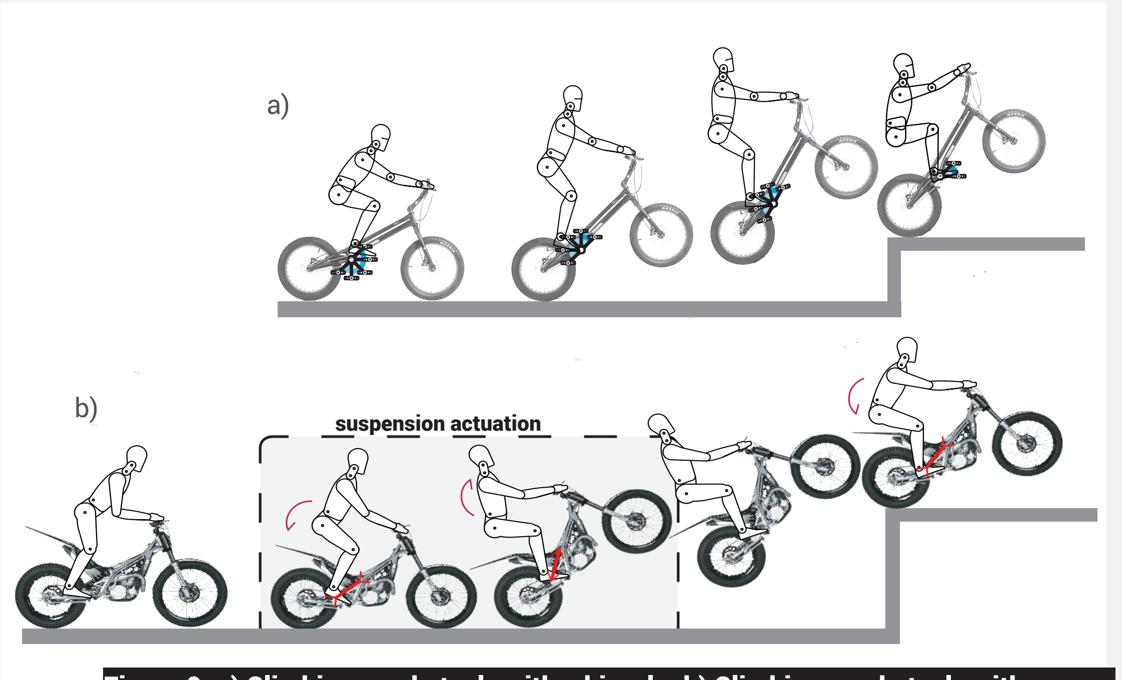


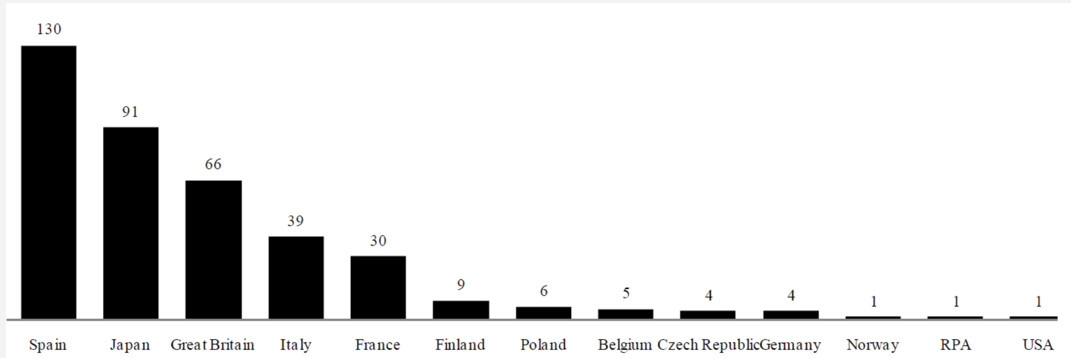
Figure 9. a) Climbing an obstacle with a bicycle. b) Climbing an obstacle with a motorcycle where suspension compression and body gesture are shown in red.

In conclusion, it has become clear that learning to coordinate with the suspension is key when performing moves with a trial motorcycle. Essentially, the riders must learn to compress the suspension and wait for the rebound before proceeding with the next move, as demonstrated by the quotes from LeRiche and various instructional videos and articles. Furthermore, when comparing the same move performed on a motorcycle or a bicycle, it is apparent that doing this move on the motorcycle requires an additional step (Figure 9).

LOCATIONS

Motorcycle trials is a sport recognized worldwide, however it is practiced mainly in Europe. A high level of this sport is mainly encountered in Spain, Japan, Great Britain, Italy, and France (Graph 1). It should be stated that the development and popularity of motorcycling is associated with a few countries, often with trial biking traditions (Tarnas et al., 2011).

From observing results lists of European and international trial competitions (Trial central, 2018) .Results it has been deduced that the age group in which competing in motorcycle trial is most popular ranges from 21 to 38 year old. Furthermore, participation among males is currently much higher than among females. As a conclusion, the population of interest consists of adult European males.



Graph 1. FIM (Fédération Internationale de Motocyclisme) motorcycle trial world championships from 1997 to 2011. Reprinted from Tarnas et al, 2011, p. 303.

ERGONOMICS

ANTHROPOMETRICS

Anthropometric data has been collected from DINED anthropometric database (Molenbroek, 2017). The measurements available that are considered of interest of the human anthropometrics and that can be useful for dimensioning a bicycle are the stature, popliteal height, buttock-knee depth, elbow-grip length, and the sitting height (Figure 10). The percentile used for the study is 50% since there is no major conflict for shorter compared to larger people on the resulting outcome (Appendix D). Furthermore, in order to obtain the average weight of the main trial population an average has been calculated with the use of data collected regarding weight of athletic men in various countries ("Male Body Image and the Average Athlete", n.d.). This has resulted in an average weight to be used of 80kg.

CENTRE OF GRAVITY

For further development on the design, it is of interest to locate the center of gravity of the overall weight of the bicycle and rider on the bike. Whereas on most bicycles the center of gravity is static or has little variation as the rider is sitting in a static position, on a trial bicycle the rider is not sitting down and therefore his center of gravity varies as his body moves (Figure 11). Identifying the location of the center of gravity is useful when developing suspension systems as it provides more accurate kinematic properties.

To track the most extreme locations that the center of gravity may reach, a special set-up has been constructed. A 3D articulated human model in combination with a bicycle is used to track the possible location of the center of gravity (Appendix E). The mannequin weighs 80kg and is 170cm tall,

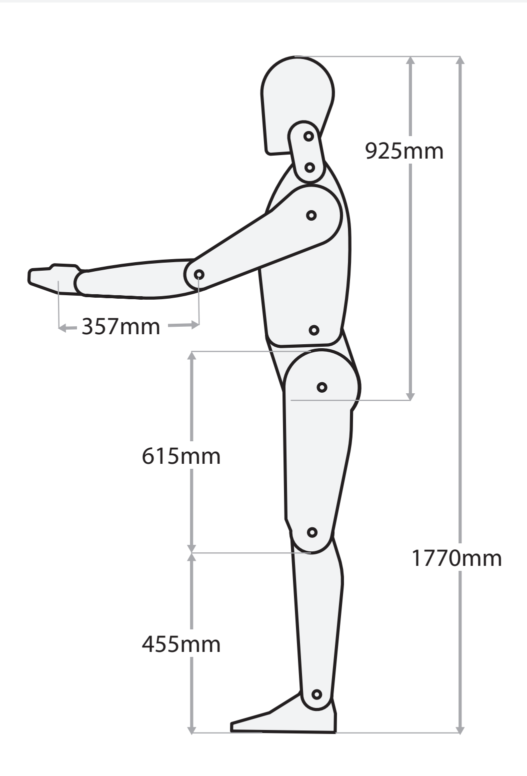


Figure 10. DINED measurements of European adult males applied to a 2D mannequin. Adapted from Link, 2016.

corresponding to the average weight and height of the target group. The length of the relevant parts of the body have been adjusted according to the anthropometrics obtained and the average weight of each body part has been adjusted according to those given in the book "Human Body Dynamics" (Tözeren, 1999). The mannequin has been positioned in various extreme positions which a rider may adapt when performing trial moves.

The measured results are the average and minimum height of the center of gravity from the bottom bracket considering the vertical height of a standing bike with both wheels on the ground. The average height that is most frequently encountered is 520mm over the bottom bracket, and the minimum height is 355mm. These values are of use for weight distribution design and for adequately calibrating the suspension system.

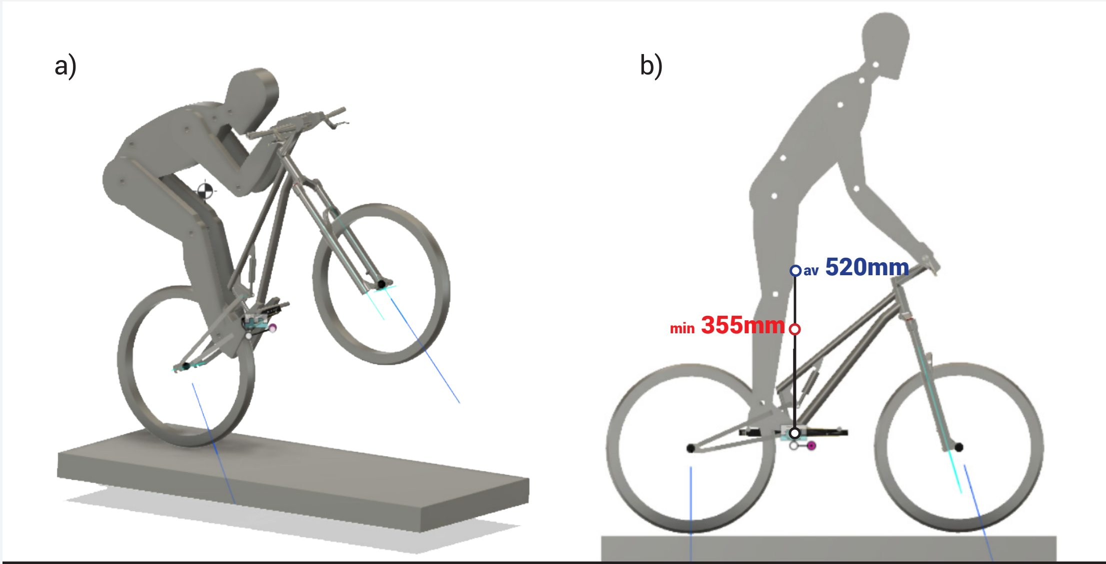


Figure 11. a) Mannequin in 3D used to locate the center of gravity. b) Average and minimum height of the center of gravity. Adapted from Link, 2016.

REGULATIONS AND MAINTENANCE

REGULATIONS

The transit of trial motorcycles is submitted to the limitations given by rules and regulations of each state and country. For instance, most trial motorcycles do not follow the general regulations of traffic required to transit on the roads of countries in the European Union. According to article 10.2 of the General Regulations of Vehicles RD 2822198, vehicles must have a license plate and be submitted to the official periodic vehicle inspection (Código de Tráfico y Seguridad Vial, 2019). Trial motorcycles are usually not prepared to pass the inspection, the first reason is that most of the time they do not have a license plate. Furthermore, they also do not have rearview mirrors, light blinkers, and other obligatory components. The purpose of a trial motorbike is not to be ridden on the road, however, it often might be required to access the trial parkour environments.

Trial motorcycles are mainly meant to be ridden in natural environments, wherever there is some irregular terrain with interesting natural obstacles. However, there are also laws regulating which territories can and can not be accessed by motorbike. For instance, in Spain the Consolidated Legislation states in article 54.2 that motorized vehicles are only allowed to go through wide paths in the forest and shall not go off the path and into the forest with the vehicle (Código de Tráfico y Seguridad Vial, 2019, pp. 24-25). Therefore, the locations where going on the trial motorbike is allowed and where there is suitable terrain for training becomes quite limited.

Figure 12. "Solutions to save the field motorbike", 2015

MAINTENANCE

Trial motorcycles need more maintenance than most other motorcycles as they are constantly submitted to high impacts, caused by jumps and falls (Trialworld, 2019). In addition, they also get dirty during a training journey.

Many maintenance tasks are recommended to be done after every single training journey. Therefore, every trial rider requires a minimum of maintenance expertise and a basic tool kit to carry out these periodic tasks. Mechanics recommend cleaning the air filter of the motorcycle (Figure 13.b) at least once after every two days of riding (Trialworld, 2019). The chain often needs to be oiled and loses tension (Figure 13.a), screws get often lost, etc.

These reparations are simple things motorcyclists should be able to do on their own, however there are many reparations that require expert motorcycle mechanics with the required tools and skills. Trial riders assume this as part of the sport. Josep Garcia, owner of four trial motorcycles, says "my children and I only use the motorbike in the summer holidays, however I have to take all motorbikes to the mechanic at least once or twice each season".

The higher the level of the rider, the more perceptive they are to issues in the performance of the bike. Due to the increased level of difficulty, there is greater impact on the motorbike, therefore the maintenance required increases exponentially. For instance, professional trial rider Xavi Casas claims he has to change the tires and clutch almost every two weeks.

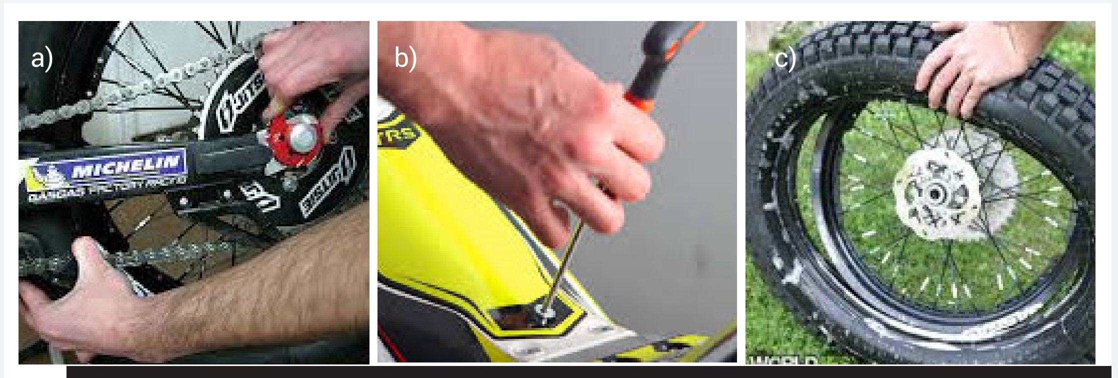


Figure 13. Some of the maintenance procedures that need to be performed regularly.

THEORY OF TRAINING

To better understand the influence of sports gear in trials and how it fits into the routine of a trial rider, it is important to have some basic knowledge of sport education and training theory. Every sport is unique, therefore, athletes focus their training on the specific needs of their sport. However, there are some sport theories that apply to all or most types of athletes and we will see how these apply to trial riders.

Dedicated athletes (either if they are professionals or passionate amateurs) give an orientation to their training based on their personal goals. These goals might be, for instance, winning a specific competition or something more basic such as being able to overcome a specific type of obstacle.

Any advanced athlete that intends to progress and reach their goals should have at least some basic knowledge about the following topics.

FITNESS COMPONENTS

One common misconception in the sports world is that a sports person gets in shape by just taking part in their chosen sport. In reality, an athlete that wants to gain maximum efficiency, must participate in conditioning programs to adapt adequately to all components of fitness (Tancred, 1995).

Nine components have been identified that comprise the definition of fitness (Table 1). These components are: strength, power, agility, balance, flexibility, local muscle endurance, cardiovascular endurance, strength endurance, and the last one that involves them all is coordination (Tancred, 1995; Caspersen, Powell, & Christenson, 1985). Coordination is the ability to integrate the aforementioned components so that effective movements are achieved (Tancred, 1995).

Figure 14. Trial rider planning the season. Reprinted from trialworld, physical training plan to improve on the trial bike (2018).

Trial riding is considered to be particularly a technical sport as difficult moves are conducted at slow speed on a vehicle the sport person must adapt to. Therefore, trials is particularly demanding on anticipation, balance, and coordination (Dodd, 2009). Trial motorcycling requires more coordination than trial biking as there are more elements to control, however it is expected that practicing trial on a bicycle provides more cardiovascular endurance and local muscle endurance. Professional motorcycle rider Jordi Pascuet reveals: "Most of my unspecific sport is dedicated to gain cardiovascular endurance and muscle strength."

CROSS-TRAINING

Cross-training is the practice of engaging in two or more sports or types of exercise in order to improve fitness or performance in one's main sport (Oxford Advanced Learner's Dictionary, n.d.). According to fitness instructor Jessica Matthews, the main benefits of cross-training are: reducing the risk of injury, enhanced weight loss, improving total fitness, enhancing exercise adherence, and learning sport specific skills (Matthews, 2009).

Sport specific skills are voluntary, coordinated tasks with sport-specific goals (Sánchez, n.d.). These skills are gained through practice so that the basic movement patterns can be properly adopted (Bompa & Haff, 2009). Fundamental motor skills "are movements that have specific observable patterns" ("Fundamental Motor Skills and Sports Specific Skills", n.d., para 1). There are three types of fundamental skills: Locomotor skills, such as running and jumping; Manipulative skills, such as throwing and catching, and; Stability skills, such as balance and twisting ("Fundamental Motor Skills and Sports Specific Skills," n.d.). A variety of specific movements that are performed in a coordinated way to meet a goal are also referred to as "sports gestures" or "technical sport gestures" ("Technical Gesture", n.d.; "What is a Technical Sports Gesture", n.d.).

COMPONENTS OF FITNESS		MOTOBIKE	BICICLE
Trial specific	Agility	=	
	Balance	=	
	Coordination	+	
Trial adaptation	Cardiovascular endurance		+
	Local muscle endurance		+
Other general conditioning	Strength		
	Power		
	Flexibility		
	Strength endurance		

Table 1. Fitness component demanded for training in a trials discipline.

Cross-training is used in many sports, mostly for the obvious training benefits it may bring to the athlete, but occasionally it is also used as a substitute when the training conditions of the main sport in practice are not available or inadequate (Bompa & Haff, 2009). For instance, a snowboarder might want to practice his sport in summer when there is no snow on the slopes. An option for this athlete is to practice a similar sport, such as skateboarding or surfing, as the motor skills required have some similarities (“Snowboarding Cross Training”, 2019). In the same way, a motorcycle trial rider is often limited due to the fact that in many places it is forbidden to use a trial motorcycle, therefore they can replace it with some other type of ride.

It is generally agreed that the skills, control, and driving experience acquired from trials are essential for developing the required technical skills for other cycling and motorcycling sports (Thomas, Miny, & Jidovtseff, 2018). Enduro motorcycle rider Jonny Walker says “cross-training with trials is about applying technique that emphasizes balance, traction and throttle/clutch control” (Walker, 2016). Furthermore, there are many online forums with trial motorcyclists asking for advice on what is the best bicycle for cross-training (“Trials Bicycle for Cross-training”, 2015).

TRAINING PERIODIZATION

Periodization is the process of dividing a training plan in specific time phase along a training season, where each phase has a particular goal and provides different types of stress (Bompa & Haff, 2009). This allows the athlete to create some intense training periods and some easier periods to facilitate recovery. Trial is usually performed during the warm seasons. For instance, in the interview with Xavi Casas he explained that in Spain it tends to last about eight months, starting in March and ending in October. As the main goal for trial riders is to achieve good results in a specific tournament, the periodization for trial is built to succeed in this event.

Figure 15. Introduction to cross-training.

A season is composed of three Macrocycles: preparatory, competitive, and transition (Bompa & Haff, 2018). Each of these macrocycles last about 3-6 months and are based on a set of phases, also known as Mesocycles, which last 3-6 weeks. Mesocycles, in turn, consist of Microcycles which typically last around a week and are set, for instance, to empower a certain muscular endurance (SportMedBC, 2019).

During the preparatory phase, athletes mainly train using general strength and conditioning exercises that are not sport specific (SportMedBC, 2019). During this phase trial riders will typically work on incrementing their aerobic resistance, force resistance, maximum force, coordination, and incrementing mobility and flexibility. The competitive phase is focused on sport specific training to get ready for the competitions (Bompa & Haff, 2009). Thus, most of the training during this period is conducted on the motorbike while simulating competition conditions. Finally, the last phase is the transition phase and is used to recover from competition with fun exercises and working the body as a whole, in this phase cross training is recommended (TrialWorld, 2018).

VEHICLE COMPARISON

As previously described, trials is a technical sport where coordination and balance play an important role. The riding abilities of an athlete are for a large part also dependent on the vehicle they are riding.

In this section, a comparison is made between the trial bicycle and the trial motorcycles, and the trial bicycle is compared to other types of bicycles. All these vehicles have in common that they are two wheeled, however, the shape, the construction elements, and the interactions differ between each.

TRIAL VEHICLES

In both bicycle and motorcycle trials, the rider has to overcome obstacles while avoiding to put their feet on the ground, however the performance is quite different depending on the type of vehicle. Let's explore constructively what makes them so different.

INTERACTION OF THE VEHICLE

The main difference between a bicycle and a motorcycle has to do with the power source because this influences all the other parameters. As a result, bicycles are light and easy to manipulate with the use of human strength only, although they have little power to pass over large obstacles. On the other hand, motorbikes are much heavier and every move requires the coordination of many more elements. This makes for a less agile ride but with much more power, so it is easier to overcome larger obstacles.

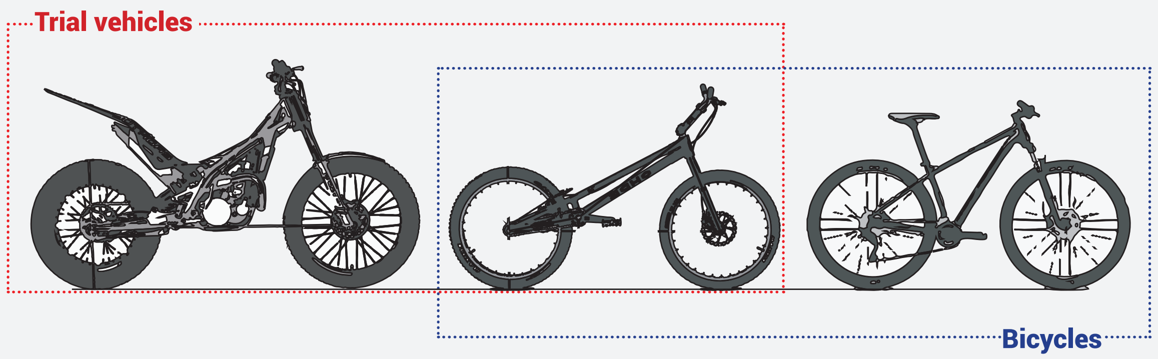
Many of the elements to be controlled are located in different positions on a bicycle compared to a motorcycle. The power in a motorbike is controlled through components located in the handlebar, which are the gas and the clutch. In a bicycle this is totally different, as it is done with the feet through the pedals. In addition, the brakes are also slightly different in the two vehicles and are activated with different actuators. Furthermore, the motorcycle usually has up to five gears (although when doing trials generally only three of them are used), while the bicycle runs on a single speed.

Furthermore, technical steps taken with these sports involve pivoting and jumping with the wheels, often while being static with the use of power and muscles from arms and legs. Whereas, trial bicycles have a stiff reaction to the ground as they have no suspension, trial motorcycles have a more bouncy effect.

CUSTOMISATION OF THE RIDE

It should be taken into consideration that there are certain modifications that can be implemented on a bicycle or a motorcycle so that the rider can adjust the vehicle to their riding style and physical ability. Regarding the bicycle, there are three standard frame dimensions which are based on the use of three different sizes of wheels. The sizes are 20", 26" and 24" which refer to the diameter of the wheel (Vastola, Coppola, Albano, Daniele, Elia, 2017). The athlete's height is not necessarily the most important factor to select the dimension of the bicycle, because there is no saddle and the steam's length can be chosen accordingly, so the frame's dimension becomes less relevant (Vastola et al., 2017).

In the case of the trials motorbike, the frames are a standard size so all bikes have more or less the same size. However, the rider can adjust his vehicle by selecting the engine capacity. Standard capacities usually range from 125cc and the largest ones are usually between 250 and 300cc (Fédération internationale de Motocyclisme, 2019). Most adults aim for the largest range. In addition to this there are two types of combustion motors used in trial that behave differently: two stroke and four stroke motors. There is also a newer category in Trials (since 2019) that competes separately from conventional trials, this is the category of electric trial motorcycles.



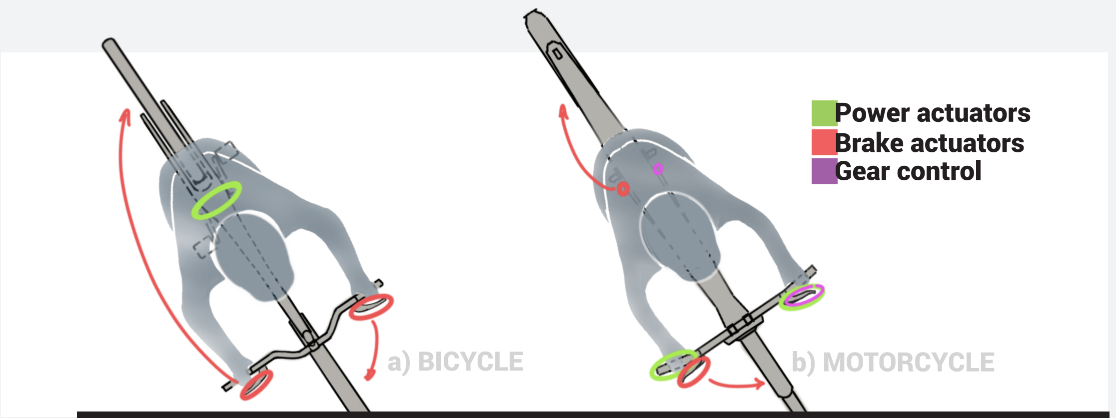


Figure 16. Location of controllers on a) bicycle compared to b) Motorcycle (top view)

	Bicycle	Motorcycle
Power source	Human powered	Combustion engines
Weight	8/12kg	62/70kg
Suspension	None	Front and back
Gears	Single gear	Five gears
Customization	Wheel dimension 20″ 24″ 26″	Engine type and Capacity 125cc, 250cc, 300cc

Table 2. Characteristics of each vehicle.

BASE POSTURE
A characteristic from the motorbike that could be of interest to implement on a trial bicycle is the "reach". The reach is the distance from where the rider stands (on the foot peg for the motorcyclists or the bottom bracket as an intermediate point for the cyclists) to where he holds himself from (the handle bar). Therefore, this should be taken into consideration when designing a trials bicycle that is suitable for cross-training, so that the posture that the rider adopts resembles more closely to that of a trial motorcyclist.

The difference between the reach of a bicycle compared to that of a motorcycle (Figure 17), is that it is larger in horizontal direction on the bicycle, while on the motorcycle it is taller in the vertical direction. This results in the rider standing more upright on a motorcycle.
This implementation can be of interest because then the whole body coordination and position as it is on a motorcycle can be integrated into the new design. The technical sport gestures of the body will be included as an influence of integrating suspension, and the body posture as an influence of modifying the reach. It is to be seen, to what extent the other, non-included parameters will influence the gestures and posture of the rider.

CONCLUSIONS
The main elements that should be integrated in a cross-training bicycle are suspensions in the front and the back, as it has a large influence on the performance of trial moves (page. 26). Furthermore, as agreed by Xavi Casas and Jordi Pascuet (professional motorcyclists), the main difference between the bicycle and the motorcycle are the inertias. Inertias are caused by the power and, as a motorcycle is clearly much more powerful, the inertias are more abrupt. However, by implementing a motor in a bicycle, it would no longer be a bicycle, so this defeats the purpose of the project. Fortunately, there are interesting alternatives to investigate in the bicycle development, such as electric batteries that could evoke an intermediate relation of power and inertias of the sport. The same applies to interaction with brakes and gears: alternatives can be searched in the bike

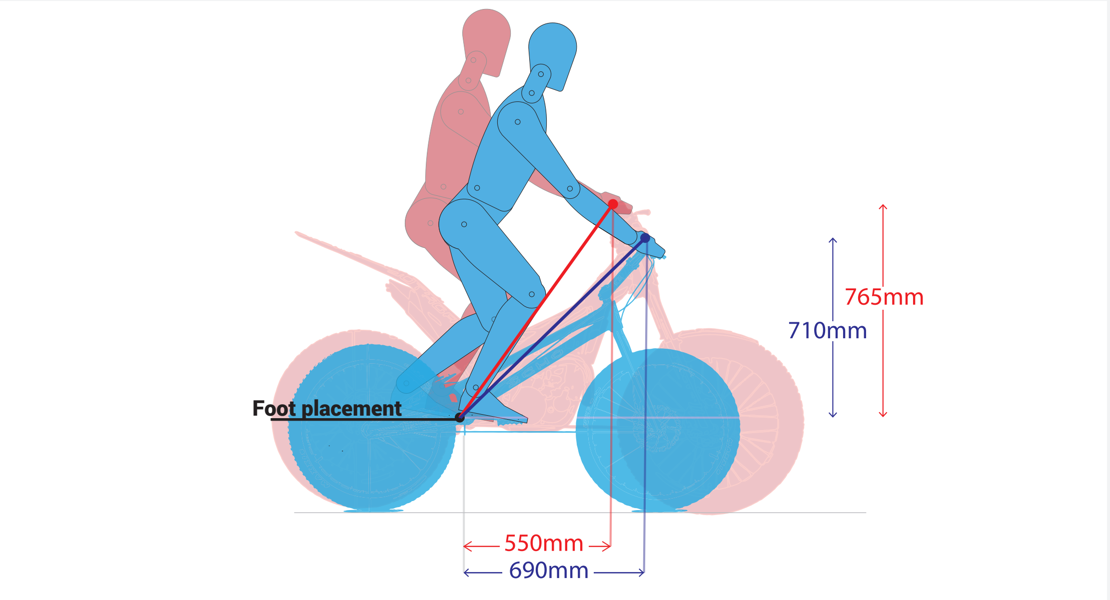


Figure 17. Reach on a bicycle compared to reach on a motorcycle and its influence on the posture

component market, however their influence is less important when training specifics.

Regarding the posture, it is best to aim for a frame size of 24 inch wheels for two reasons. Firstly, it is the size that resembles more to that of the motorbike in regards to posture. Additionally, the bigger the wheel, the harder it becomes to perform specific trial moves and so a bike of 26 inch with suspensions would be very hard to manoeuvre. Furthermore, the shape of the bike frame should be modified to have a reach that is more similar to that of the motorcycle.

It is expected that by integrating these aspects, the body coordination and position as it is on a motorcycle would be integrated into the new design. The technical sport gestures of the body would be included as an influence for integrating the suspension, and the body posture as an influence for modifying the reach.

BICYCLES

Bicycles are known to be a simple, affordable, and sustainable means of transport (Biofriendly planet, 2018). In the recent decades bicycles have evolved into a wide range of cycling sports, such as road bicycle racing, mountain biking, BMX freestyle, trial bike, and many others (Union Cycliste Internationale, n.d.). Although all bikes are composed of two wheels, pedals, a frame, and a handlebar, each discipline has its own requirements. As a result bikes have different shapes and components depending on the discipline they are made for. Bicycle components and parts are annotated in appendix B.

PERFORMANCE USAGE

In this section the usage of trial bicycling is compared with the common usage of bicycles where the main purpose is transportation (such as road bicycles, mountain bikes, city bicycles...). It has been observed that whereas the mountain bikes are mainly designed to be used standing over both wheels, the trial bicycle is designed to also be used standing over only the rear wheel as many essential trial moves require the rider to assume this position (Dodd, 2009). In addition, on a trial bike, the rider's mobility must be extensive as the cyclists rides slow and will need to balance, manoeuvre, and make explosive movements that involve the whole body. For this reason, there is no seat on a trial bicycle.

Regarding components, it is observed that trial bicycles generally have stronger brakes, a wider handlebar for more balance, one single speed for maximum pedal sensitivity, and no saddle so the rider can fully move their body. As a result of having no seat and having bottom bracket rise (geometry aspect), the frame ends up being very thin. Also, trial bicycles have usually smaller wheels than bicycles as this has an influence on the weight of the vehicle and the momentum efforts when manoeuvring on the bicycle (Bike Trials Geometry Guide, n.d.).

GEOMETRY

A geometry comparison has been conducted to identify the peculiarities of a trial bicycle frame compared with other bicycles (Table 3). The comparison has been performed by measuring the dimensions of five conventional and five trial bicycles with the use of AutoCAD, a 2D digital drawing software (this can be found in Appendix F). Figure 18 and Table 3 show an average range of measurements for both disciplines. The measures taken are the base frame geometry aspects (Denham, 2013).

Regarding the geometry aspects, trial bicycles are distinguished in the fact that they have a large wheel base, as it provides a more stable platform on which to balance. In addition, they have a pedal box located a few centimetres higher than the wheel axles since this provides more stability when balancing on the rear wheel. This is a special distinction of trial bicycles, as bicycles from other disciplines have the pedal box lower than the wheel axles. Furthermore, they have a short chainstay length so that it is easier to balance on the rear wheel, and a reach distance which is lower but further away than in other bicycles ("Bike Trials Geometry Guide", n.d.).

DIMENSIONS		Trial bike	Normal bike
A	Wheel base	1042mm	1046mm
B	Reach		
BH	Reach horizontal	505mm	354mm
BV	Reach vertical	430mm	580mm
C	Boottom bracket height	-45mm	48mm
D	Chain stay	360mm	428mm
E	Head tube	71 °	66 °

Table 3 . Average geometry dimensions of a trial bicycle frame in contrast with a more conventional bicycle.

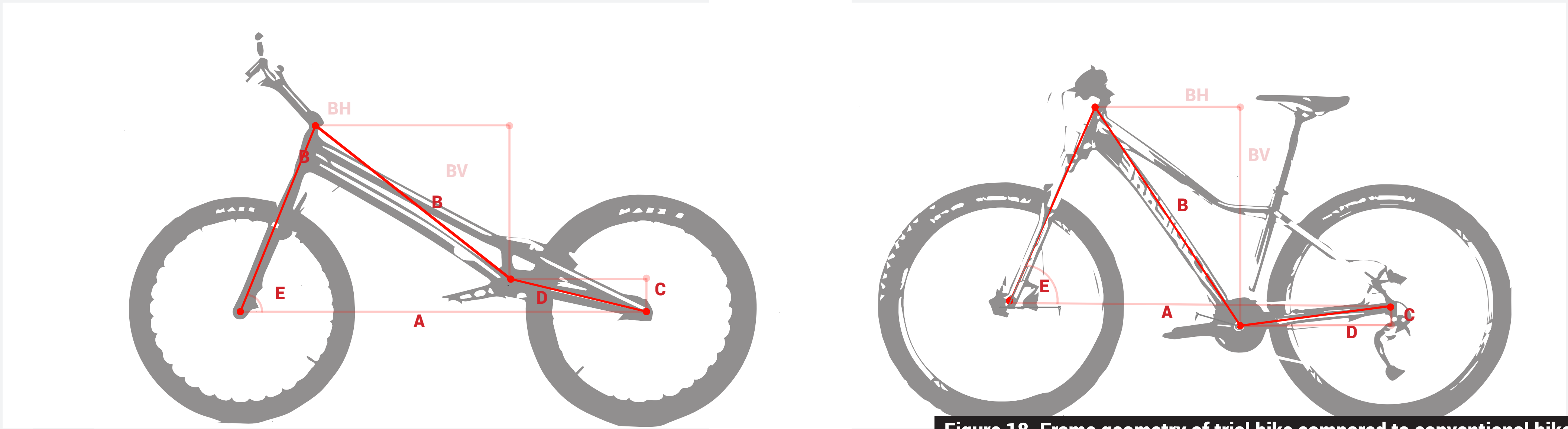


Figure 18. Frame geometry of trial bike compared to conventional bike (see average measurements in Table 3).

BICYCLE INNOVATION

In the bicycle industry, many advances have been developed that are interesting to take into account as they can serve to improve the performance of the bike, reduce maintenance, or even just reduce the amount of components.

Some of these developments could prove to be interesting for the new design because they might offer innovative solutions to help minimize the differences between trial bicycles and motorcycles as previously described (pg.36-38) that prevent the possibility of cross-training. These interaction aspects have to do with the power that propels the vehicle, the gear transmission setup, and the interaction with brake controllers.
Therefore, an overview of the innovations and trends in the domain of bicycles is presented below.

Electric bicycles

There has been a hype with the development of electric bicycles in the recent few years (Oortwijn, 2019). These are bicycles with an integrated electric motor which can be used for propulsion. Many types of setup for these bikes are available, from bikes that only have a small motor to assist the rider's pedal-power, to a throttle system where the vehicle does not require pedalling to be propelled. These systems are composed of an electric battery, an electric motor, and a torque sensor ("How Do Electric Bikes Work?", n.d.).

There are two main types of electric bike systems that are determined by the location of the motor ("Electric Bicycle Types Explained", 2018). On the one hand, there are the hub motors (figure 19.a), these are the most simple as they are placed on the hub of either the front or the rear wheel. They are used to convert conventional bikes, however, they create an uneven distribution of weight ("Electric Bicycle Types Explained", 2018). On the other hand, there is the mid-drive motor (figure 19.b). The motor is placed in the center of the bike frame and integrates it with the bottom bracket and cranks. This option offers many design benefits over a hub motor, making it the system of choice for most pedal assist production bikes ("Electric Bicycle Types Explained", 2018).

Geared hubs

While the derailleur and cassette still dominate today's bike market, there has been consistent advancement in internal gear hub technology (Figure 20.a). Once limited to three gears, internally geared hubs are now offered in 8, 11, and 14 speed

Figure 19. Electric bicycle systems. a)Hub motor , b) mid-drive motor.

models ("Why Use an Internal Gear Hub?", 2011). There are two advantages to these systems. First, they offer reliability as all the moving parts responsible for shifting are completely contained in a sealed unit, the hub, which also makes them easier to maintain as the main thing you need to do is keep the proper tension on your chain and lubricate it periodically ("Why Use an Internal Gear Hub?", 2011). In addition, since a chain on an internal hub is always in a straight line and does not have multiple gear wheels and pulleys to pass over, it also causes less wear and tear. Secondly, shifting gears can be done while standing still, so you no longer have to be pedalling while shifting ("Why Use an Internal Gear Hub?", 2011).

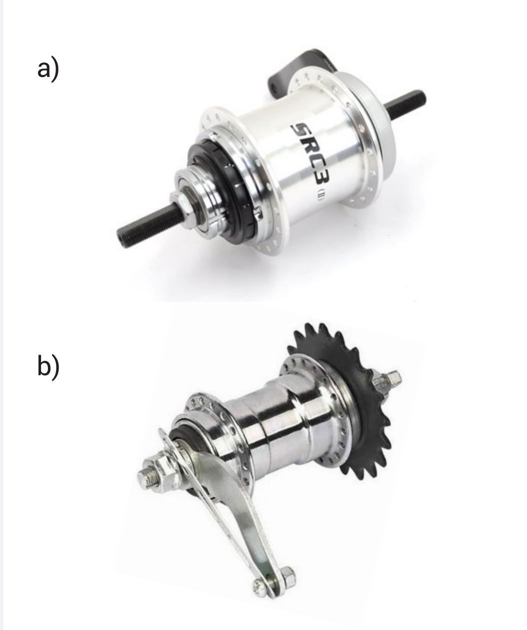


Figure 20. a) Geared hub, b) Coaster brake.

Coaster brake

The coaster is combined with a hub gear on the back wheel (Figure 20.b). The braking action is conducted by the cyclists by pedalling backwards. This operation can be a bit insensitive, with a lack of feel, and the starting position is often a bit awkward since there is no easy way to rotate the pedals to a starting position (Brown, 2008).

CONCLUSIONS

The main geometrical aspects of a trial bicycle frame should be maintained as these help make trial bikes as manoeuvrable as they are. These include a bottom bracket that should be from 0 to 12mm higher than the rear wheel axle, a chain-stay with a length of 360 to 400mm, and a head angle of 71 or 72° ("Bike Trials Geometry Guide", n.d.).

Furthermore, regarding the innovative bicycle integrated systems, electric motors could be of interest as the main difference between the trial bicycle and motorbike is the power, which has consequences in control over the inertias. Although these systems could help mimic a bit closer the

motorcycle. Integrating a geared hub could be of interest as it reduces the pedalling efficiency problems usually caused with derailleurs and cassettes since the chain is always tensioned ("Why Use an Internal Gear Hub?", 2011). Usually, trial bikes are single speed, however having multiple speeds could make it more functional and contribute to resistance training. According to Jordi Pascuet (Appendix C) motorcyclists mainly train specific, however they should also do some weight lifting and cardiovascular resistance training. Ultimately, the back pedalling brake is not of interest. The reason for this is that, in trial biking, the pedalling actions consist mainly of pedal kicking and rear pedalling, so this would just make the practice impossible.

SUSPENSION DESIGN

Trial bicycling is a subcategory of the wider bicycle discipline mountain biking. Mountain bikes have started integrating suspension systems in the early 90's and these systems have improved a lot ever since (Fuss, Subic, Strangwood & Mehta, 2016), however this has never been done on a trial bicycle. Suspension systems let the wheels move up and down to absorb bumps while keeping the tires in contact with the ground for better control, and it also helps the rider absorb large shocks when landing jumps (Pasteris, 2018). The nomenclature of bicycle components and parts are annotated in appendix B.

Common suspension technology for bikes include telescoping front forks with up to 200(mm) of travel, combined with rigid or pivot/linkage-based rear suspensions with similar amounts of travel (Fuss et al., 2016). Cross-country riding or racing (on relatively smooth trails) requires low weight and relatively little suspension travel (often front only) of perhaps 100-120mm (Figure 21). Longer ranges of travel are mostly relegated to downhill riders and racers (Figure 21), where trails are rough and obstacles severe (Fuss et al., 2016).

FRAME CONFIGURATION

The heart of the fully suspended mountain bike is the mechanical connection between the front and rear structures of the frame (front triangle and rear triangle). Bicycle suspension mainly consist of a kinematic chain constructed with a set of bars with pin revolute joints. The movements and forces that control the displacement from the drive train, are guided with the use of a shock. The shock consists of an elastic (spring) and viscous (damper) component mounted in parallel between the wheel drivetrain and the front frame (Nielsens & Lejeune, 2004).

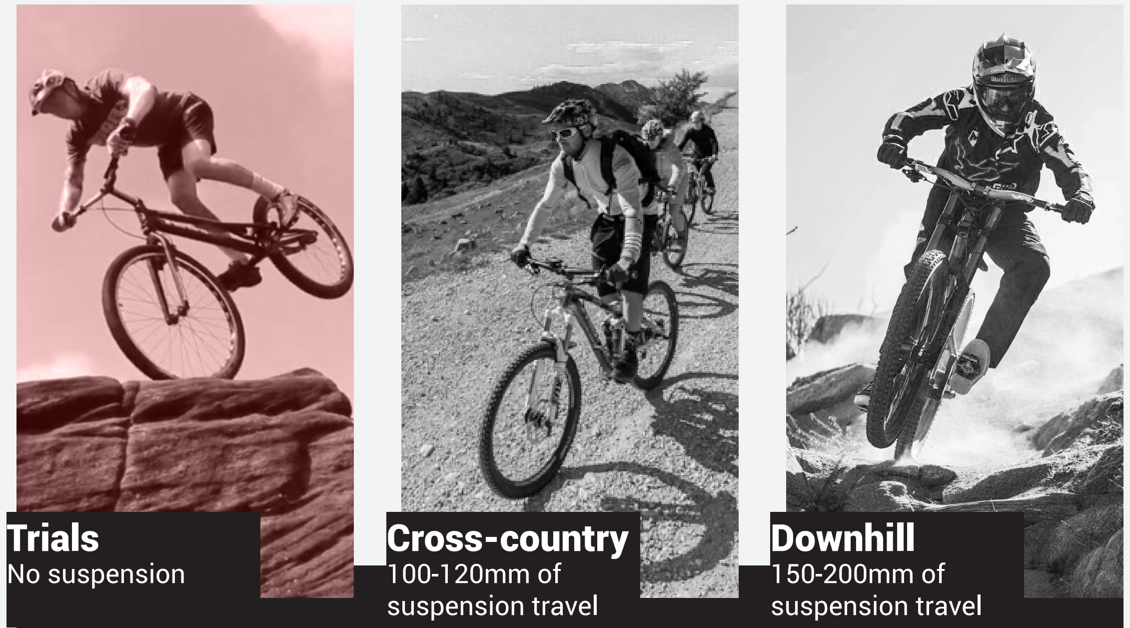


Figure 21. Mountain bikes and their suspension distinctiveness.

The simplest form of suspension design is the single-pivot (figure 22.a). The rear wheel is attached to the 'rear triangle' which rotates around a pivot attached to the front triangle of the frame, and its range of motion is controlled with a shock linkage (Stott, 2018). The wheel axle path is therefore an arc with the center at the pivot point. Other than the single pivot system, most suspension systems are generally composed of a four bar mechanism (figure 22.b). Four bar mechanisms make it easier to adjust kinematic parameters to the requirements of a specific riding style. Four bar mechanisms are formed with a fixed length, a pivoting joint attached to the front frame, a moving length and a rocker arm that actuates as a ternary link by connecting the front frame to the shock and the moving length of the quadrilateral (Scullion, 2018).

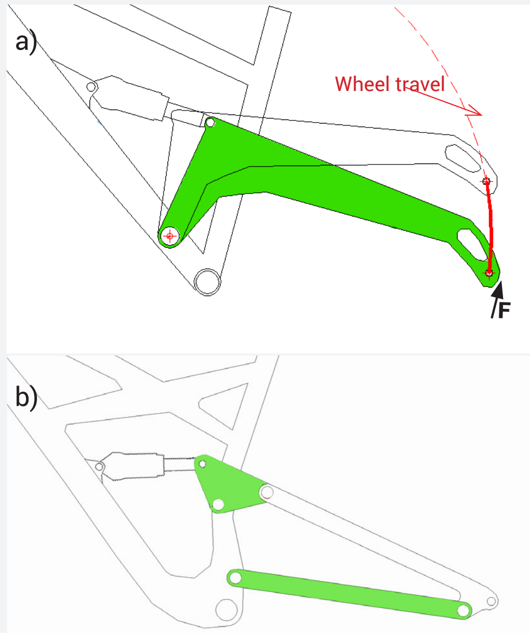


Figure 22. Form of suspension design a) Single pivot. b) Linkage

FORKS AND SHOCKS

Controlling the response of the bike to external inputs, are the front fork and rear shock (Figure 23). Forks are composed of two legs of inner and outer telescoping sleeves, creating linear, relative motion (Fuss et al., 2016). The inner sleeves move inside the sliders on bushings.

A compliance element and a damping (energy dissipation) assembly are housed separately in each fork leg. Compliant elements can be steel or titanium coil springs, elastomer or air springs (piston/cylinder), with air spring being by far the most prominent (Fuss et al., 2016). Air springs can be user charged to an appropriate pressure (around 7kPa). Separate control of both low- and high-speed rebound and compression damping is common in current high performance forks (Fuss et al., 2016).

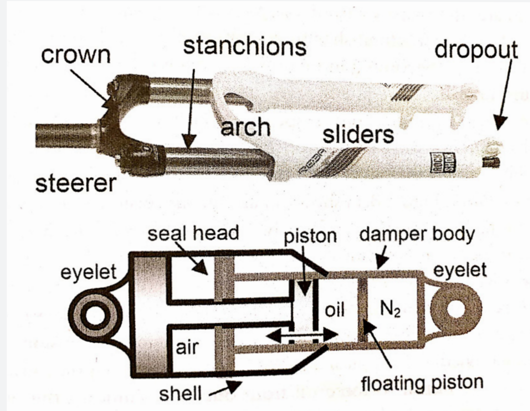
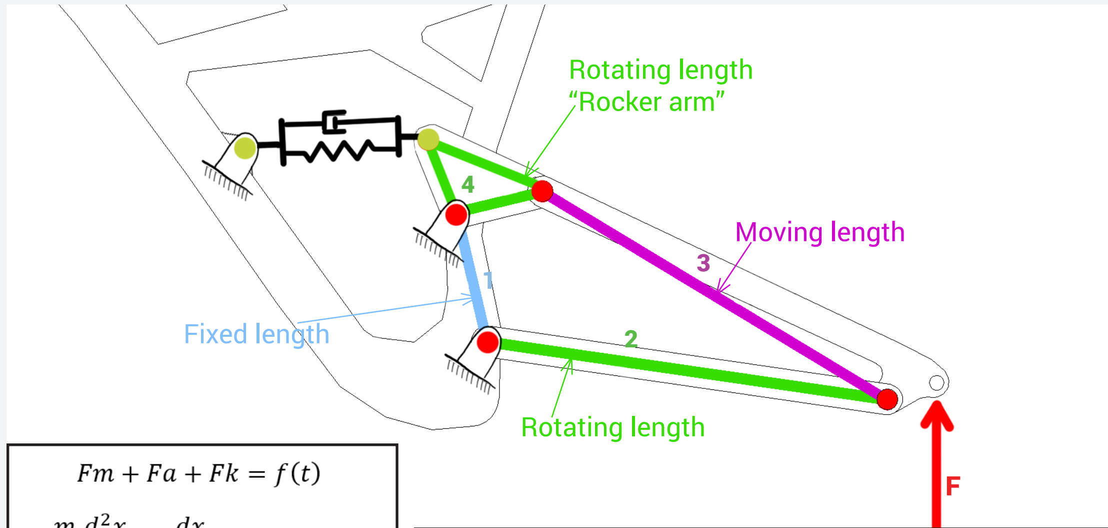


Figure 23. Schematic representation of fork and a rear shock.

Rear shocks have nearly the same features as a fork but in a much smaller package. Shocks operate with leverage ratios. The ratio of rear wheel vertical travel to shock compression are two or three to one, which means that the forces are much higher than in a fork (Fuss et al., 2016).

MECHANICS OF A LINKAGE

The quadrilateral of a bicycle suspension is a mechanism with only one degree of freedom with one of the links considered to be the fixed ground (in this case the front triangle of the frame), and all the joints that compose the mechanism are pins. The range of travel and force requirement of the quadrilateral is controlled with a spring-mass-damper system, connected in parallel (Scullion, 2018). The spring-mass-damper system is attached to the rotating link



$$Fm + Fa + Fk = f(t)$$

$$\frac{m}{gc}\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx = f(t)$$

Figure 24. Symbolic description of the mechanism.

and to the ground with two pin joints. The mechanism is actuated with a force applied to the wheel axle (Scullion, 2018). This force is the result from the weight of the bicycle rider, and the pressure applied on the wheel when there is a change on the terrain.

The spring-mass-damper system consists of a direct force (N) a spring with stiffness (k) and a shock absorber with a damping coefficient of (c) (Edwards, 2001). Combining those terms into a torque balance describes the shock motion as a function of position, velocity, and acceleration.

Linkage design allows a non-circular rear wheel path relative to the main frame, which results in a changing instant centre of

rotation (see figure 24). This greatly affects the dynamics of acceleration and braking (Fuss et al., 2016).

The trajectory of the rear wheel depends on where its axle is located on the rear triangle (see figure 25) (Fuss et al., 2016). If the wheel axle is located on the rotating length (chain stay), the trajectory will be circular just like on a single pivot system. In order for the wheel axle to move in a non circular trajectory, this must be placed on the moving length and its motion is described by an instant centre of rotation (Stott, 2018). Some bike designers maintain that carefully shaped wheel paths provide better suspension performance (Fuss et al., 2016). Having an instant centre of rotation is an advantage because the design can be more easily optimized to minimize coupling between the pedalling actions of the rider and the motion of the suspension (Fuss et al., 2016).

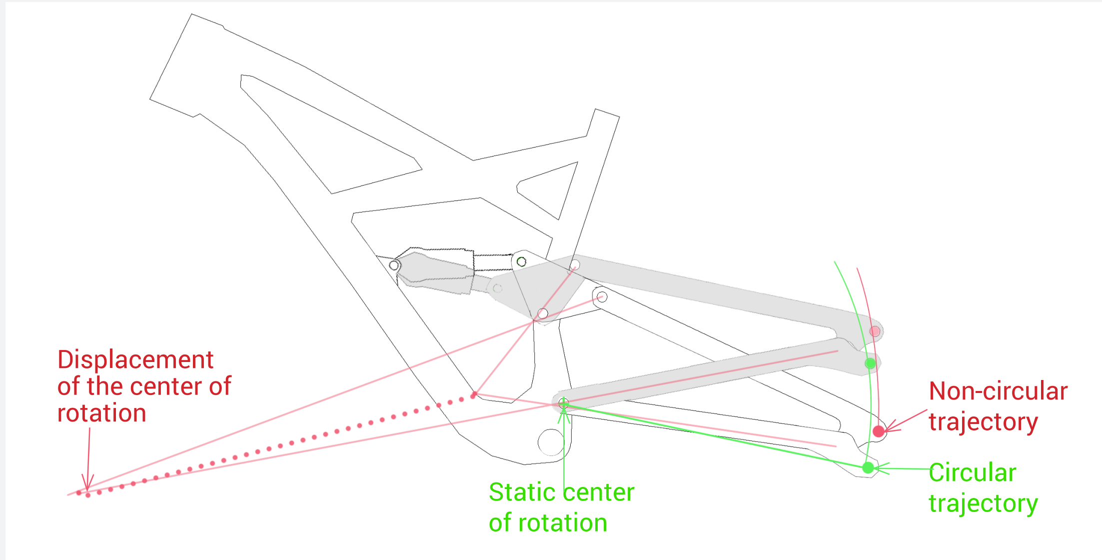


Figure 25. In green a system is described with a circular trajectory and in red a system with a non-circular trajectory.

03 DEFINITION

Applying the empathy findings to establish clear, human-centered needs and insights, and define a meaningful challenge.

MOOD BOARD

Off road cycling corresponds to a lifestyle which involves taking risks caused by speed, jumps, and other tricks. These types of sports produce lots of adrenaline and strong emotions and attract people who enjoy gathering together to show off and push the limits of their abilities. The bikes in correlation with the rider's skills and imagination can generate unique moments: it is not about the vehicle but about the rider and how they play with the terrain. However, a good vehicle can enhance the performance of the rider and lead to a more satisfying interaction between rider and their environment.

Figure 26. Inspiring environments, shapes, colours, style, etc...

DESIGN DRIVERS

Many insights have been gathered during the empathize stage of this project. The main important insights collected are regarding the user's characteristics, the influence a suspension has on the coordination of trials, and the training requirements that dedicated motorcycle trial riders must face to improve in the sport.

Motorcycle riders

Professional

Most professional motorcycle trial riders have been initiated with the bicycle discipline.

Professional motorcyclists avoid using the bicycle because it generates confusion in their technique.

Intermediate

Intermediate motorcyclist have difficulties training due to available time, costs, and traffic regulations.

For intermediate motorcyclists alternating bicycle and motorcycle is not a problem.

Trial motorcyclists have difficulties learning basic moves directly on the motorcycle.

Influence of the suspension

The suspensions on the motorcycle are an added element the athlete must learn to coordinate with. When performing any type of trial gesture that requires lifting one or both wheels, the athlete will have to compress the suspension and then wait for the rebound before finishing the sport gesture.

Cross-training trials

Trial motorcyclists mainly need to train sport-specific to improve in the sport. In this case it means riding the motorbike through obstacles to practice their agility, balance, and coordination. In addition, to gain optimal fitness they usually have to compensate with some cardio endurance and local muscle endurance workouts.

PERSONA

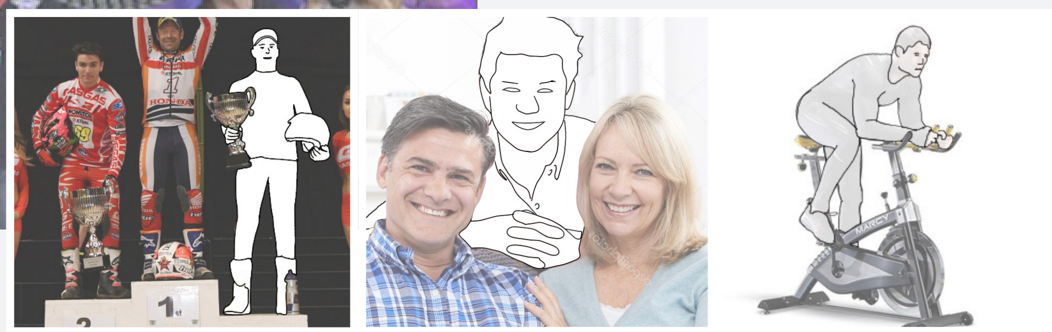
PROFESSIONAL RIDER

Jack is a professional motorcycle trials rider. At a young age he started doing some trials with the bicycle, and at the age of 15 he switched to the motorcycle discipline. He has now been competing for over five years and his main goal for the next years is to be among the best 15 trial riders in the Trial2 World-cup. Jack is sponsored by a good motorcycle brand that provides all the required equipment and pays him a fair amount depending on the results he obtains. He recently moved to a location near the mountains where he can train on a daily basis.

As a professional, Jack is fully dedicated to training, however, he encounters the issue that his motorcycle often requires maintenance and this interrupts his training routine. He is often tempted to use the trial bicycle he still owns from when he began practicing trials, however his coach advises him not to do so in order to avoid adopting the wrong posture and moves. Furthermore, Jack has to go to a gym to do some power and endurance training, although for him it feels like a pity because he would rather train these aspects while practicing trials.

JACK RIDER

BRITISH
23 YEARS OLD
ELITE TRIAL RIDER



AMATEUR RIDER

Alex is a passionate motorcycle trials rider. He lives in the city and therefore, in order to train regularly, he goes almost every week to the residence his family owns near a forest that is popular among trial riders. There, he meets with friends and they spend numerous hours riding and having fun. Alex takes this sport seriously; has begun to attend numerous competitions and he is starting to have some ambitious goals.

He is having a hard time achieving his goals because he can only train his favourite sport during the week-ends because it is forbidden to use a trial motorbike in the city. Alex would like to encounter a different way of practicing that can help him get in a good physical condition and enhances practice of specific trial moves in a fun way.

ALEX GARCIA

SPANISH
28 YEARS OLD
MECHANIC

DESIGN DIRECTIONS

The interaction and structural differences from trial vehicles and general bicycles have been compared and analysed. This study provides us with more knowledge about two-wheeled vehicles, and a wide range of design opportunities that could be interesting to integrate from one discipline to another (Chart 1).

As defined in the problem definition, one of the main goals is to integrate suspensions, however other interesting properties have been identified that differ in terms of interaction between the trial bicycle and the trial motorcycle. In addition, interesting alternatives from the bicycle industry have been considered as they might provide an intermediate between the bicycle and the motorcycle.

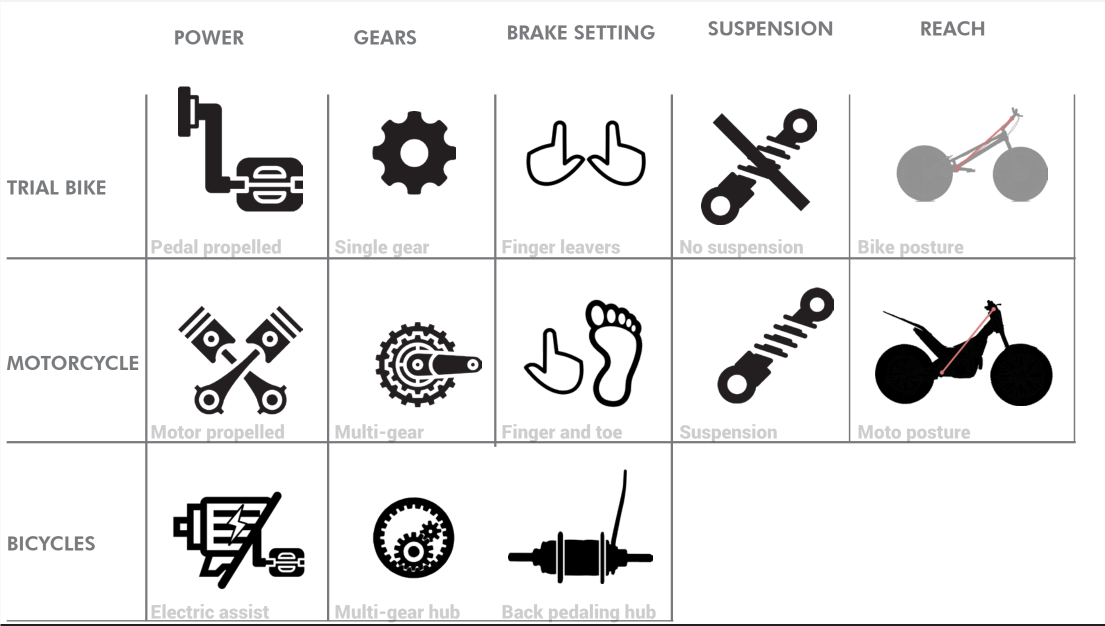


Chart 1. Distinguishably components/interactions of the analyzed two wheeled disciplines.

Regarding the geometry aspects, several required dimensions have been identified from the trial bike which must be kept in order for a bicycle to respond to the cyclist's actions in the way these particular bicycles do. In addition, a possible geometry adaptation (the reach) from the motorcycle trial has been identified and it could be of interest to integrate in order to mimic more closely the posture of the cyclist on a motorcycle.

In addition, the anthropometrics of the target users have been identified. Not so much to determine the dimensions for the final design, but more to encounter the centre of gravity of the user combined with the bicycle, as this can be useful when developing the weight distribution and the suspension system for the final design (Figure 27).

DIMENSIONS		Trial bike	Motorbike
B	Reach		
BH	Reach horizontal	"690mm"	550mm
BV	Reach vertical	"710mm"	765mm
C	Bottom bracket height	0mm - (-12mm)	
D	Chain stay	360mm - 400mm	
E	Head tube angle	70 °-72 °	
F	Wheel diameter	"24"	

Table 4. Trial bicycle and trial motorcycle relevant dimensions.

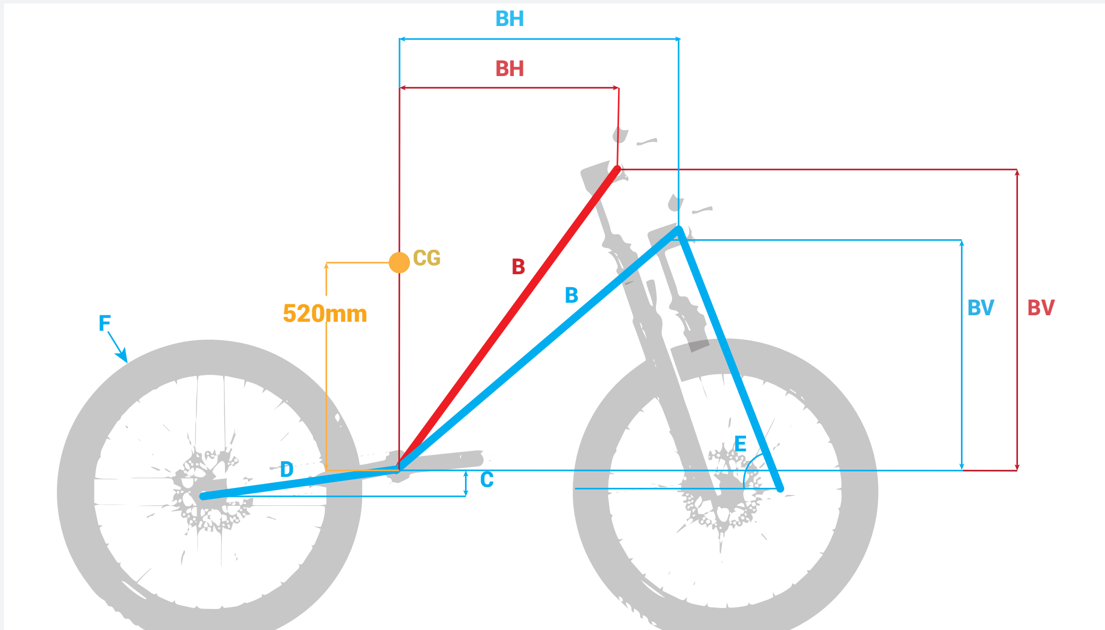


Figure 27. Dimensions required for a bike to behave like a trials bike, reach dimensions from the motorcycle, and height of the center of gravity.

MEANINGFUL CHALLENGE

Now that sufficient information has been collected regarding the user's needs and wishes, and many implementation possibilities have been explored, some generic decisions regarding the characteristics of the new design can be made.

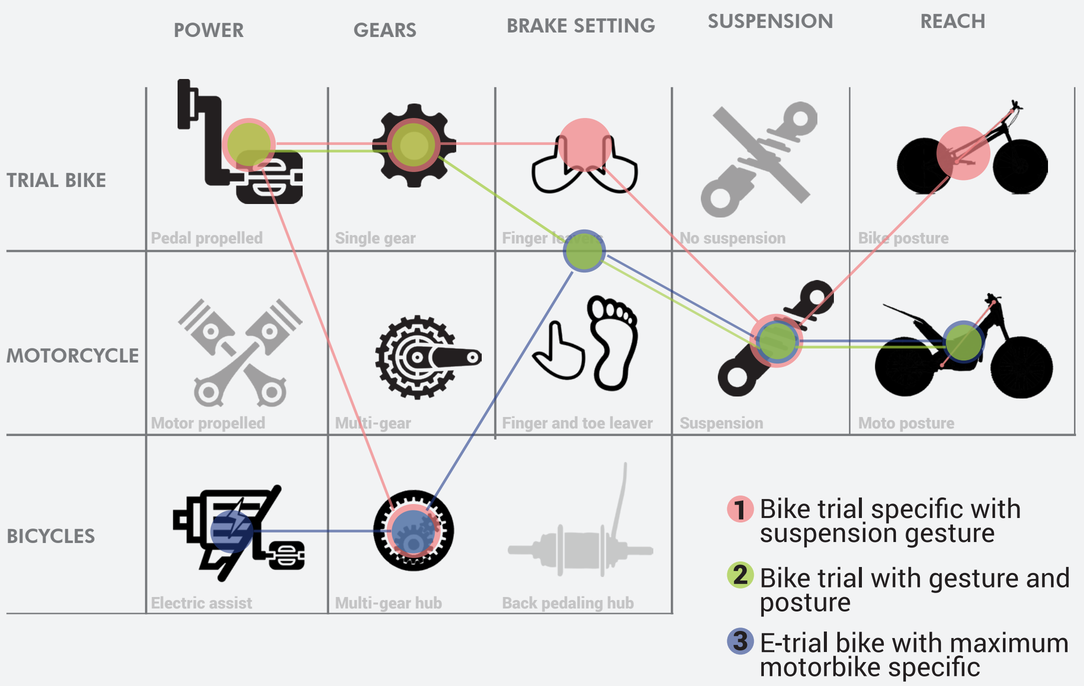
MORPHOLOGICAL CHART

A morphological chart has been developed by deconstructing the overall functions into sub-functions. This method is used to help generate principal solutions in an analytical and systematic way (Van Boeijen, et al., 2014).

The subsections are divided into columns and correspond to: power source, gears, brake setting, suspension, and reach.

Furthermore, the rows correspond to the trial motorcycle, the trial bicycle, and interesting bicycle innovative systems. Three main interesting possibilities have resulted from the chart.

Three sub-functions have been discarded as they are not fit for the design requirements. First, it must be a bicycle, therefore it can not have a combustion engine. Furthermore, the back-pedalling hub is not suitable for trials as the action of pedalling backwards is required in many trial moves. In addition, analysing the influence of suspension is the goal stated on the design question that the client has approached me with, so it is important that this element is included.



REFLECTION

Three principal solutions have been identified with the use of the morphological chart. Solution one stays closest to the bike trial discipline by integrating the suspension as the only differentiation factor. The second option, intends to integrate more aspects in order to become more motorbike specific in terms of gestures and posture by adding brake alternative and adjusting the geometry to motorcycle reach. Furthermore, option three approaches closest to the motorcycle discipline specially with the inclusion of an electric motor, being the most versatile and facilitating the closest match between the technical sport gestures.

Upon comparing the options with the design requirements, it is clear that option two is the best fit for a number of reasons. The first reason is that professional motorcyclists need high specificity to accept a product of this type, for that reason the first concept was not selected. Furthermore, although the third option could be the most attractive in terms of mimicking the usability of trial motorcycles, e-bikes are currently in a much higher price range. As it is not yet clear whether our consumers would be willing to invest in this technology, this makes option three risky from a marketing standpoint. It has been decided to aim first for the basics so as to explore the advantages of this idea before engaging in a more challenging product that would require more resources and time to be properly developed and tested.

GESTURE
Suspensions
Brake setting
Power

POSTURE
Reach

VERSATILITY
Gears

Challenge

Design a trial bicycle that integrates the main gestural and postural qualities from the trial motorcycle discipline, resulting in a minimum viable product (MVP) which can serve as a point of departure for further development. The goal of this project is to evaluate the design based on the sport specific skills of motorcycle trials in order to answer the following research question: whether the integration of a suspension system in a trial bicycle will allow it to mimic more closely the usability of a motorcycle trial, in order to be suitable for cross-training of trial athletes.

LIST OF REQUIREMENTS

To describe the characteristics that the final design should meet, a list describing the concrete, main requirements has been made below. This information serves as a checklist to describe all the design objectives and will later be used to select the most promising ideas.

PERFORMANCE
The product must be mainly actuated as a bicycle, with the use of pedals, and it should enhance (through the use of suspensions) the learning of sport specific skills related to motorcycle trials.

ENVIRONMENT
It must be resistant to dirt and water, and it must be able to withstand long cycles of the typical shocks and impacts that a trial vehicle is submitted to.

LIFE IN SERVICE
It is a product submitted to a lot of load along usage, therefore it should last about 5 years if used once a week.

MAINTENANCE
Product submitted to periodic maintenance due to wear of components. Reparability shall be suitable to users with basic bicycle repair skills and basic tools. Reducing the amount of components or unions are interesting approaches as components get easily broken.

TARGET PRODUCT COSTS
The estimated consumer costs for this product is of approximately € 2000, with an estimated cost price of unit produced of € 900 .

QUANTITY
The trial market is small, but there are not many direct competitors, therefore it is expected to sell approximately 70 bicycles per year.

PRODUCTION FACILITIES
The product should be designed to be manufactured with the use of existing production facilities and will be outsourced by a specialist bicycle manufacturer. However there are little finances available so usage of the most standard materials and facilities is a plus.

SIZE AND WEIGHT
Lightweight is a pro, although due to the new integrations the MVP is expected to weight up to 14Kg. In addition, compactness is important to reduce weight as well as space. It is of interest to evolve towards a thin frame, such as the ones conventional trial bicycles have, both for functional and aesthetic reasons .

AESTHETIC, APPEARANCE
There is no specific house style associated, however it should be recognized that it is to be used for trials and give a hint that it has some association with the motorcycle. However, it should look professional with a neutral, long-lasting design.

STANDARDS: With regards to standards of the construction, the design must be suitable to fit standard trial bike components.

RULES AND REGULATIONS
As a hybrid design dedicated to training purposes, this bicycle does not need to fit with the regulations of any specific discipline. However, it should not be limited by traffic laws.

ERGONOMICS
The product is made to fit with the anthropometrics of the average western European male (percentile 50). With an approximate height and weight of 170cm and 80Kg. Therefore the weight distribution on the of the suspension system must particularly adopted for this target.

SELECTION CRITERIA

Since the design will be mainly focused on the development of a bicycle frame with suspensions, more specific selection criteria have been established.

These have been chosen based on the list of requirements and they are considered to be key requirements for the new design. Therefore, they will be used throughout the ideation phase to select ideas and concepts and evaluate the iterations generated.

Not all selection criteria are equally important, these are organized in the list from most important at the top, to less important at the bottom.

Kinematic values
This requirement refers to how likely the concept is to fulfill the suspension’s kinematic ranges that will be determined.

Readjustment
This refers to the ease of the idea to re-adapt the kinematics or other aspects in future iterations without having to radically switch to other alternatives. A modifiable can be progressively modified until encountering the wanted-setup

Low maintenance
The product to be built is a bicycle submitted to many impacts and shocks, so the less attachments and articulations, the better, because then less reparations will have to be made.

Feasibility
The design must be built by using existing facilities and by taking as much profit of standard manufacturing materials and resources in order to produce the bike at a low cost.

Compact
Trial bicycle frames are very thin compared to bikes from other disciplines and integrating a suspension system requires more space. For this reason, the concepts are evaluated on how compact they can become if properly integrated.

04 IDEATION

An activity aimed at gaining familiarity with suspension design through basic knowledge and an iterative process. Further concepts are ideated and evaluated resulting in some final design characteristics.

Product ideation process at Mission Bicycle, 2016

SUSPENSION KINEMATICS

When talking about bicycle rear suspension, there are many jargon terms used to describe the kinematic properties such as: anti-squat, progressivity, etc. These terms are used to describe the influence of a suspension design's behaviour on the perception of the rider and the terrain. Nonetheless, not many of us really understand what these terms actually mean, so this sention will provide further explanation.

Generally, rear suspensions are integrated in a bicycle's frame and so they are not readily available independently, however front suspension can be acquired seperately. As suitable front suspensions are already available on the market, the new design should include an existing front fork suspension, and a self-designed rear suspension. To develop a rear suspension system that best suits a trial bicycle, the behaviour of this system will be determined by deducing which kinematic properties would be suitable when performing trials and meet our requirements.

The program Linkage (version X3; Racooz Software, 2019) simulates a kinematic structure consisting of a non-deforming main frame, a specific kind of suspension linkage (rear suspension) balanced by a telescopic shock and a telescopic suspension (front fork) (Figure 28). Regarding physics, the program uses a kinematic model, so no mass is involved, and the force cases are calculated for a static position of the structure.

The most important suspension parameters to bear in mind when designing a suspension are: the leverage ratio, anti-squat together with its repercussion on kickback, and the values of anti-rise.

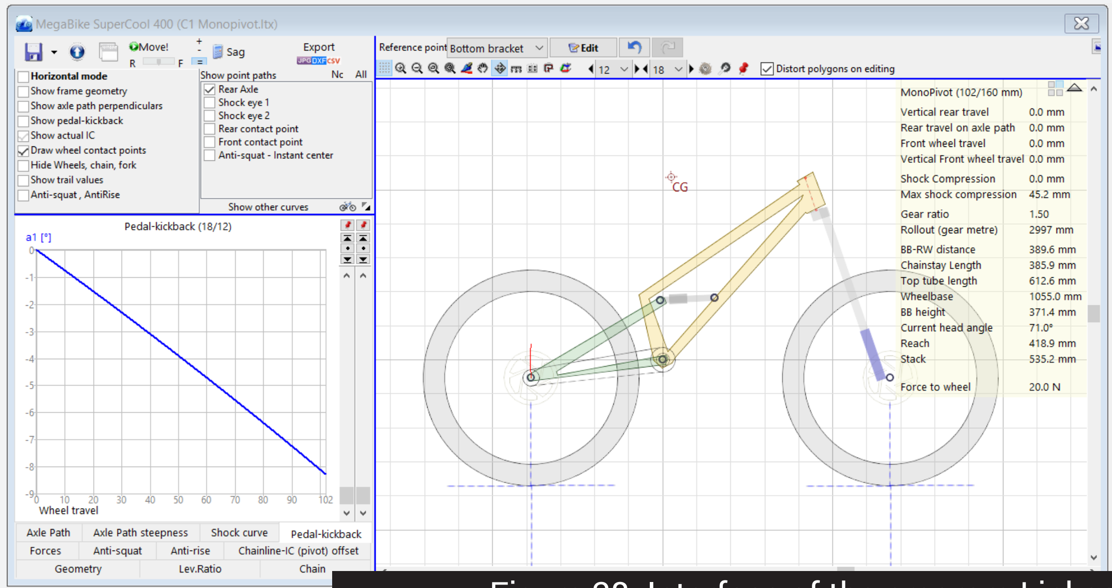


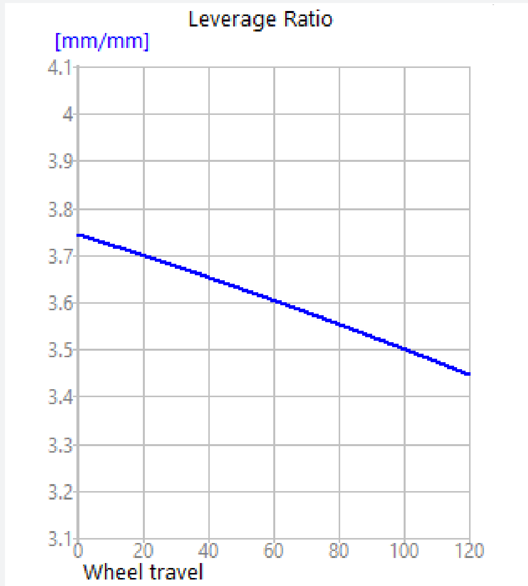
Figure 28. Interface of the program Linkage.

LEVERAGE RATIO

The leverage ratio is the ratio between the amounts of wheel travel and the shock compression ("Basic Terms", n.d.). The progressivity of a bicycle suspension is determined by how much variation the leverage experiences during the travel. A progressive suspension "stiffens up" at larger travel positions, while a regressive suspension feels more supple and is easier to bottom out ("Basic Terms", n.d.). The values of leverage ratio while traveling have a big influence on how a rider perceives the suspension when activating it, and therefore it also plays an important role in determining its performance (Needle & Hull, 1997).

The leverage ratio is customizable on a bicycle suspension mechanism formed by a quadrilateral. These values can be modified by customizing the rocker arm and the positioning of the shock pivots (Needle & Hull, 1997). A bicycle single pivot suspension system (that is not based on quadrilateral) tends to be linear and its values can be only slightly modified (Stott, 2018).

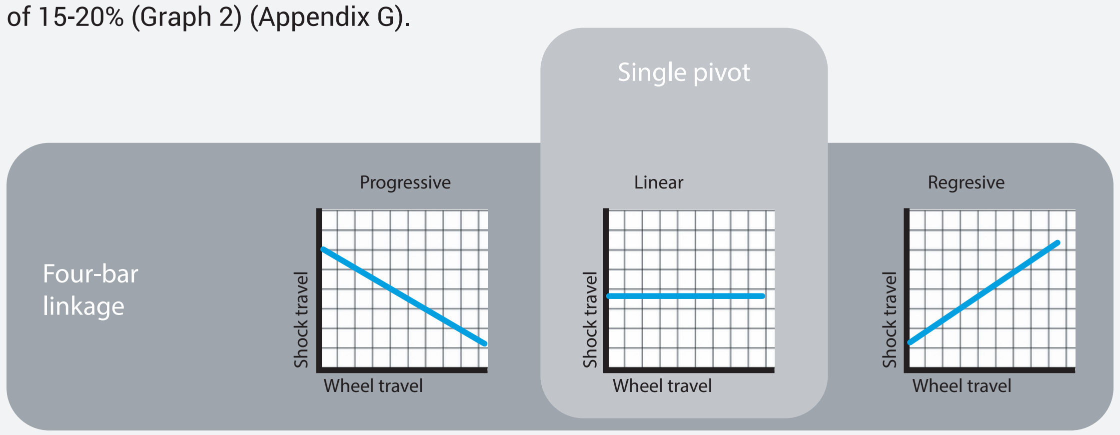
Trial motorcycles have a leverage ratio of approximately 2-2.5, and a light progression of 15-20% (Graph 2) (Appendix G).



Graph 2. Show the aproximate values of leverage ratio of a trial motorcycle (Appendix G).

$$Leverage\ Ratio = \frac{Rear\ wheel\ travel}{Shock\ travel}$$

$$Progression\ \% = \frac{(Leverage\ start - Leverage\ end)}{Leverage\ start} x\ 100$$



ANTI-RISE

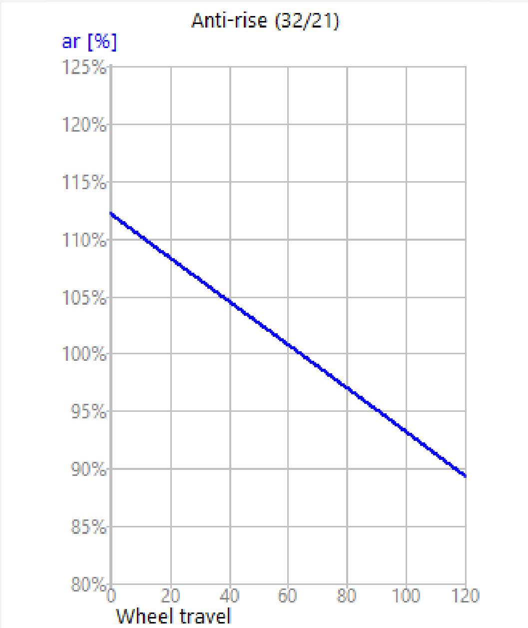
Anti-rise is given by the force created by the decelerating mass of the rider that causes the rear end to contract or extend (Stott, 2018). It is the propensity of a suspension to stay active under braking conditions by counteracting this brake jack using appropriate pivot placement. By adjusting the values of anti-rise, it will be determined whether the rear suspension of the bicycle will contract or will extend while decelerating on a bicycle (Stott, 2018).

To determine the values of anti-rise, the Linkage software draws a straight line from the wheel axle coordinate on the ground, through the main pivot point, and ending in the vertical axis that meets the front wheel axle (Figure 29). The anti-rise value is dependent on the height of the end point relative to the centre of gravity of the bicycle and rider. Here, the previous study to locate the height of the centre of gravity of our target user comes in handy.

Generally, the ideal case scenario is that the anti-rise value of suspension systems stays at 100% when the athlete stands on the bike (Stott, 2018). For that reason, at travel zero anti-rise tends to be slightly over a hundred, and it decreases along travel causing that the suspension slightly extends under braking conditions (Benedict, 2018a). This is the case in many bicycle suspension systems and also on trial motorcycles (Graph 3).

Anti-rise under rear braking	
Anti-rise > 100%	Shock compression
Anti-rise < 100%	Shock extension

Shock response to anti-rise values



Graph 3. Shows an approximate values of anti-rise of a trial motorcycle.

ANTI-SQUAT AND KICKBACK

Anti-squat determines the suspension's mechanical resistance to compression due to forces from the engine (on the bicycle the engine is human) (Stott, 2018). When the suspension compresses, chain needs to "grow" or give out from either end of the chain. Therefore, anti-squat is the resistance to compression under acceleration and pedalling forces ("Basic Terms", 2015).

Pedal kickback is a consequence of anti-squat and it describes the change in length of the chain-stay over the spring extension phase. This is determined by the direct distance between bottom bracket and rear wheel axle. During extension, the distance between bottom bracket and rear wheel axle increases, which results in a change in chain length pulling the crank backwards against the pedalling movement ("Basic Terms", 2015).

To find the anti-squat value, the same technique has been applied as for finding the anti-rise value (Figure 29), but instead of drawing the line through the main pivot point, this one goes through the instant centre of rotation. The final value of anti-squat is dependent on the height of the end point relative to the centre of gravity of the bicycle and rider ("Basic Terms", 2015).

In motorcycles, the values of anti-squat are neglected and the ones of kickback are in constant zero due to the fact that there is no change on chain tension.

Anti-squat under pedaling forces	
Anti-squat > 100%	Shock extension
Anti-squat < 100%	Shock compression

Shock response to anti-squat values

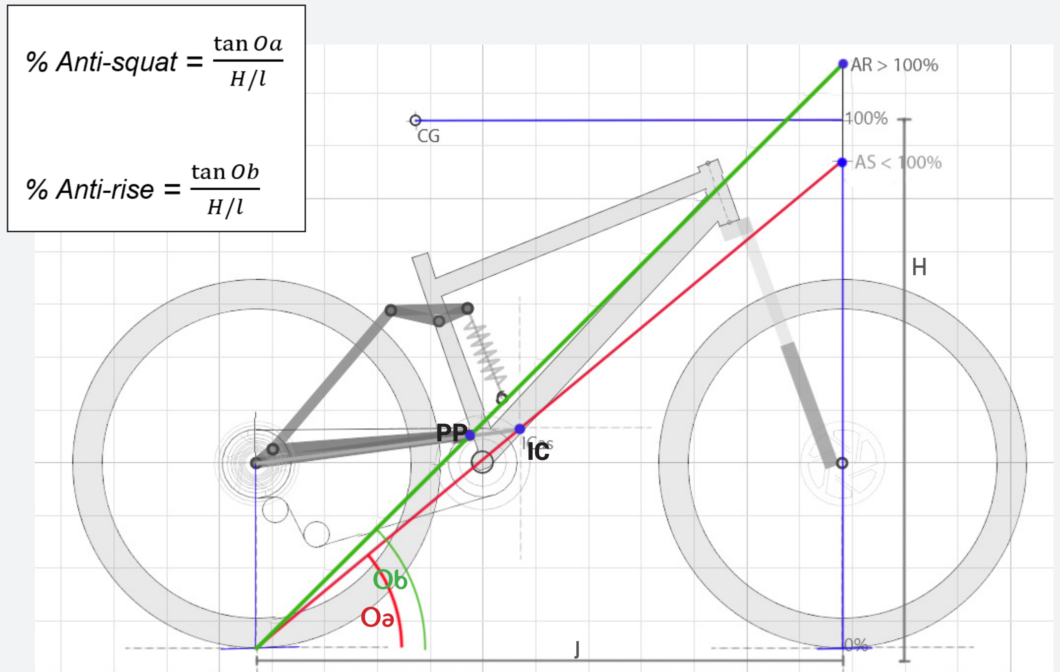


Figure 29. a) The red line goes through the instant center of rotation and is used to calculate anti-squat. b) The green line goes through the main pivot and is used to calculate anti-rise.

PARAMETERS DEFINITION

As there are no trial bicycles with suspension, the parameters for this had to be defined according to what is expected that best fits with this practice. The motorcycle trial kinematics have been analysed (Appendix G) as a generic guideline. Although the aim is to recreate the trial motorbike suspension sensations, it has been considered that the kinematics of the bicycle should slightly differ in order to compensate the lack of power provided by the motor.

Hence, the suspension travel should be short and the leverage progressive, so that the rider can still lift the wheels when making trial manoeuvres. Trial motorcycles are progressive and have a rear wheel travel of approximately 120mm with a progression of only 15-20% (Appendix G). Due to the lack of power on a bicycle in comparison with the motorcycle, it has been opted to compensate by increasing progression to 20-25%.

The effects of anti-squat are truly harmful for trials as pedalling sensitivity is essential to perform well (Dodd, 2018). Therefore, this value should remain as neutral as possible reducing kickback to no more than six degrees overall, and preferably with a relatively low value of anti-squat (less than or equal to 100%). The values of anti-rise shall also remain as neutral as possible, although preferably with low rather than high values (less than or equal to 100%). As this causes the rear shock to compress instead of extend when braking and accelerating forwards (Stott, 2018).

Trial suspension parameter limits

Travel	90-110mm
Leverage ratio	2 - 2.5 progressive
Progression	20-25%
Anti-squat	≤100%
Kickback	≤ 6°
Anti rise	≤100%

ITERATIONS

Enough information has been gathered to understand the behaviour of suspension systems and what parameters influence this behaviour. The goal now is to make decisions regarding constructive configuration of the suspension system.

Multiple configurations are evaluated, not only regarding the kinematic properties, but also regarding the other pre-established design requirements. The main goal consists of selecting the most adequate suspension system however, in addition, the issue of pedal efficiency is also approached.

The multiple ideas considered for the design, will be evaluated based on the selection criteria previously established in the define phase.

Kinematic values
This requirement refers to how likely the concept is to fulfill the suspension's kinematic ranges that have been determined.

Readjustment
This refers to the ease of the idea to re-adapt the kinematics or other aspects in future iterations without having to radically switch to other alternatives. A modifiable can be progressively modified until encountering the wanted-setup

Low maintenance
The product to be built is a bicycle submitted to many impacts and shocks, so the less attachments and articulations, the better, because then less reparations will have to be made.

Feasibility
The design must be built by using existing facilities and by taking as much profit of standard manufacturing materials and resources in order to produce the bike at a low cost.

Compact
Trial bicycle frames are very thin compared to bikes from other disciplines and integrating a suspension system requires more space. For this reason, the concepts are evaluated on how compact they can become if properly integrated.

PRECEDENTS

Many interesting suspension configurations have been studied and analysed. This exercise was done to investigate many alternatives and encounter how kinematic and constructive problems have been solved in the past. Therefore, it has triggered the problem solving ideation towards solving problems related to linkage connection, chain efficiency, and space distribution. Multiple distinctive configurations have been encountered for both linkage and mono-pivot configurations (Appendix H). Nomenclature of bicycle components and parts are annotated in appendix B.

LINKAGE BIKES
The most interesting aspect encountered in this case is the many settings of rocker arm, where each has particular kinematic properties and provides different positioning of the shock. Depending on the setup, the shock can be positioned more horizontal as it is the case in the Specialized EVO (Figure 30), or vertical like on the Focus Jam, and they are usually linked to the top tube or the down tube (Appendix B).

It is also interesting to study the pivoting attachments. For instance, most models have four clear, separate links (Chainstay, seat-stay, rocker arm, front triangle). However some models, like the Santa Cruz hightower, keep the seat-stay and chainstay together, while creating a dual pivoting point near the bottom bracket (see figure 30). In addition, the Canyon Stitched has the main pivot located concentric to the bottom bracket, therefore the chain never loses tension. This is an interesting solution to provide precise pedalling efficiency. Also related to pedalling efficiency, the Comencal Ocusa 377 integrates an added pulley to avoid chain occlusions (see figure 30).

Figure 30. Variety of inspiring linkage bicycle suspension systems.

SINGLE-PIVOT
Regarding mono-pivot systems, interesting references have also been encountered. For instance, the types of attachments between front and rear triangle. In some cases, the rear triangle and shock are mounted on the inside of the front triangle, such as on the Orange bike five, and in other cases they are more separated like on the Treck Y22 (see figure 31). In addition, there are some basic set-ups known as soft-tails frames that have no pivots but that slightly bend when absorbing shocks, so it integrates a shock with short travel (Benedict, 2018b).

Furthermore, interesting solutions to keep the chain tensioned have been encountered. For instance, on the Treck Y22 (Figure 31) the bottom bracket has been located on the rear triangle, instead of on the front triangle as it usually is. However, the problem with this design is that it locks up when you stand on the pedals (Grandzol, 2006). Another interesting option is a timing chain setup with two chains as it has been done on the e-bike Le Bui (see figure 31). This enables the separation of the bottom bracket and the pivoting point, without losing tension on the chain (Stott, 2018).

Figure 31. Variety of inspiring single-pivot bicycle suspension systems.

TYPES OF BICYCLE SUSPENSION

All bicycle suspension systems can be classified under one of the following three layouts: the single pivot, the single pivot linkage, and the Horst linkage.

The single pivot (figure 32) moves in a constant arc, centred on the pivot point. The simplicity of the design makes for easier maintenance of the pivot bearings, but one shortcoming of this design is that it offers a rather linear leverage curve (Stott, 2018). Since it is such a simple system the kinematic properties can not be manipulated.

Furthermore there are two types of main linkage configurations. The first one, the single pivot linkage (figure 33), still uses an uninterrupted swing arm, connecting the rear axle directly to the mainframe (Stott, 2018). Therefore, it has a circular trajectory, yet it incorporates some form of linkage to drive the shock. This allows the designers to manipulate the leverage curve, however with a circular trajectory other kinematics can not be improved.

The most sophisticated linkage system is a Horst-link suspension (figure 34), as it is marked out by a wheel axle located on the seat-stay instead of the chainstay. As the wheel axle is located on the moving bar of the quadrilateral, it moves in a path which is defined by its "Instant Centre" (Stott, 2018, para 3). The advantage of this system is that it provides designers with more control over the levels of all the kinematic aspects (Stott, 2018).

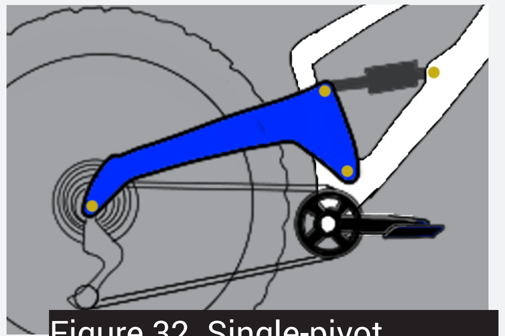


Figure 32. Single-pivot

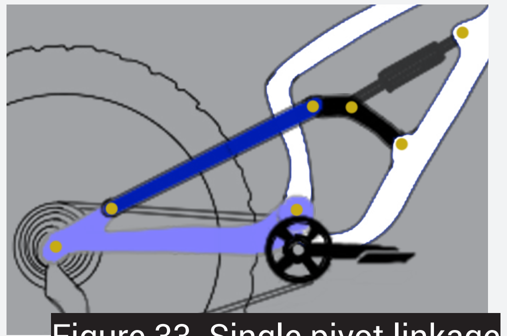


Figure 33. Single pivot linkage

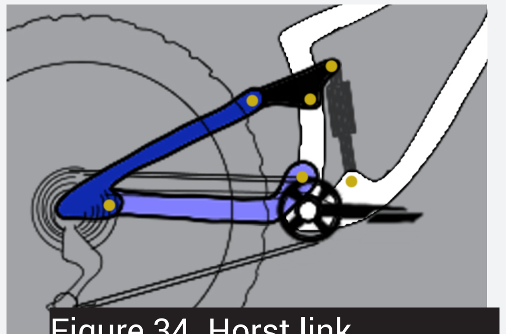
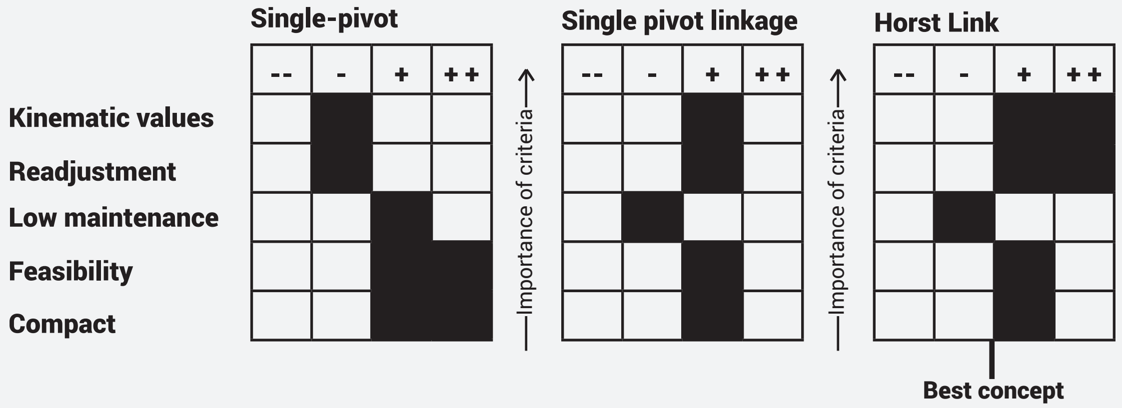


Figure 34. Horst link

FIRST ITERATION

To evaluate and compare what system is most suitable for the final design, the Harris profile method has been used (Van Boeijen, et al., 2014). This method evaluates the strengths and weaknesses based on predefined selection criteria (pg.67) and helps evaluate which concept to continue with.

Results show that the Horst linkage undoubtedly provides the best suspension properties, as all kinematic parameters can be calibrated. On the other hand, the single pivot has many advantages as it requires lower maintenance, and it is more feasible and compact. However, it has the least control over kinematic properties. Regarding the single pivot linkage, it has a lower control of the kinematics than the Horst-link and higher than that of the single pivot. However, besides this, it has the same values as the Horst link, therefore it does not really have any particular highlights compared to the others.



PEDAL EFFICIENCY

Trial biking requires high precision when it comes to pedalling. In fact the pedalling action is conducted in a considerably different way than on other bikes (Bertucci, Rogier, 2015). For instance, half strokes are used to perform jumps, and the cyclists are constantly making strokes and then pedalling backwards to put the pedals in the original position instead of making whole pedal turns. In part for this reason, trial bicycles run on a single speed and have a consistent tension on the chain.

The effects of anti-squat and kickback would undoubtedly generate a negative experience doe to the wear and tear of the chain therefore, the question here is: how can the chain tension be constant on a rear suspension system of a bicycle?

Four possibilities to solve the pedal efficiency issue on a bicycle have been encountered, however, they all have consequences. Therefore these are analysed and compared in order to encounter the most suitable option for a trial bicycle. Real examples of bicycles where these systems have been applied can be found on pages 68-69. Furthermore, nomenclature of bicycle components and parts are annotated in appendix B.

BOTTOM BRACKET ON REAR TRIANGLE
In this configuration, the bottom bracket also pivots together with the rest of the rear triangle (Figure 35). Therefore, the distance from the chain rings and the rear sprocket never changes. It seems like a good solution at first, however when the cyclists stands on the pedals without sitting down the system locks up. This basic fact makes it unsuitable considering that there in no seat on trial bike to begin with. This is the example we have seen on the bike Treck Y22 (Grandzol, 2006).

BOTTOM BRACKET PIVOT
This configuration consists of mounting the main pivot of the suspension directly concentric to the bottom bracket (Callahan, 2017). Since the bottom bracket is

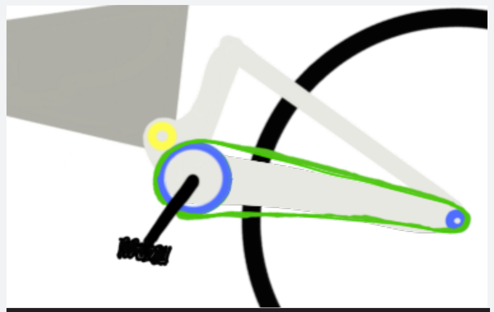


Figure 35. Bottom bracket on rear triangle

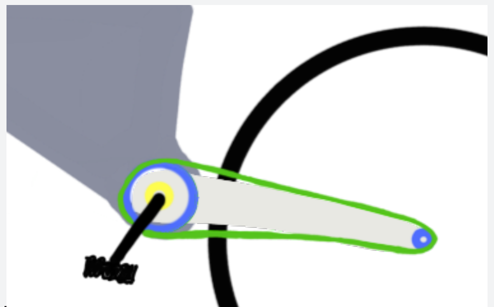


Figure 36. Bottom bracket pivot

concentric to the chain rings, once again there will be no loss of tension when pivoting (Figure 36). The major complication has to do with complexity of the bottom bracket as there must be two separate elements rotating independently. In addition, the location of the pivoting point becomes very restricted, so it limits the kinematic properties of the design.

PARALLEL GEAR SETUP
On this system there are two chainrings (Figure 37). The first one goes from the wheel axle to the pivot point, and parallel to this one there is another chain that goes from the pivot point to the bottom bracket (Coxworth, 2014). The advantage is that the main pivot can be freely located, therefore there is more freedom when designing the kinematic properties. However, it extends the mechanism adding more components than usually needed.

TRIANGULAR CHAIN
In this configuration, other than the chainrings and the rear sprocket, there is another point of attachment to the chain on an additional gear, located concentric to the main pivot point (Stott, 2018)(Figure 38). Therefore the main pivot point must be located quite a bit higher than the bottom bracket. In this configuration there might be loss of tension in the chain, however there are no occlusions on top of the gears because the chain is positioned hire (Worsey, 2019).

Chain
Pivoting points
Sprocket & chain ring
Front triangle
Rear triangle

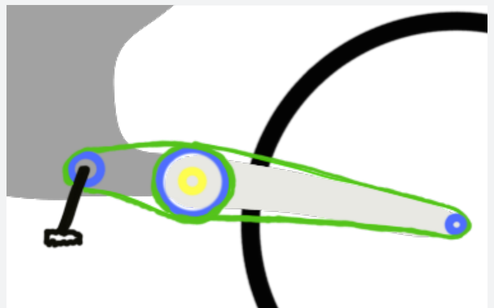


Figure 37. Parallel gear settup

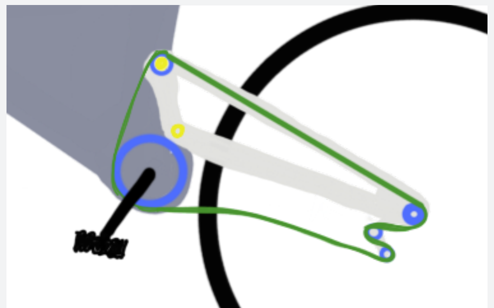


Figure 38. Triangular chain

SECOND ITERATION

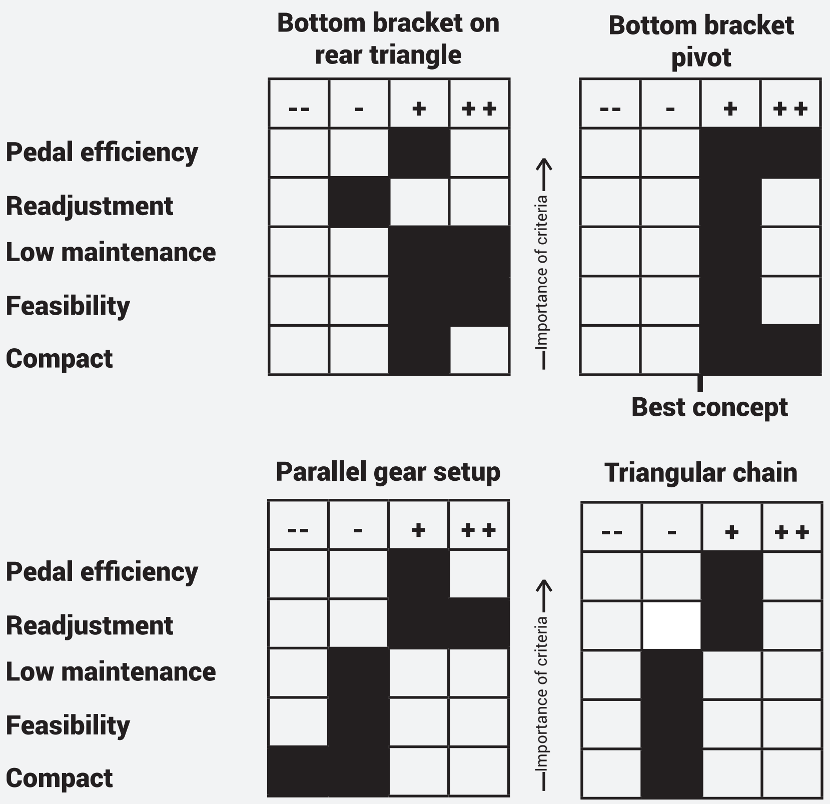
Again, the Harrison profile method (Van Boeijen, et al., 2014) is used to evaluate and select what concept to continue with. In this case, from the design requirements (pg. 67) "kinematic values" is replaced as it does not apply to this concept. Instead, the replacement requirement is "pedalling efficiency".

The best concept is in this case the bottom bracket pivot as it has positive values on all the requirements. It has good pedaling efficiency, proper readjustment of the kinematics, and it is the most compact while also being fairly feasible.

The bottom bracket on rear triangle is the simplest, most feasible and requiring the least maintenance, however the kinematics are not adequate because the system gets blocked if the cyclist stands on the pedals.

Finally, the parallel gear setup most likely has the best range of kinematic adjustment possibilities, however it is the most complex, two chains makes it less efficient, and it is not very compact.

The triangular chain setup is interesting although more should be known about how this setup behaves. In addition it is quite complex and requires quite specific placement of the pivot points to work correctly.

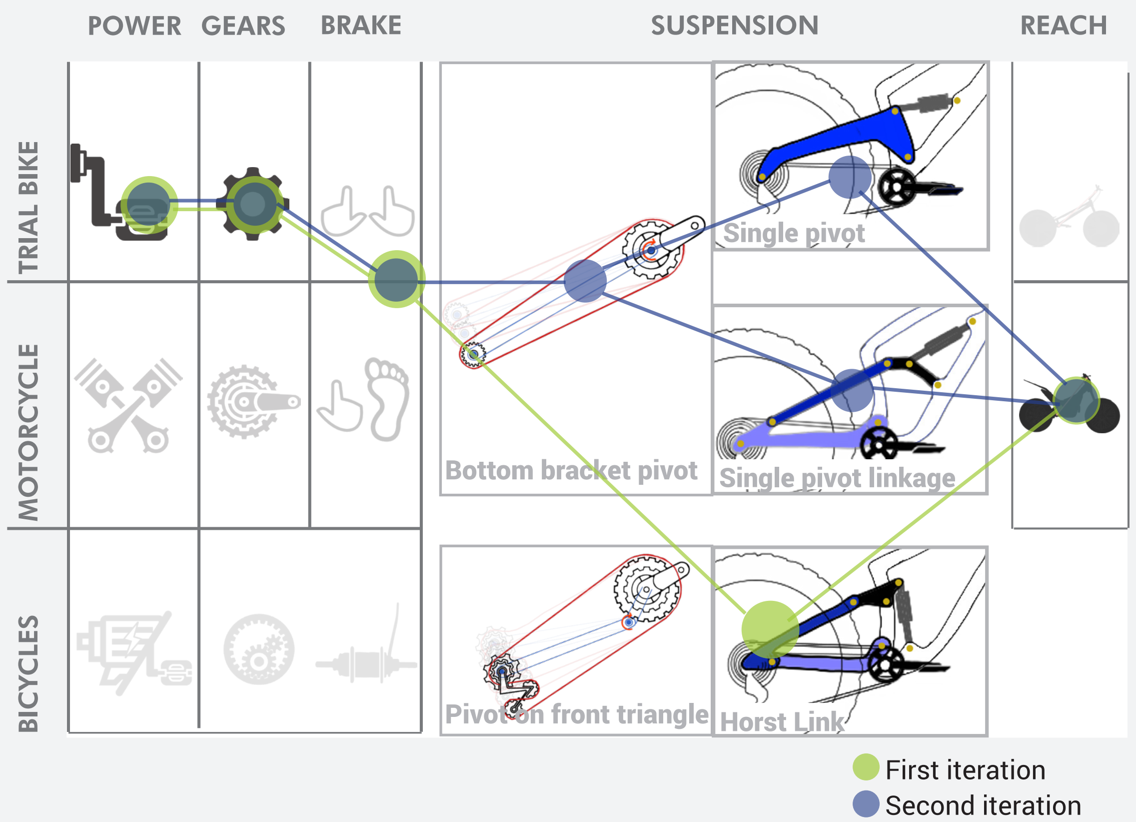


INTEGRATING A BOTTOM BRACKET PIVOT

Implementing any of the previously described and selected systems only makes sense on a single pivot suspension system as it does not work on, nor would it provide any benefit to, a Horst link system (Table 5). Therefore, the selected concept from the first iteration is no longer the best choice if a bottom bracket pivot is integrated. In this case, the single pivot linkage is the one with the best properties, however the single pivot is still an interesting choice thus it has not yet been discarded.

	PARAMETER CONTROL		
Suspension system	Leverage	Anti-squat	Anti-rise
Horst Link	Yes	Yes	Yes
Single pivot	limited	One or the other	
Single pivot linkage	Yes	One or the other	
Integration of a bottom bracket pivot			
Single pivot	limited	Not a problem	Yes
Single pivot linkage	Yes	Not a problem	Yes

Table 5. Parameter control of suspension systems when integrating a bottom bracket pivot.



CONCEPTUALIZATION

Now that major construction decisions have been established and certain parameters have been set, the characteristics of the final design are becoming quite clear. However, there is still room for creativity, therefore some ideation sketching is carried out before developing three concepts from which only one will be selected to proceed with.

IDEATION

Bicycles are basically two dimensional objects; by drawing the profile you can already obtain a lot of information. In order to ideate and explore a wide variety of configurations, a mockup with general dimensions was created, on top of which freehand sketches were made of the multiple ideas to be explored. Although it is an ideation process, it is established that all sketches have to be a single pivot or single pivot linkage with a bottom bracket pivot.

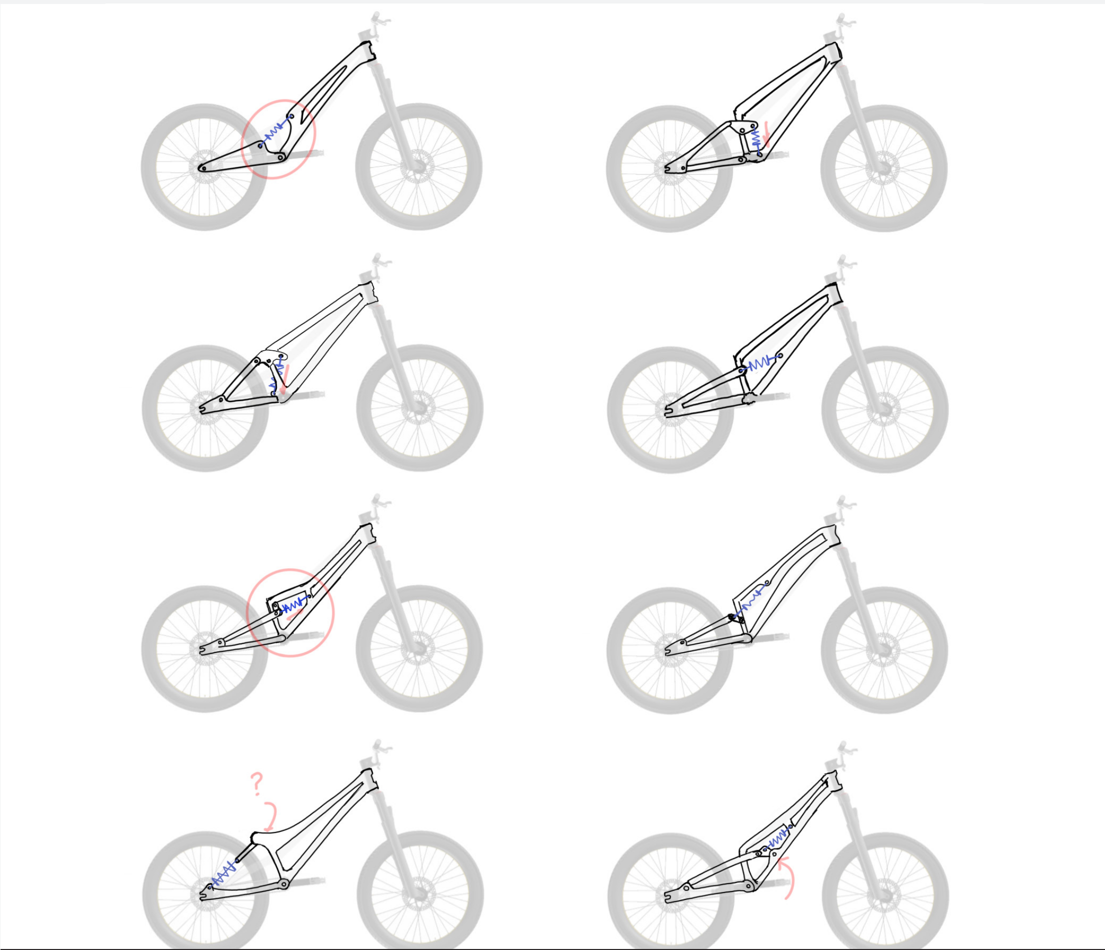


Figure 39. Template used to sketch ideas by hand.

Different configurations of rocker arm positioning and a single pivot have been made on the sketchpad and with the use of Linkage (version X3; Racooz Software, 2019) the leverage properties have been compared. Surprisingly, they all have remarkably different properties. Configuration 1 is quite progressive in terms of leverage ratio, while Configuration 3 is regressive. Configuration 2 is the most versatile as it can be either progressive or regressive. Configuration 4 is single pivot and it is quite linear with a little bit of progression in the leverage ratio.

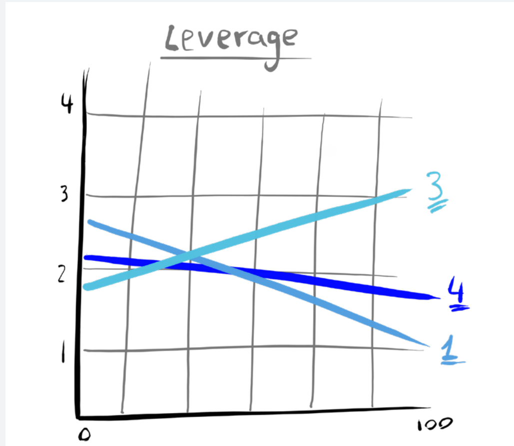


Figure 40. Comparison of approximate leverage ratio values on the compared configurations.

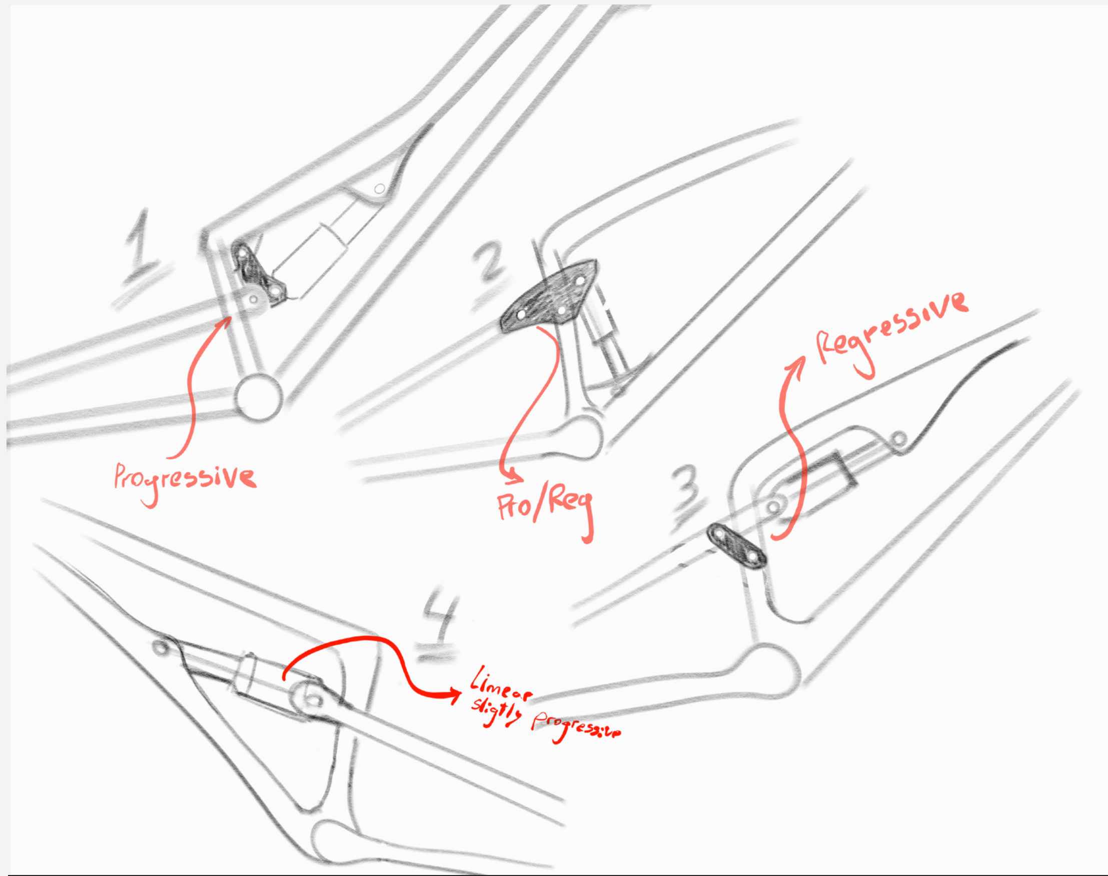


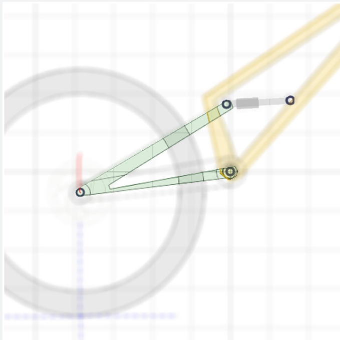
Figure 41. Configurations investigated and compared in terms of leverage ratio.

CONCEPT GENEARTION
After obtaining considerable knowledge on suspension design, having selected many design specifications, and having done adequate ideation and evaluation, three concepts have been generated. These concepts are based on three different suspension systems defined through iterations with the programme Linkage and experimenting with alternatives that could fit with the kinematic properties described to be of interest for a suspension on a trial bicycle.

The three concepts have in common the dimensions, that they all integrate a bottom bracket pivot, and that they are single pivot or single pivot linkage mechanism. From these concepts, only one will be further developed. A description of the different alternatives, together with a range of kinematic values that appear to be possible without altering too much the design, are shown in Table 6. These concepts have been discussed with the client and manufacturers and the final selection has been based on the list of requirements.

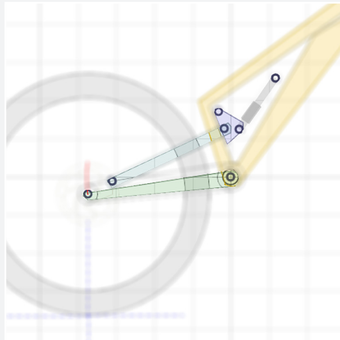
	DESIRED	CONCEPT 1	CONCEPT 2	CONCEPT 3
Leverage	progressive	2. - 2.0	2.4 -1.8	2.4 -1.7
Anti-Rise	≤100%	108%-90%	104%-88%	109%-98%
Travel	80mm-120mm	108-120mm	92-120mm	80-120mm

Table 6. Approximate kinematic value ranges for the three concepts.



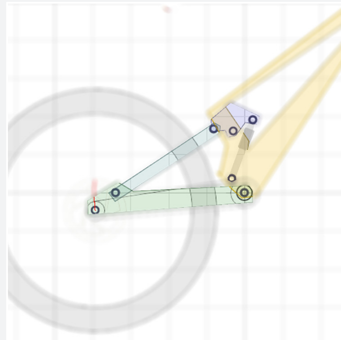
CONCEPT 1
SINGLE PIVOT

Structurally, this is the simplest concept, with only one pivoting attachment and a quite simple structure, therefore requiring less maintenance. However, the kinematics are not ideal as the progression of the leverage can only be controlled to a small extent. Furthermore, in general there is little control over the kinematics for future iterations of the design.



CONCEPT 2
LINKAGE SINGLE PIVOT, HORIZONTAL SHOCK

This concept is structurally less feasible than Concept 1 but more feasible than Concept 3 for the elaboration of a fast prototype. It provides a fair amount of freedom in kinematic adjustment, and the positioning of the shock is quite simple and takes profit of the little space available on the frame.



CONCEPT 3
LINKAGE SINGLE PIVOT, VERTICAL SHOCK

This is the concept that provides the best control over kinematic properties, however the construction is more complex as the shock must be placed more vertical. In order to save space, the shock can be placed in diagonal, making a complex seatstay.

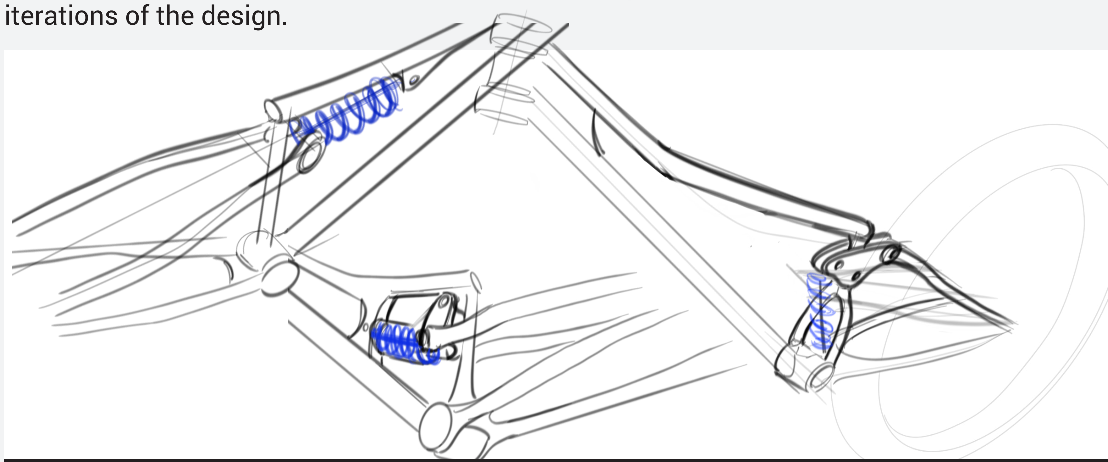
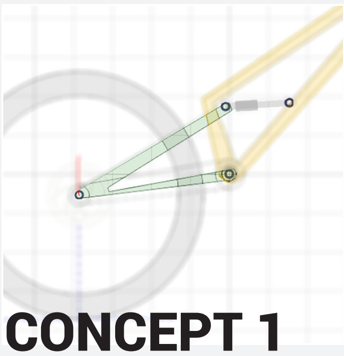


Figure 42. Drawings of all three concepts.

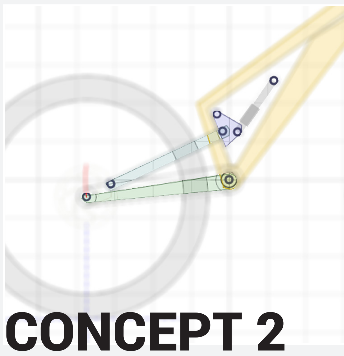
CONCEPT SELECTION
Again, the Harrison profile method (Van Boeijen, et al., 2014) is used to evaluate and select what concept to continue with. Selection is done evaluation the selection criteria properties (pg. 67).

Finally, upon evaluating each concept separately and discussing the characteristics with multiple parties involved in the project, Concept 2 was selected for further development .

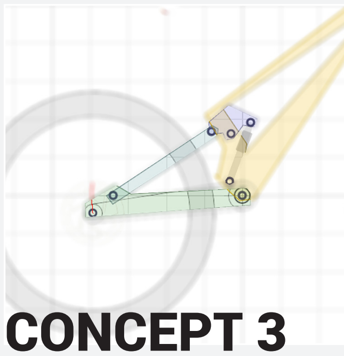
As can be observed from the following table, Concept 2 has the best balance of kinematic performance and ease of integrating properties. It is the only concept that has no negative aspects in comparison with the other two. Concept 1 has the best values regarding integration of the system although the kinematics are not ideal, and Concept 3 has perhaps the best kinematic values but the implementation of the system is more complex regarding the frame requirements.



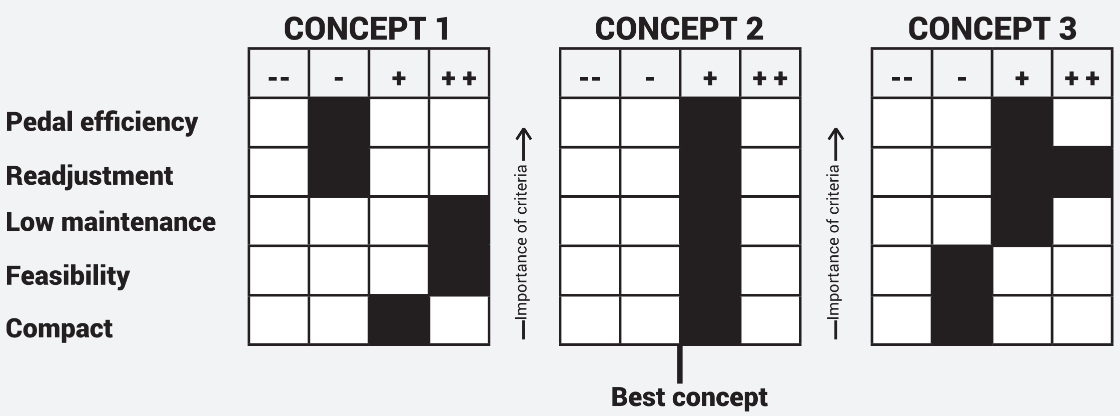
CONCEPT 1
SINGLE PIVOT



CONCEPT 2
LINKAGE SINGLE PIVOT, HORIZONTAL SHOCK

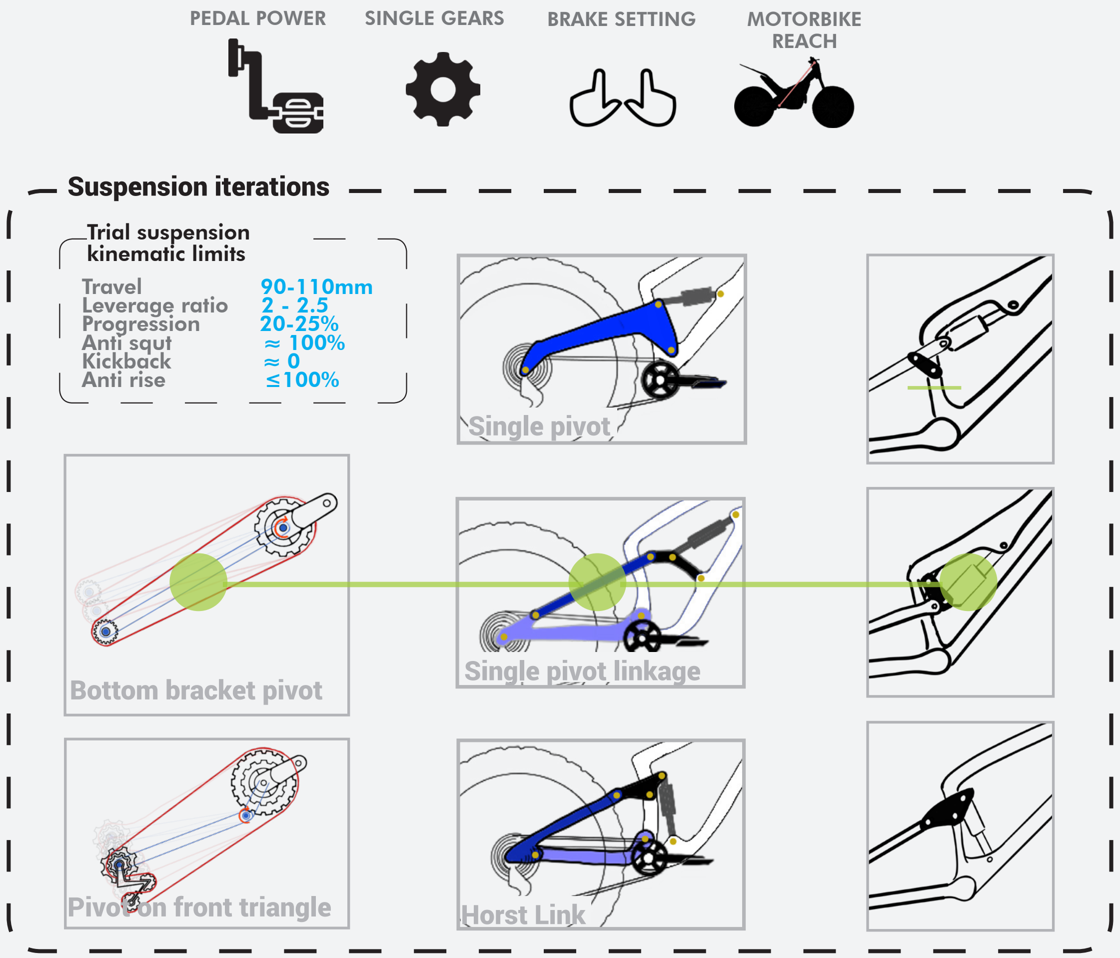


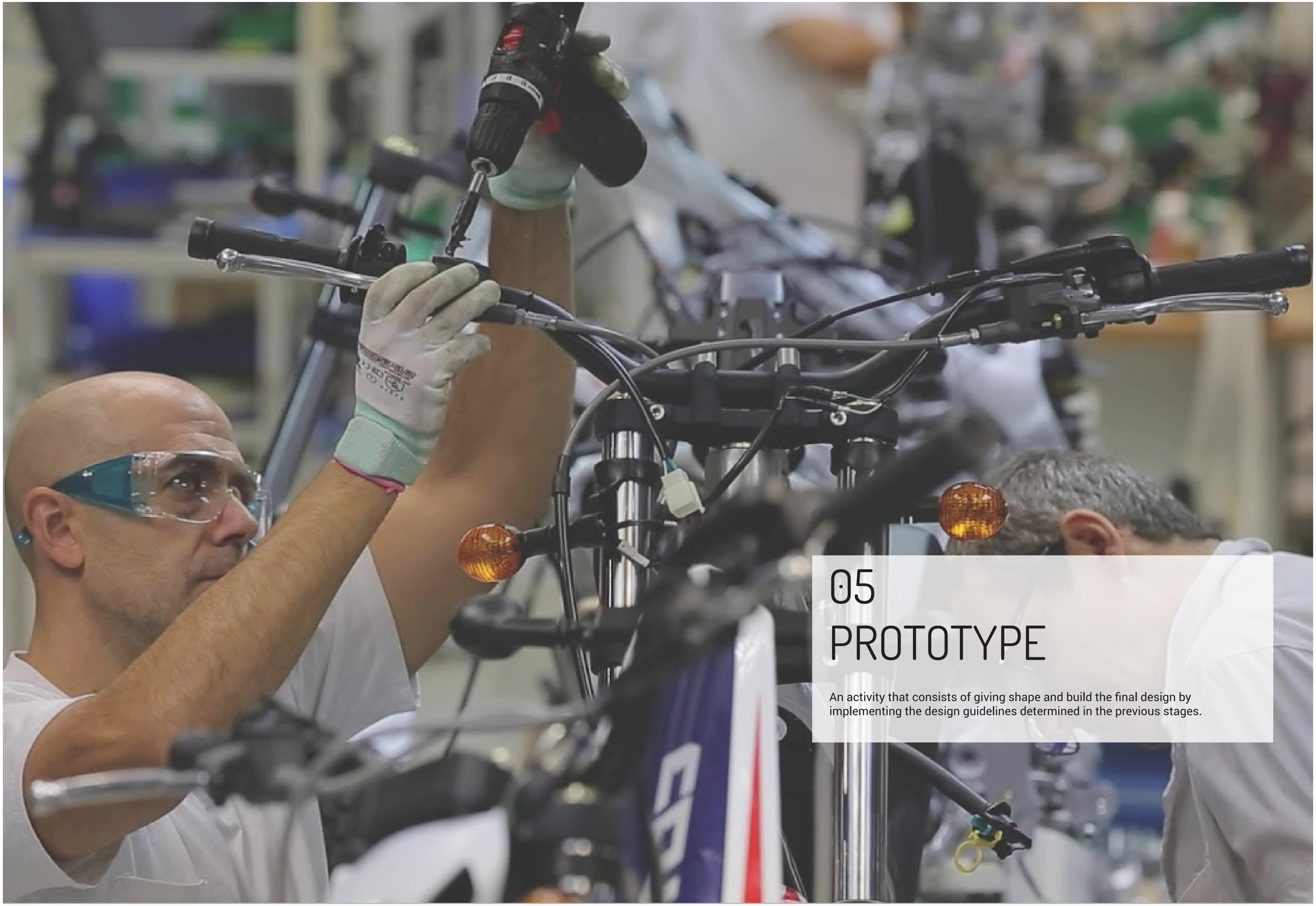
CONCEPT 3
LINKAGE SINGLE PIVOT, VERTICAL SHOCK



DESIGN FREEZE

Thus, the full suspension set-up to be integrated on the trial bicycle has been determined. To begin with, a bottom bracket pivot will be integrated to provide maximum pedalling efficiency by avoiding kickback and anti-squat effects. In addition, the type of suspension system to be integrated is a single pivot linkage, as this one can properly integrate the previously mentioned bottom bracket pivot and it matches best with the design requirements. Finally, the linkage set-up consists of a rocker arm placed inside the front triangle with one pivot point on the top of the frame, another one on the end of the seat-stay, and the last one on the shock. The shock is placed horizontally occupying the least amount of space inside the frame (nomenclature of bicycle components and parts can be found annotated in appendix B).





05
PROTOTYPE

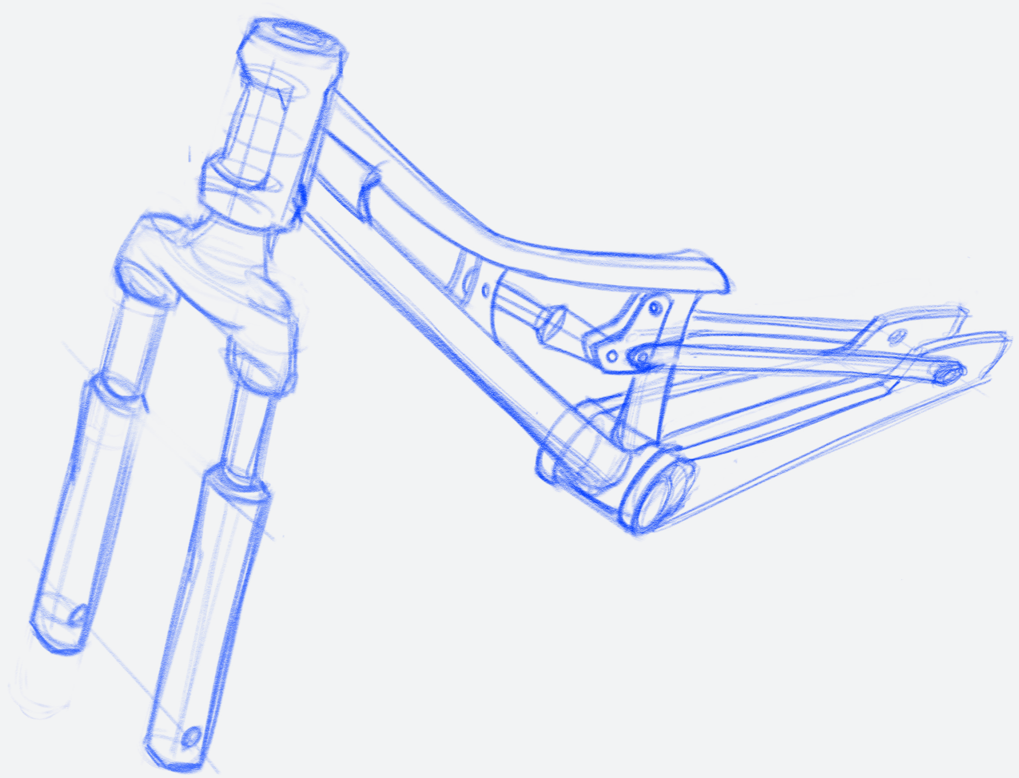
An activity that consists of giving shape and build the final design by implementing the design guidelines determined in the previous stages.

Factory of Montesa Cota, 2018

MINIMUM VIABLE PRODUCT

Upon having determined the main parameters of the new design, the following consists of technically developing the design for production. A minimum viable product is to be designed and built in order to conduct user tests and evaluate whether it complies with the expected performance requirements that make it more suitable for motorcyclists to train with compared with conventional trial bikes, as stated in the hypothesis.

Parametric 3D drawing software has been used to give shape to the full complexity of the design. Once the design was completed, drawings and other files have been facilitated to a metal manufacturer specialized in building motorcycle frames (Derivados Del Motor S.L.) who have built the final model.



FINAL KINEMATICS

All design guidelines are now placed together to conclude with a final design that is chosen to be further developed. The design is first drawn in 2D on the program Linkage (version X3; Racooz Software, 2019) to specify the final kinematic values.

As a consequence of having a suspension, the bicycle frames experiences deformation, therefore the geometry slightly changes along wheel travel. It has been considered that the geometry design guidelines must be reflected in the frame when this is in its neutral position. The neutral position in this case is considered to be the position of the frame when the rider is positioned on top of the bicycle. This is also known as the "sag" position of the bicycle (Setting Sag on Mountain Bike Suspension, n.d.). In the sag position, the front and rear suspension should compress approximately 25% of their total travel (Setting Sag on Mountain Bike Suspension, n.d).

The final design has the following kinematic properties for the rear suspension. To begin with, the total suspension travel is of 101mm. A shock with 40mm stroke is used therefore it has a leverage ratio of 2.5 (Graph 4.a). In addition the leverage properties are progressive, with a progression of 25% (starting at 2.65 and ending at 2 mm of wheel travel per each mm of shock travel). The leverage is slightly progressive at the beginning and becomes steeper upon overpassing the sag level (at 25 mm of shock travel).

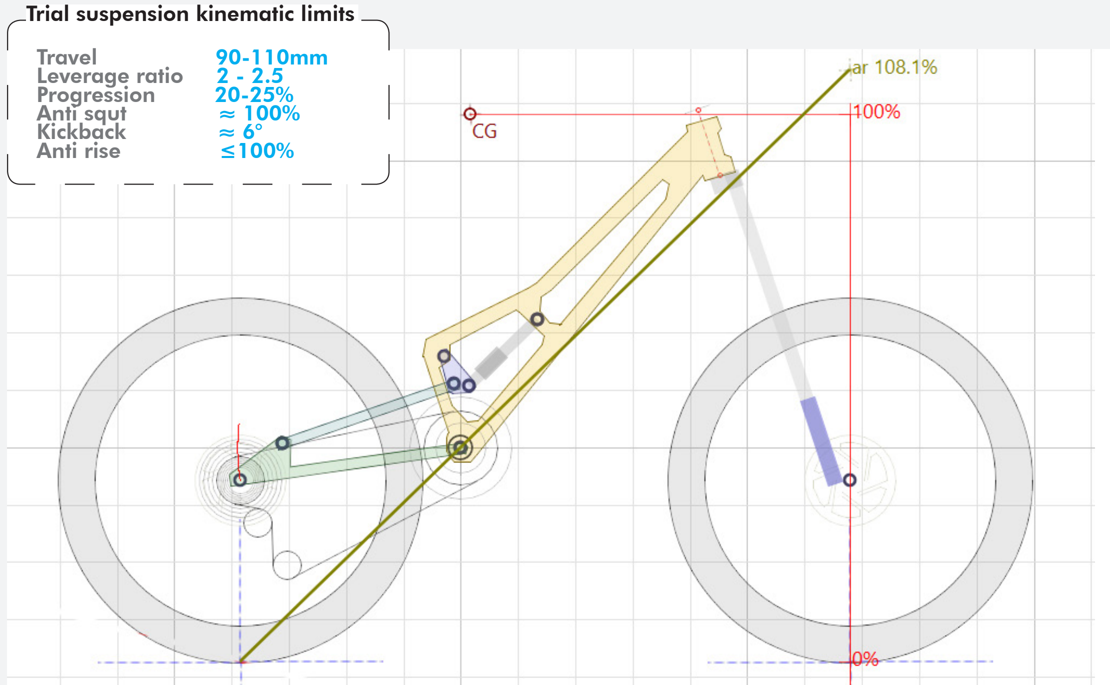
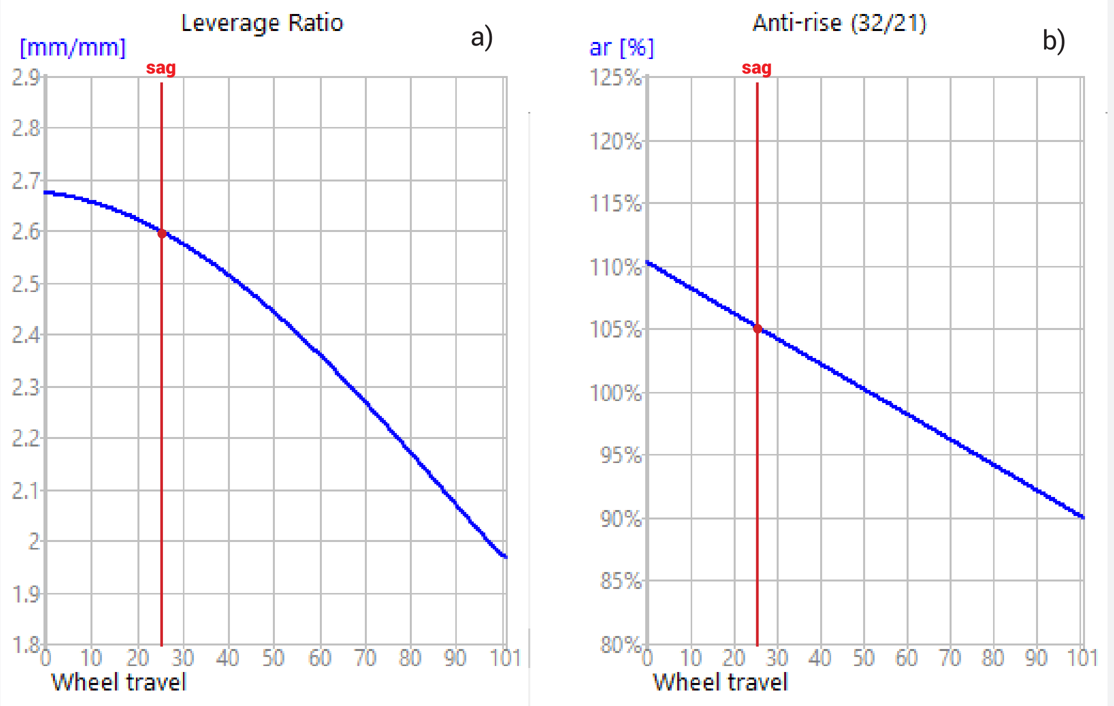


Figure 43. Final design in the sag position, developed with the use of the software linkage.

Regarding the anti-rise values, considering a center of mass (combined weight of cyclist and bicycle) at a height of 520mm over the bottom bracket, it ranges from 110% to 90%. With a value of 105% approximately at the sag position (Graph 4.b).

Summing up, the model ultimately has an expected rear suspension, with 5-10% more leverage than trial motorcycles to compensate the lack of power. In addition, the shock should remain quite stable under braking forces of the rear wheel, with the possibility of causing some slight extension of the shock.



Graph 4. a) Leverage ratio along wheel travel. b) Anti-rise along wheel travel.

DESIGN 3D MODELING

Based on the 2D scaled template of the final bicycle model obtained with Linkage (figure 44), the whole model of the bicycle has been drawn with the use of 3D modeling software Fusion 360 (Version 2.0.5688, Autodesk, 2019).

The five required components for constructing the frame (front triangle, chain-stay, seat-stay, rocker arm, and bottom bracket holder) were modeled first. Subsequently, all of the other standard bicycle components were added to the model to make sure they fit properly and that there would be no collision.

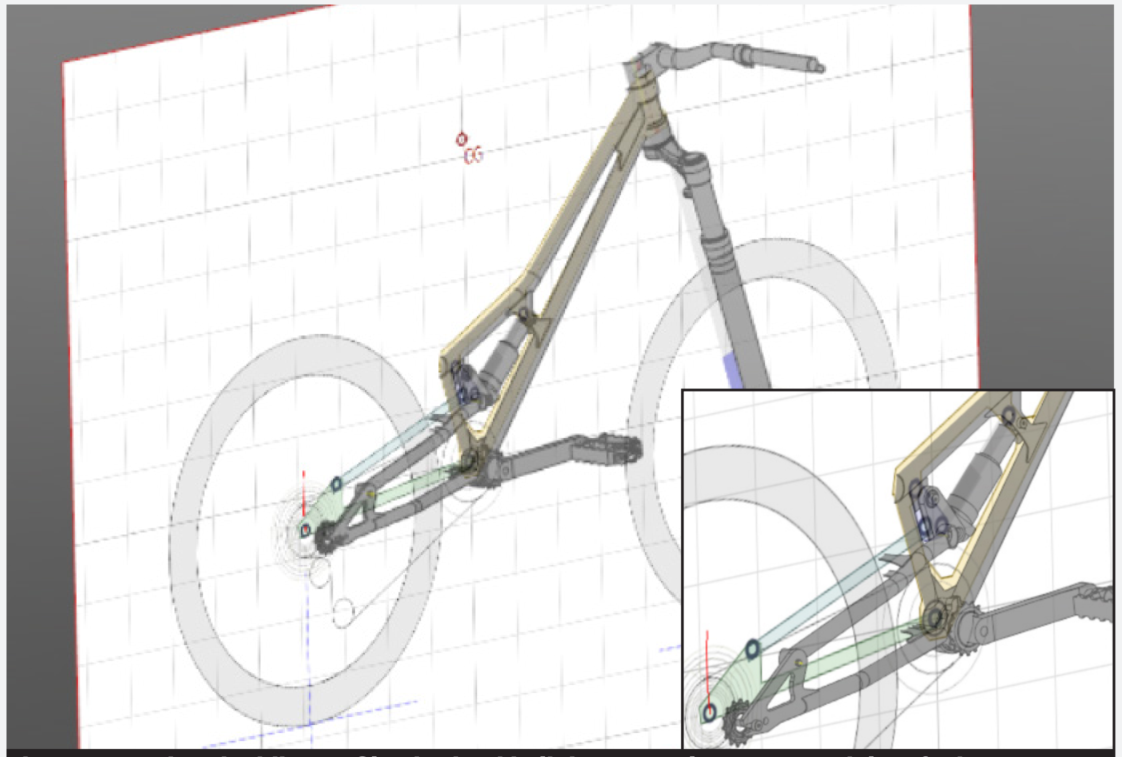


Figure 44. Using the bike profile obtained in linkage as a layout to model on fusion 360.

The main components of the frame were assembled together with the use of articulated unions, most of the time pin revolute unions (it restricts 5 degrees of freedom and lets free one degree of rotation). With the use of this unions it could be directly observed whether there would be any collision of components along the whole distance traveled by the suspension.

All components were modeled with multiple separate bodies because many of these components require welding multiple bodies that are manufactured separately. By separating the components into bodies, the manufacturers can obtain separate digital files and work properly.

All the processes are metal manufacturing related and this included bending tubes, sheet laser cutting, milling, and in some occasions some turning.

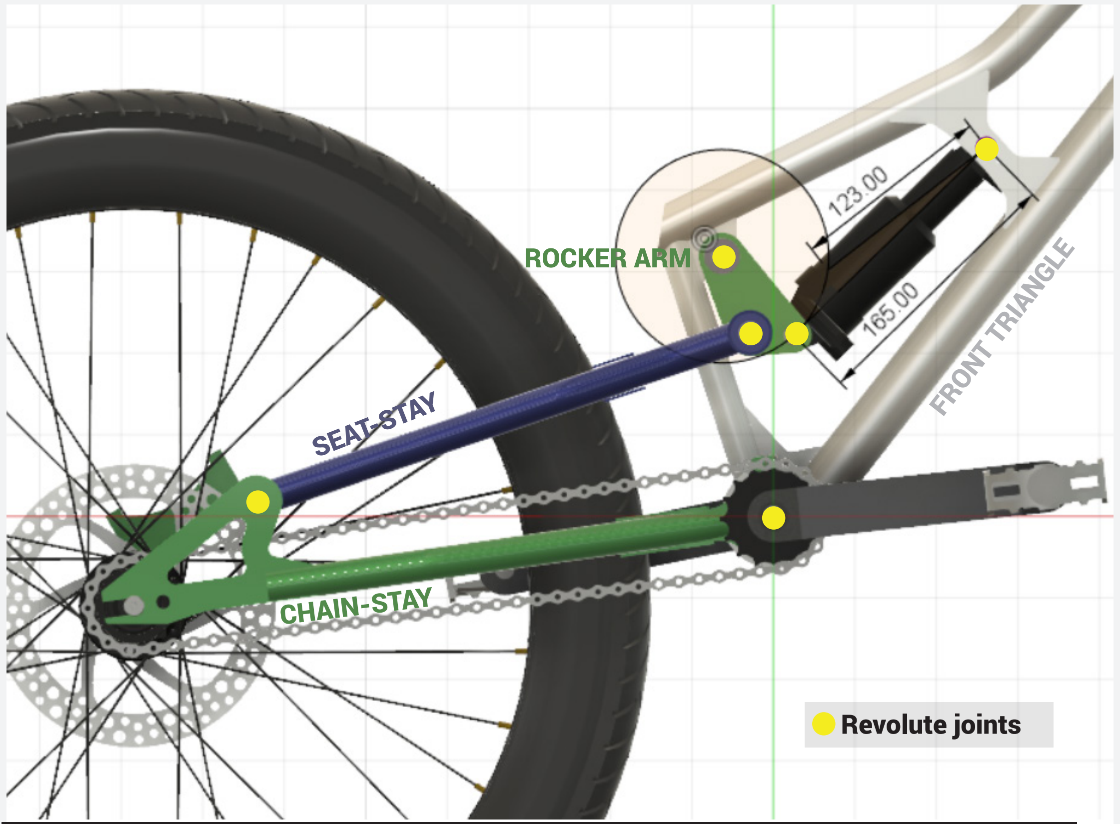


Figure 45. Complete 3D model naming each separate component of the frame.

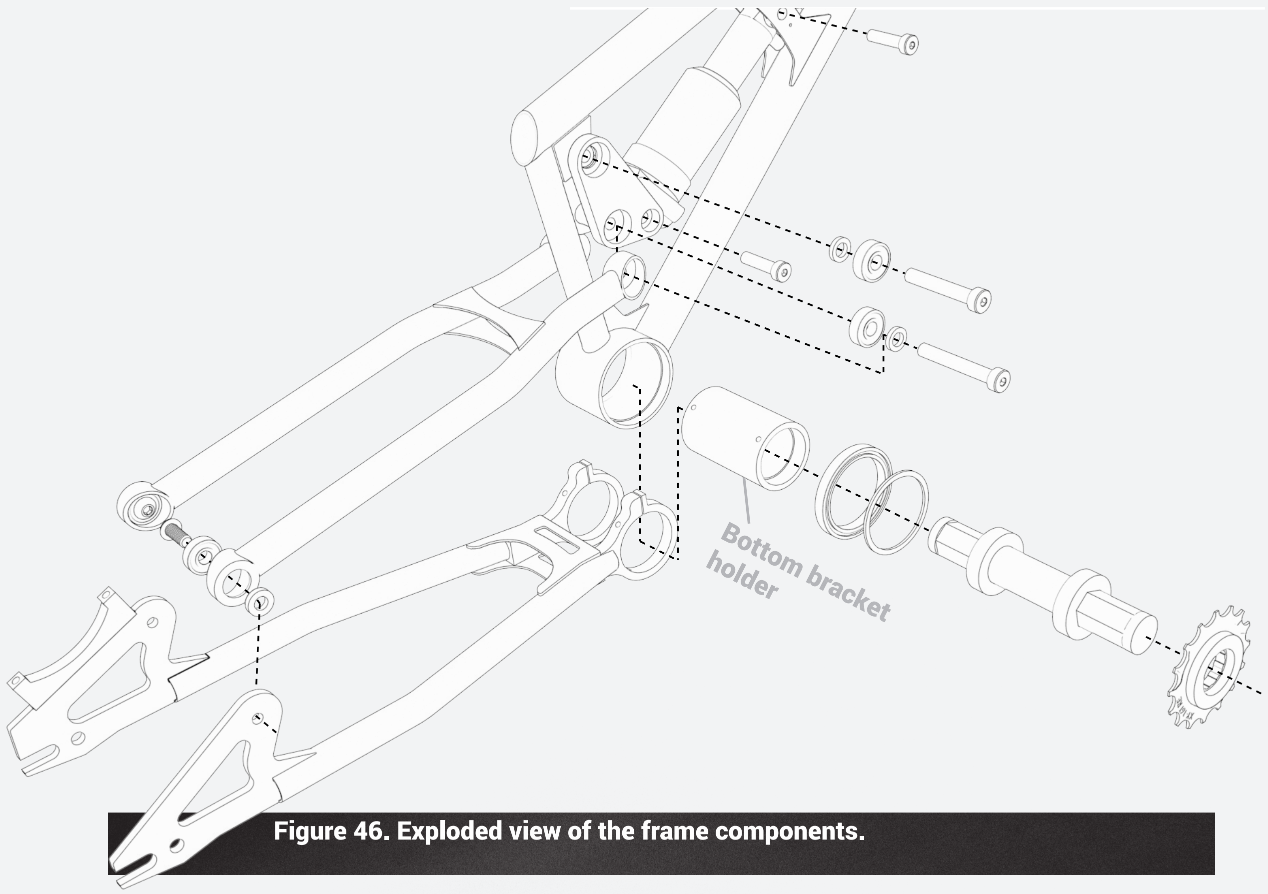


Figure 46. Exploded view of the frame components.

UNIONS

For the construction of the frame, all bodies are welded to their corresponding component. Furthermore, as each component is part of the quadrilateral, they are assembled to each other with a pin joint.

A pin joint is a joint with only one degree of freedom that consists of a rotation. For a smooth rotation, these assemblies are done with the use of bearings inserted in the many frame parts. The attachments and proper separation of components is done with the use of bolts, nuts, and washers.

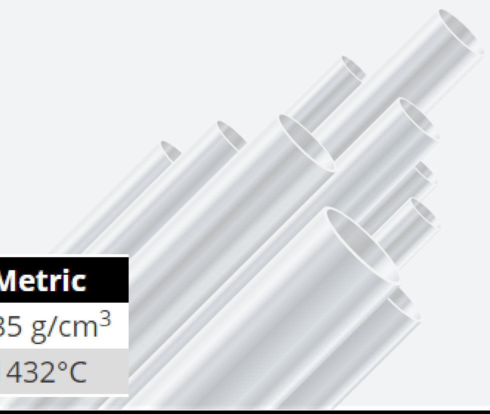
MATERIAL SELECTION

The entire frame is created from the same material. The material chosen for this development is an AISI 4130 alloy steel, also commonly referred to as a chromoly steel. This is known to be a material with good weldability and low oxidability.

AISI 4130 has great mechanical values and it is relatively cheap, however it is not a light material. For the elaboration of a minimum viable product it has been decided that it is good enough, considering that the lighter options are more complex to manufacture and would therefore greatly increase costs. The tensile strength of this material is approximately 560MPa, it has a density of 7.8e3 Kg/m3 and an approximate cost of 0.7 €/kg (Table X).

In addition, this material is commonly found in the industry in sheets, tubes, and blocks, which makes it very versatile for working on many different types of manufacturing processes to develop complex structures.

A material selection process has been done following the Ashby method on software CES selector (Cambridge Engineering Selector) (Granta, CES Edupack, 2018). A filter has been applied to only compare metallic materials that can be machined and welded. Furthermore, these materials have been compared in terms of Young's modulus and cost of the material (Appendi K). The values for AISI 4130 were found be cheap and resistant .



Properties	Metric
Density	7.85 g/cm^3
Melting point	1432°C

Properties	Metric
Tensile strength, ultimate	560 MPa
Tensile strength, yield	460 MPa
Modulus of elasticity	190-210 GPa

Table 7. Some of the properties from AISI 4130 (AZom, 2012).

SIMULATIONS

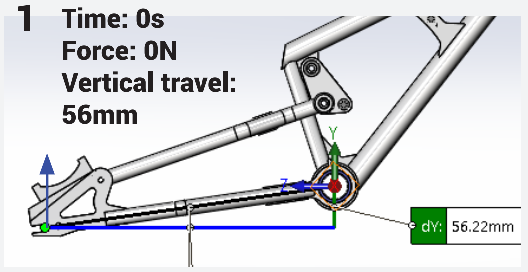
With the use of Solidworks simulation software (SolidWorks SP0.0; Dassault Systèmes, 2019) in combination with the motion study add-in, certain simulations have been carried out. First, the behavior of the suspension system has been observed when an estimated force is applied to it. Second, a finite element analysis was conducted to measure tensions on the component submitted to the most stress.

MOTION STUDY

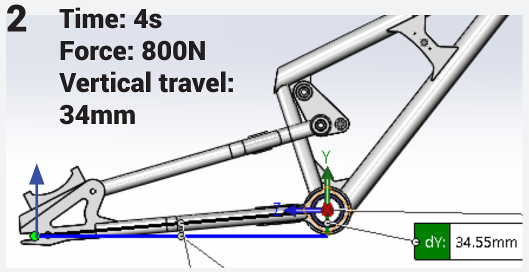
The mechanism of the bicycle frame has been replicated on Solidworks, a spring damper system positioned, and a sequence of force have been simulated, to see how the frame deforms when submitted to variable forces.To describe the travel, the vertical distance between the bottom bracket and the rear wheel axle are measured at different stages.

The force sequence applied simulates a cyclist performing a jump. The first force applied, is the weight of the cyclist, therefore 80Kg (as this has been determined to be the average weight of a target user) in second 4. Then the rider performs a jump so 1881N are progressively applied and then the cyclist lands and gets off of the bicycle. The value of 1881N is considering that the cyclist applies a force to the pedals of 2.4 times their mass (Mazmanian, 2018).

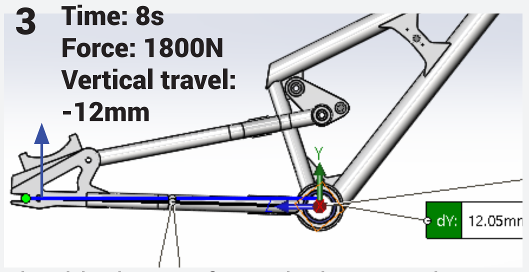
As a result, the maximum force is applied during the jump, where the wheel axle makes a vertical travel of 68mm.



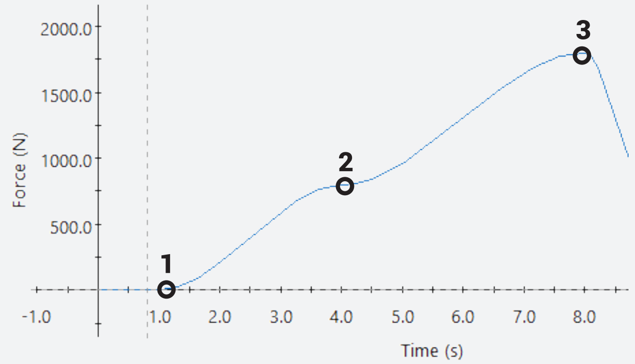
No weight is applied on the mechanism, therefore there is no rider on the bicycle.



The rider climbed over the bicycle and is in a static position (sag position).



The rider has performed a jump on the bicycle.



FEM SIMULATION

As this is the most critical step in the motion study simulation, a finite element analysis has been carried out on this movement, thus, in a case scenario of a jump with the bicycle, with a force of 1881N on the rear wheel. The analysis was conducted specifically on the rocker arm since it is the component that experiences the most tensions. For the analysis the front triangle has been fully constrained.

The results given show a maximum load of 2.069e08 (N/m^2). Considering that the elastic limit of AISI 4130 is approximately 4.600e08 (N/m^2), it can be estimated that the design is safe from plastic deformation, with a safety factor of 2,2.

In addition to the rocker arm, a separate simulation has been done on the chainstay housing part that holds the bottom bracket holder. However, it has been encountered that this component is far from suffering deformation or getting broken as the maximum stress it suffers is of 27.47Mpa and the material has a yield strength of 460Mpa.

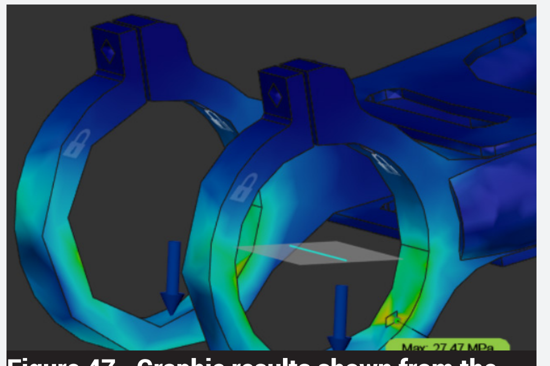


Figure 47. Graphic results shown from the FEM analysis on the chain-stay housing.

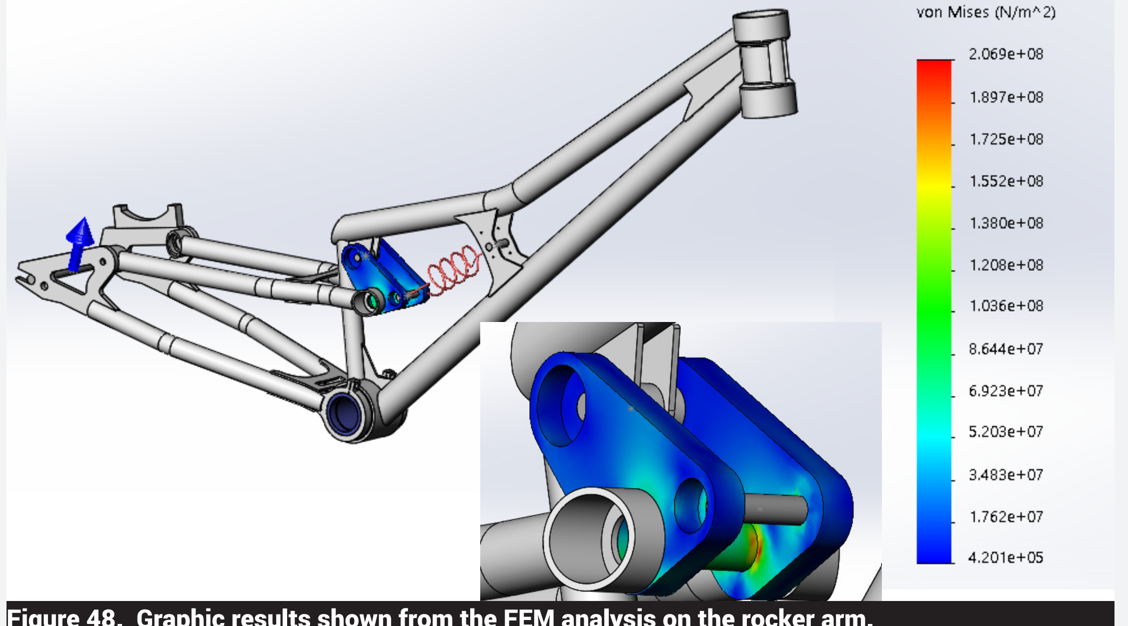
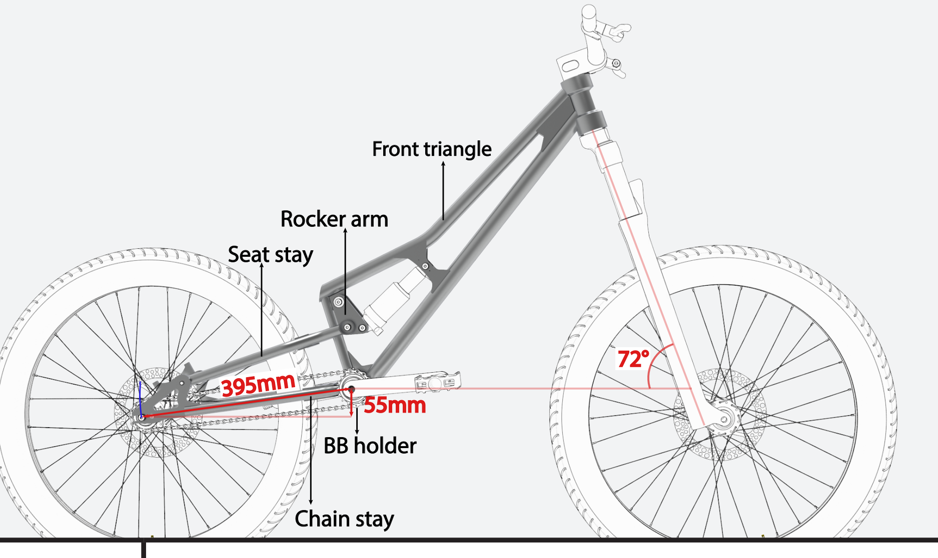


Figure 48. Graphic results shown from the FEM analysis on the rocker arm.

MANUFACTURING

The whole model has been constructed with the idea of producing an inexpensive prototype. Therefore, the manufacturing process used, are for a low production amount of units. However, to test the model properly it is essential to make a fully functional prototype that can be used to validate our hypothesis.

The frame has been constructed with the use of steel parts manufactured with laser cut steel, bent tubes, milled and turned parts, and finally all the parts were positioned on jigs to weld them together with maximum precision. The overall weight of the frame is 5,7 kg.



Item	DESCRIPTION
Front triangle	Tube bending and cutting, laser cutting sheet, turning and welding it all together with the use of a jig.
Seat stay	Tube bending and cutting, laser cutting sheet, turning and welding it all together with the use of a jig.
Chain stay	Tube bending and cutting, laser cutting sheet and welding it all together with the use of a jig.
Rocker arm	Laser cutting sheet, turning and milling.
Bottom Bracket Holder	Turning and drilling.

A close contact with the manufacturers has been established ever since the design was in its first stages of 3D modeling. Furthermore multiple meetings took place to evaluate the model and discuss all the construction arrangements.

Before engaging in the construction of the final design, drawings were sent to the manufacturers together with 3D files. Then they developed the three jigs required to construct the front triangle, the chainstay, and the seatstay. After that, they developed all the parts separately and then they placed all the components on the jigs where they were finally welded.

The total cost of developing the frame for this minimum viable product was of €1200 for the three jigs required, and €1500 for the frame components. With an overall cost of €2700.

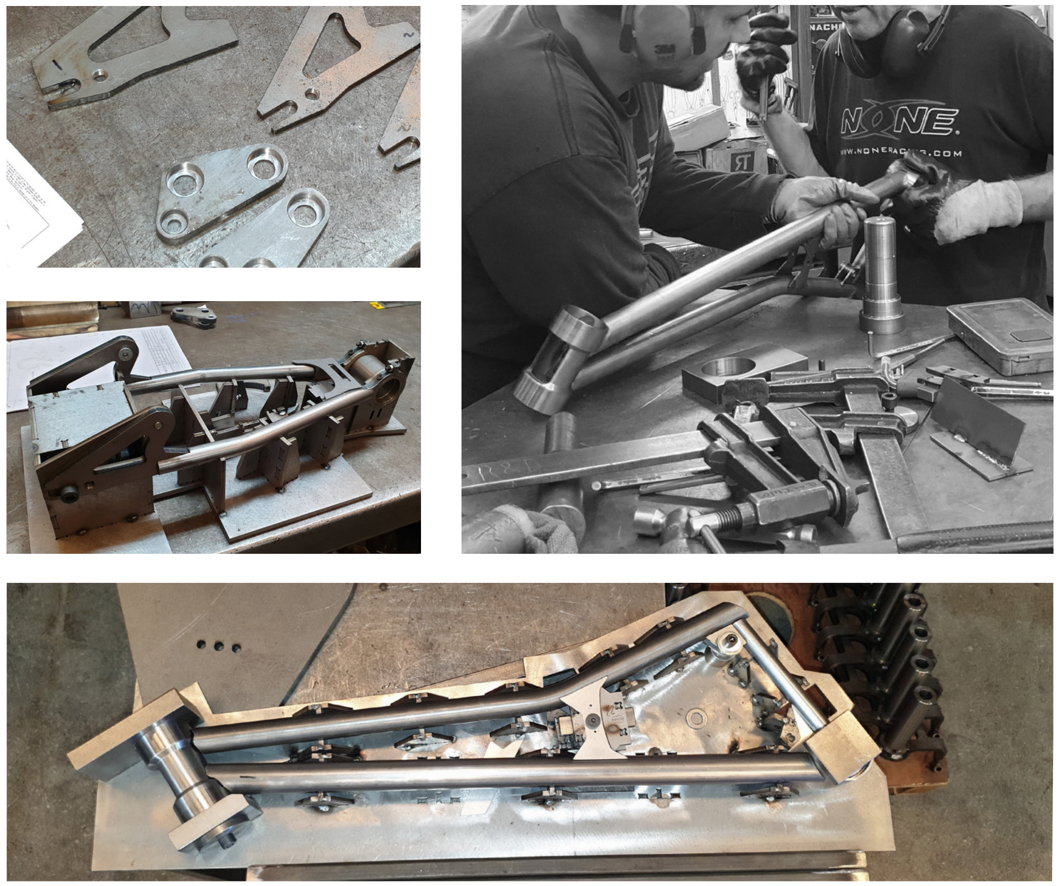


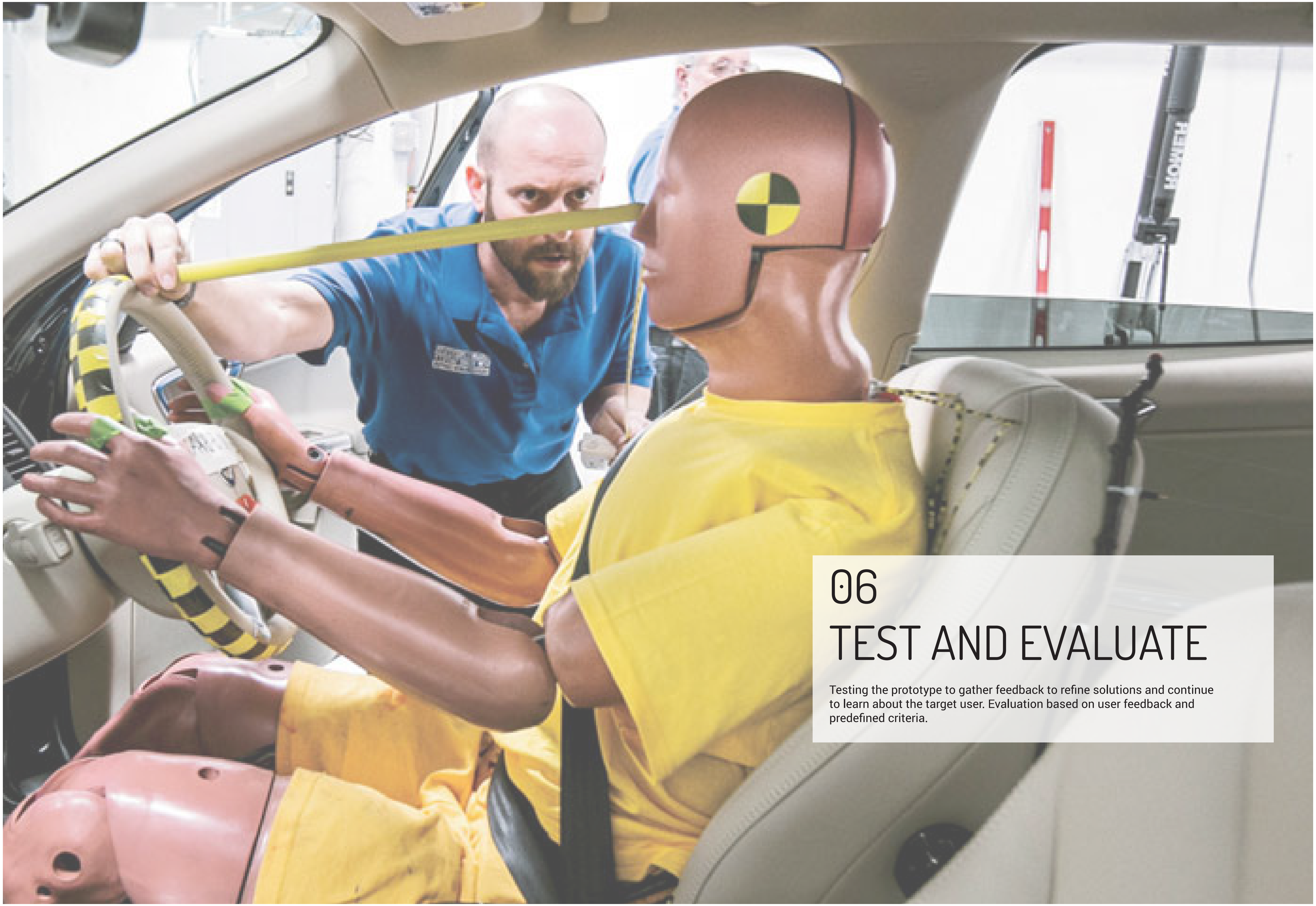
Figure 49. Photos taken during the assembly journey at the Dmotors factory (Engine derivatives).

PROTOTYPE

Upon building the components of the frame and assembling them all together, the rest of the bicycle components were mounted. The components used are components designed specifically for trial bicycles, such as rims, tires, handle bar, disc brakes, steam, chainring, crank arms, etc.
Regarding the suspension shock and fork, adjustable air pressure systems are used so that the correct settings of air pressure and rebound can be encountered by testing. The suspension fork has a stroke of 160mm, and the rear shock measures 165mm overall with a stroke of 42mm.

The cost of all the added components was approximately €1300. Therefore, the overall cost has been about €4000 for the construction of this prototype.

Figure 50. Completion of the minimum viable product in adequate conditions for testing.



06
TEST AND EVALUATE

Testing the prototype to gather feedback to refine solutions and continue to learn about the target user. Evaluation based on user feedback and predefined criteria.

Crash test, Rubolino, 2018

USER TESTING

Now that a working prototype has been built, this one can be tested in order to evaluate and prove the hypothesis that has been defined. During this process, the prototype was first tested in order to get some first impressions about the sensations it evokes and how it reacts when performing trials.

After getting used to the sensations of the new product, a video analysis set-up was prepared in order to observe and compare in a more analytical way the interaction of the new product in contrast with the trial motorcycle and the trial bicycle. This is done as an exercise to gain more insights about the gestures, and the general influence of the new implementations.

Figure 51. Final prototype being tested at a bike-trial park by a professional trial rider.

SUBJECTIVE OBSERVATIONS

Throughout this process, the bicycle was tested and some objective feedback from the sensations it evokes were discussed. Furthermore all the settings were properly adjusted to obtain the best sensations possible, such as the air in the wheels, pressure in the shock and fork, angle of the handlebar, among others.

The main impressions from design is that it indeed feels like a bicycle to perform trials as the pedaling sensation is impressive and it responds in the same way as a trial bike to pedal strokes.

Furthermore, the implementation of suspensions can not be ignored as the bike has an innate bounciness totally which is unusual in these bicycles. Performing trial moves is possible, but it only works well if the rider coordinates their gestures with the compression and rebound from the suspensions.

Finally, the vehicle feels slightly too heavy, as it weighs 14kg overall, while most trial bicycles tend to range from 8 to 12kg. This aspect is not so negative if you consider that motorcycles are much heavier, so in a way it is closer to the sensation of being on a motorcycle, however it does decrease the performance ability of the cyclist.

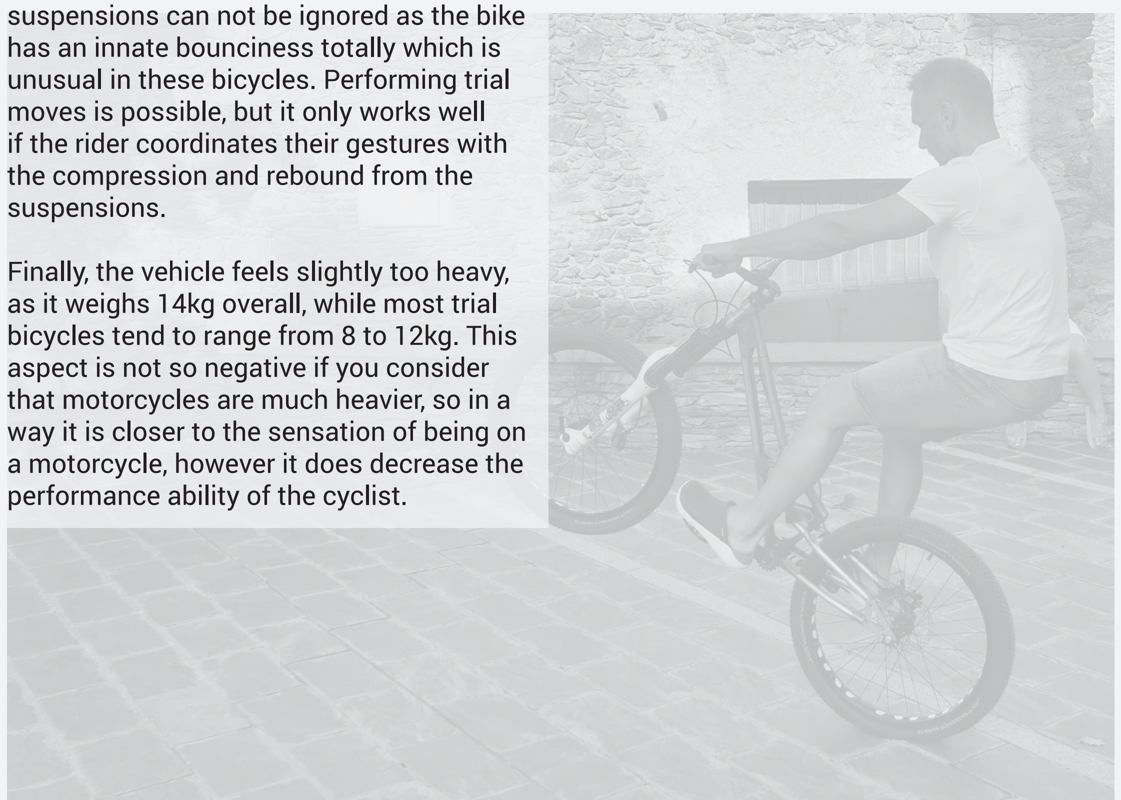


Figure 52. Trial rider Xavi Casas testing and adjusting the setting for ideal performance.

VIDEO ANALYSIS

In this case, the goal of conducting a video analysis is to obtain more objective information to test whether the performance of the cyclist on the new product mimics more closely the way it is done on the trial motorcycle so that motorist can do training of specific components of fitness. Therefore, the exact same obstacle will be overpassed with a conventional trial bicycle, a trial motorcycle, and the new design and video footage will be compared. With this information and the feedback from the user that tested the bicycle, a more accurate description of the new design can be done, and the hypothesis can be proven or disproven.

Video analysis is the most objective source in terms of feedback of sport technique improvement, because it provides the most objective feedback and understanding (Grahammer, Newton, 2013). In this case, video analysis enables objective feedback, in part because the technique will be observed, but also the behavior of the bicycle. Three main aspects are to be analyzed: first, the trajectory followed by the front and rear wheel to see whether there are differences in the pattern they follow. Second, the flexion of extremities will also be observed as it provides information regarding the gestures of the rider. Finally the pattern of compression and extension from the front and rear shock on the new product will be compared to the motorcycle to observe product behavior.

The recording setup is performed in an environment with some obstacle for the athlete. In addition a camera placed stable on a tripod films the athlete performing the same move on all three vehicles. The filming must be done in parallel to the profile of the rider at all times to maintain the scale of the image. Afterwards the footage is observed with the use of the computer software Kinovea (Kinovea.org) that has some basic functions to measure location, trajectory, joint angles, speed and acceleration. The results are not precise as there is some image distortion, however it provides a useful approximation.

Footage from many separate obstacles, which require different essential moves, where recorded. However due to the extent of the study, only one obstacle has been analyzed. Climbing obstacles (described on page 25) consists of an athlete climbing an obstacle while moving forwards. The photo sequence of this obstacle with each vehicle is available in appendix J.

WHEEL TRAJECTORY

In figure 53 it is graphically shown the obstacle that had to be overpassed. First, on the conventional trial bicycle (1) then with the trial motorcycle (2) and finally with the new hybrid design (3). The trajectories from both wheels are shown, in blue the one from the rear wheel and in red the trajectory from the front one.

The most significant factor encountered when performing this move with the motorcycle and the new design, is that in both cases, the edge of the obstacle was hit with the front wheel to generate a kicker effect and compress the suspensions. However, this gesture was much more accentuated in the case of the motorcycle. Other than that, it is interesting to see that the take-off with the motorcycle took place from further away than with the two bicycles. The trajectories of the front wheel upon landing go in two very different directions, but that has more to do with how the athlete continued his course after passing the obstacle.

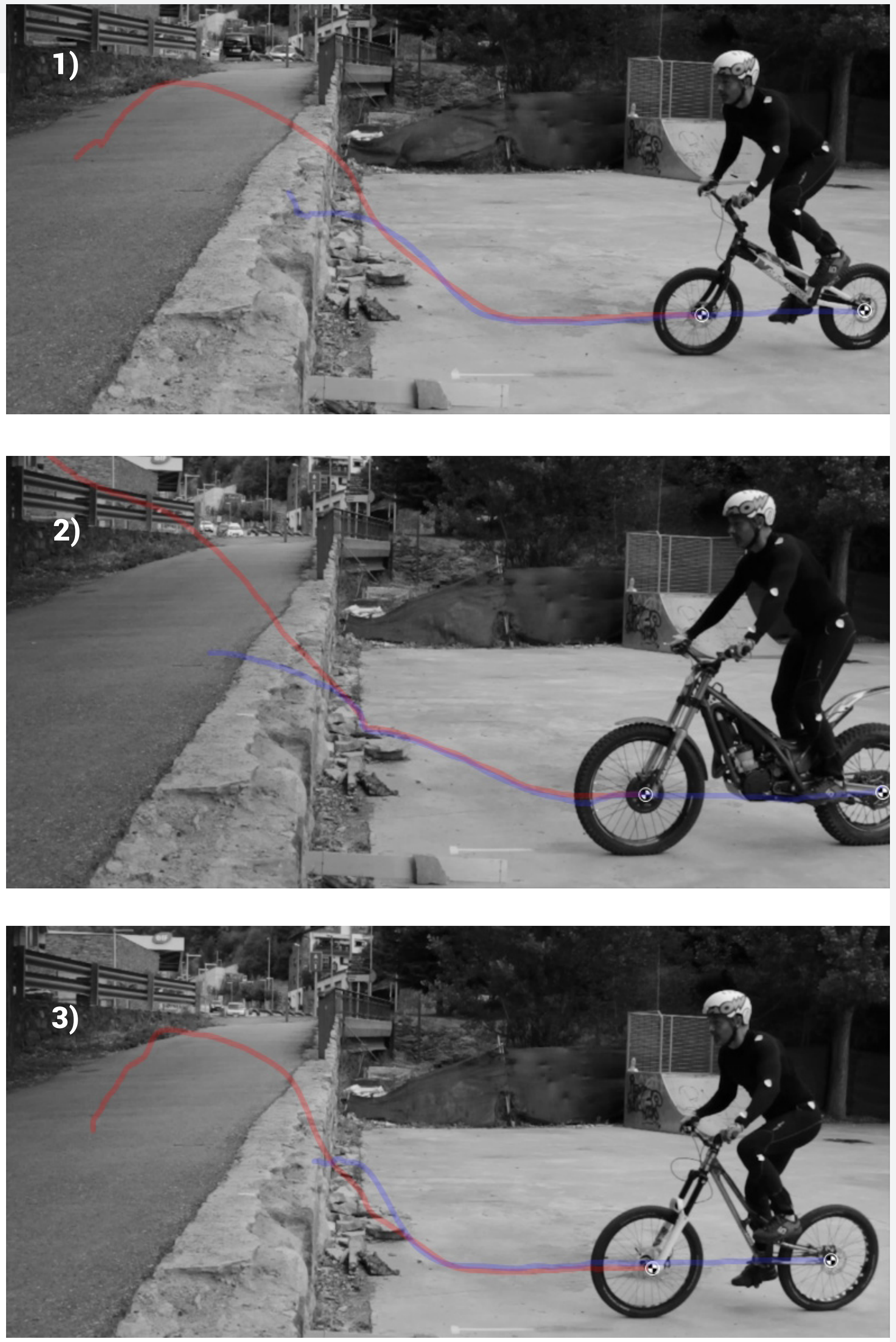


Figure 53. Wheel trajectory on the (1) bicycle, (2) motorcycle and (3) hybrid vehicle.

Gesture performance
With the use of Kinovea, the following six phases of jumping were identified: Preparation, Loading, Impact, Take-off, Flying, and Landing. This phases are slightly modified from the ones suggested in a different study that are specific for bicycle trial (Vastola, Coppola, Albano, Daniele, Elia, 2017), because an added step is identified with the suspensions, namely the “impact” phase. With the use of Kinovea, the frame of these specific phases were identified and captured (Figure 54).

The goal is to observe and compare how much the athlete has to flex and extend arms and legs when performing with the different vehicles. Unfortunately, it was only possible to measure the flexion of the arms, due to the unstable position of the feet on the bicycle. To measure the flexion, a straight line was drawn and measured from the center of the handlebar to the shoulder of the cyclist. The results can be seen in graph 5, where on the vertical axis you can see the degree of arm extension (where high values mean an extended arm and low values a bent arm) and on the horizontal axis the identified phases are shown. Unfortunately, not enough knowledge is available to be able to better comprehend and compare the technical (body motion) performance of the athlete on each vehicle.

It is expected that the athlete on the motorcycle will have to flex their arms less than on the bicycle. Due to the implementation of a suspension and the fact that aspects of the geometry are more similar to a motorbike in the new hybrid design, it is expected that its

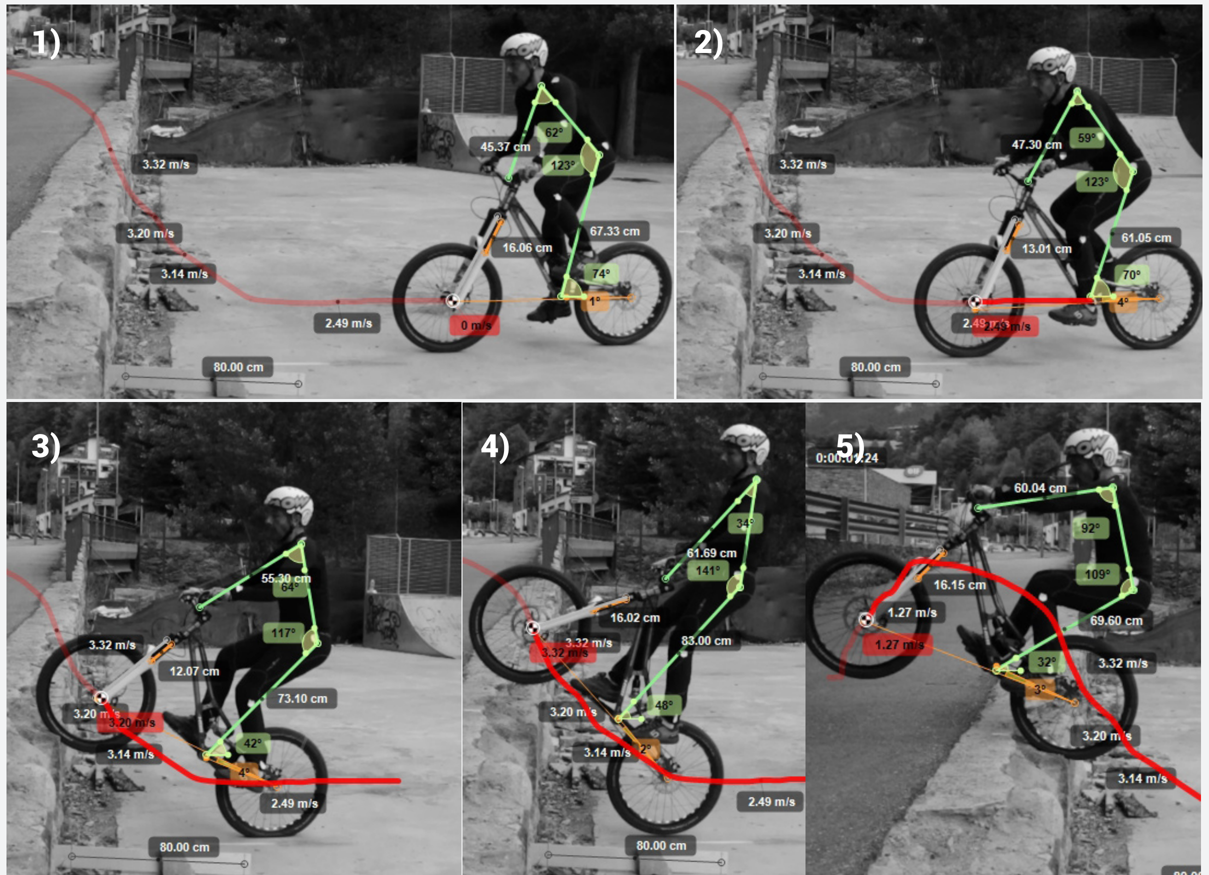
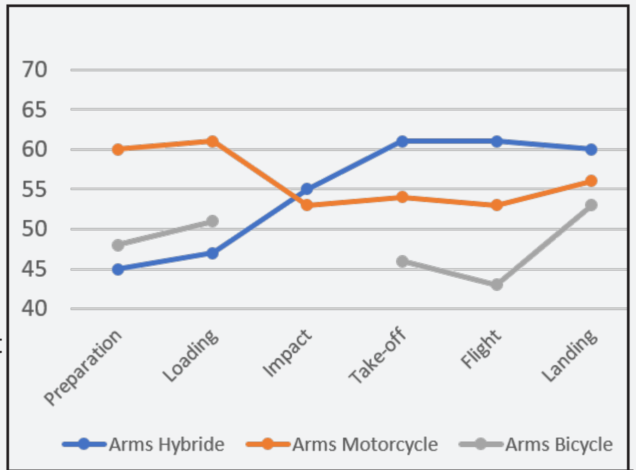


Figure 54. (1) Preparation, (2) Loading, (3) Impact, (4) Flying, (5) Landing

patterns of flexion/extension should mimic more closely those on a motorcycle.
As can be seen from graph 5, in the hybrid design, the pattern of flexion/extension at the beginning of the jump is more similar to the bicycle, with a high degree of flections in the preparation and loading phases. At the end of the jump, there is much more arm extension in the subsequent phases. The hybrid bike is most similar in terms of posture to the trial motorcycle in the impact phase.

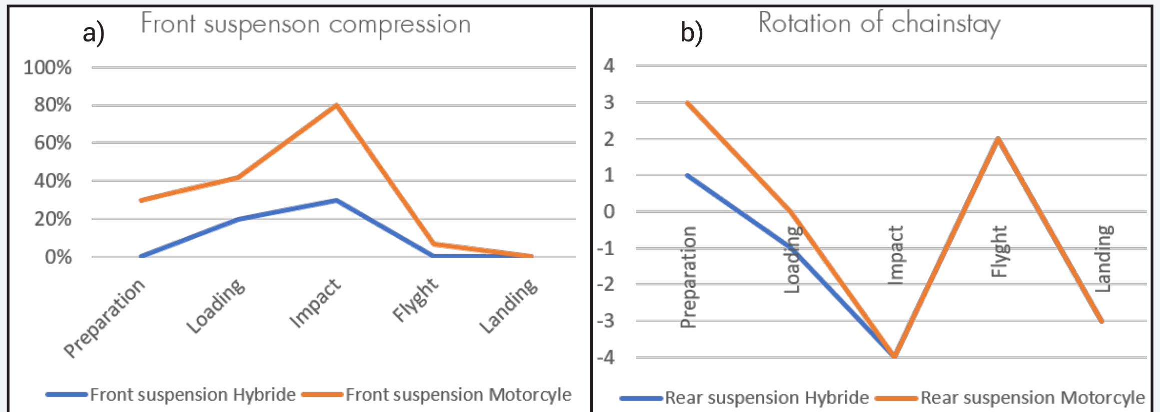


Graph 5. Arm flexion and extenssion on the three rides (Arm length is 70mm).

SUSPENSION ACTUATION
A final comparison is made of how the actuation of the suspension systems takes place in each phase. In this case, only the motorcycle and the hybrid bicycle are used for the analysis. The front suspension is easier to analyze as it has a linear motion, therefore results are shown in percentage compressed from the total travel (Graph 6.a). For the rear suspension, the angle (°) of rotation that the chain-stay experiences in respect to the main pivot point is observed (Graph 6.b).

It is observed that in both cases, the suspensions experience the same traveling pattern, which confirms that the athlete performs the same technical sport gesture. As can be seen in the graph, both vehicles experience the highest degree of compression during the impact phase.

Another observation, is that the suspension of the motorcycle experiences more compression. For instance, during the moment of impact, the front suspension on the motorcycle compresses up to 80% of its total travel, while on the bicycle only 25%. It is assumed that due to the power and much heavier weight of the motorcycle, the athlete is more confident in using the edge of the obstacle as a kicker, while on the bike a strong impact is more likely to cause failure.



Graph 6. a) percentege of compression from the front suspension (%). b) Rotation of the chainstay (°).

EVALUATION AND SUGGESTIONS

GENERAL EVALUATION

Upon having tested and analyzed certain aspects from the performance of the new design, an evaluation can be done regarding the new properties and their influence in trial performance.

The resulting vehicle is a trial bicycle that responds to pedal strokes in a similar way as common trial bicycles do, however the cyclist stands slightly more upright and, most importantly, can get used to the use of suspensions when performing trial moves. One of the first sensations noticed when testing the bike, is that the bicycle worked well but a little bit too heavy for performing trials comfortably. The presence of suspensions was also immediately noted, as the response from the vehicle is very different when trying to perform any type of jump.

Furthermore, from the video analysis it was observed how the integration of the suspension requires the athlete to do an additional step when performing trial moves. These extra steps require the rider to practice moves that are uncommon with the trial bicycle, such as using kickers for jumping. It was also observed that the pattern of compressing and extending the suspension was the same although its usage was more accentuated on the motorcycle.

This product is expected to be of interest for professional trial motorcyclists as it allows them to occasionally go back to biking while reducing learned skill errors usually transferred with common trial bikes. In addition, the product is also of interest for amateur trial motorcyclists as it provides a fun way to train that enhances the learning of basic, essential trial skills. Furthermore, training can be done more regularly as it is more economical and it can be used wherever they like.

The appearance of the design is familiar to those acquainted with trial biking, however it could convey its relation to the motorcycle discipline more in the aesthetics. Although the total cost of the prototype (considering cost of frame, jigs, and components) was about €4000, it is estimated that the final cost of production and mounting components could be of approximately €900 per unit.

RESEARCH QUESTION

With the full development of the design being conducted and a functional prototype being tested, we now have enough insights to answer the research question (page 7). The question was: Does the integration of a suspension system in a trial bicycle mimic more closely the usability of a motorcycle trial, and does this make it more suitable for cross-training the motorcyclists?

It was discovered during the design process that suspensions have a large influence on the coordination of trial riders when performing essential trial moves, as they have to actuate this element before making any type of jump. Learning to properly use the suspension is complex since it requires the athlete to adjust the timing of compression well and wait for the rebound before performing the next move. In addition, interviewed trial riders insisted that (due to the technicality of the discipline) in order to become good at trials, they mainly have to train sport-specific, which for them consists of doing obstacles with the motorcycle.

The main components of fitness used in trials are anticipation, balance, and coordination. These same elements are also the most determinant for bicycle trial riding. However, as there are less elements to control on a bicycle, the coordination is easier and different. The integration of a suspension makes coordination more similar on both vehicles, which as a result confirms that a trial bike with suspension is more suitable for cross-training motorcyclists than a conventional trial bicycle. On the other hand, suspensions were not found to be the most differentiated element of the interaction, rather this was the difference of power.

These statements were later supported when testing the minimum viable product. It was observed that when performing a trial essential move, the new vehicle enhanced additional phases of the sports gesture which are common in the motorcycle trial discipline but not in bicycle trial. However, the actuation of the suspensions was much more delicate than on the motorcycle, which is presumably due to the lack of stiffness and power a bicycle has in comparison with a motorcycle. In order to partially compensate for this lack of power, the rear suspension from the bicycle was made slightly more progressive than what is common on a motorcycle. However, from the analysis we see that the actuation of the suspension in the motorcycle is still more forceful.

SUGGESTIONS

For future development of this product idea of a bicycle for cross training trial motorcyclists, some suggestions are proposed.

The advantage of the product developed up to now, is that it has considered the fundamental requirements for mirroring the usability of the trial bicycle. However, many interesting implementations can still be added (even to the already built prototype) to test more versatile options.

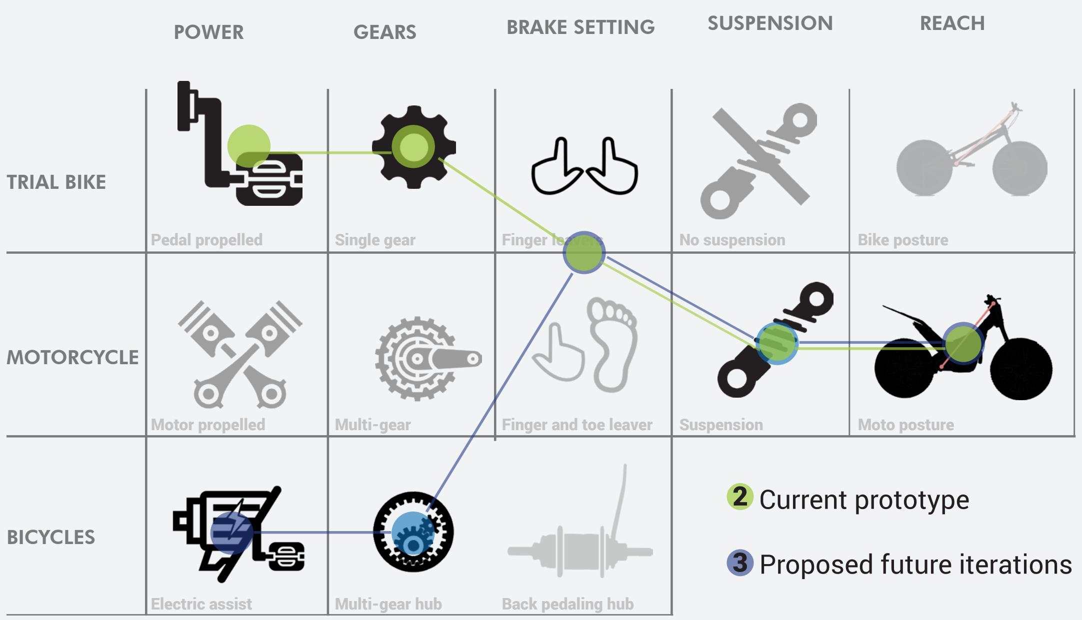
1-Repetition of user tests with a wider variety of obstacles that require different essential moves, and allowing the athlete more time to train with and get used to the new bicycle beforehand.

2-Marketing research to measure customer interest in this product and their willingness to pay, in order to assess the market potential of the product.

3-Test options to compensate the lack of power in a bicycle, as it is one of the main influences of coordination and technique on the motorcycle. For instance, I propose the following options:

a)Consider the implementation of a pedal assisted electric motor as it might increase the specificity of the motorcycle discipline.

b)Integrating a gear hub could increase the power while making it a more versatile vehicle.



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