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Measurement method for stiffness of full suspension mountain bike frames

Correlation between measured and perceived stiffness

Master's thesis in Product Development

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Abstract

The interest in mountain bike riding has grown significantly in the last decade. One reason is improved bike technology. Bikes are being developed faster and quality is raising. Bike manufacturers need to look for new methods to keep up with the rapid development. This project was carried out in collaboration with the German bike manufacturer Canyon Bicycles. Canyon needed a new method for measuring frame stiffness of mountain bikes. Frame stiffness has an impact on the riding experience. Canyon believed that the existing methods for measuring frame stiffness did not correlate with the riding experience of the bikes, especially regarding so-called full suspension mountain bikes. The aim with the project was to examine the perception of frame stiffness and develop a new measurement method in which the measured values would correlate with the riding experience.

The subjective perception of the frame stiffness was examined in a survey study that indicated that the frame stiffness had a varying degree of impact on different riders. The riding situations in which most people seemed to be affected by the frame stiffness was when cornering or riding through rough terrain. Those two situations were broken down and quantified into the forces causing the noticeable frame deflection. The most critical load case was estimated to be lateral force on the rear wheel. The deflection caused by angled as well as horizontal lateral forces towards the rear wheel were examined through experimental testing. Eight different frames were tested, and the result were compared with a subjective stiffness reference that was created as part of the survey study.

A test with a force of 450 newtons fully horizontal towards the rear wheel gave the best correspondence with the riding perceptions of the frame stiffness. More research is needed to confirm the findings and to get a better understanding of the perception of mountain bike frame stiffness.

Keywords: *full-suspension mountain bike, riding experience, feeling of stiffness, test method.*

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Word list

The following list contains explanation of topic-specific words and expressions that are used in the report. They are marked as italicized the first time they are mentioned in the text. For bike frame designations see section 2.1.1.

Berm – an inclined corner, common on bike trails, especially in bike parks.

Bike Park – area for downhill bike riding where ski lifts are used for transportation uphill.

Carbon – (carbon fiber reinforced polymer) composite consisting of carbon fiber and a polymer. Light weight and strong material often used for sports equipment such as for bike frames and components.

Cross country – mountain bike discipline with riding in mixed terrain, often with high intensity.

Crankset and crank arms – the part of the drivetrain in which the motion of the riders' legs is transformed into rotational motion of the chain and back wheel. It consists of the chainring, which drives the chain and the **crank arms** which are the levers for the pedals.

Downhill (-riding) – mountain bike discipline solely focused on riding downhill ski lifts or similar are used to get up the hill.

Dummy – a standardized replacement part.

Drive side (/non-drive side) – the right- and left-hand side of the bike respectively.

Enduro - mountain bike discipline where the downhill sections are in focus, but the rider still pedals up the hills. A little more downhill focus than *trail*.

Full suspension mountain bike – a mountain bike with suspension in the fork and in the frame.

Frame linkage – the system of different part of the full suspension frame and rear shock absorber connected with bearing or bushing that allows the frame to compress when exposed to impacts.

Hard tail mountain bike – a mountain bike with suspension only in the fork.

Pivot points – points of the full suspension frame around which rotations happens when the frame and suspension is compressed.

Rear shock absorber – the rear suspension on a mountain bike frame, constituting an air or steel coil spring with oil damping.

Rigid bike – a bike without suspension.

Stiffness – a material property indicating the resistance to elastic deformation or, in other words, bending.

Test bench/test rig – laboratory installations for testing of deformation when forces are applied.

Trail (-riding) – mountain bike discipline where the downhill sections are in focus, but the rider still pedals up the hills. A little less downhill focus than *enduro*.

1 Introduction

The first chapter introduces the subject as well as the problem to be solved and how that has been treated in the projects.

1.1 Background

The interest in mountain bike riding has grown significantly in the last decade. The main reasons are assumed to be improved bike technology and accessibility thanks to development of public trail networks (Sloss, 2021). Covid-19 caused an additional increase in interest and sales of bikes as it was an activity still possible to carry out during the pandemic. The upcoming trend is predicted to continue (Cycling Industries Europe, 2020). Bikes are being developed faster and quality is raising. Bike manufacturers need to look for new methods to keep up with the rapid development.

There are a few manufacturers that are dominating the market of the main components for mountain bikes such as drive trains, brakes, and suspension. Due to that, bikes of different brands often share the same components. Thus, the bike frame is an important part with which a manufacturer can stand out (Gerth, Haecker, & Kohmann, 2019). Another reason for the importance of the frame design is its impact on the riding experience (Vanwalleghem, De Baere, Loccufier, & Paepegem, 2017). The bike frame is the body of the bike that through its geometry and stiffness is determining the character of the bike. It is therefore important to optimize the stiffness, but despite that there is a lack of functioning tools that can facilitate the task for the developer.

There are methods for measuring frame stiffness but most of them are outdated and primarily developed for road bikes. Most importantly the results are observed to not correspond to how the stiffness of a mountain bike feels when riding it. That is the perception of the bike manufacturer Canyon Bicycles with whom this project has been carried out in collaboration with. Canyon needs a new method for measuring frame stiffness from which the measured values correlate with the perception of the stiffness when riding the bike. That information would be an asset for the development of new bike frames to both streamline the process and improve the bikes.

1.2 Canyon Bicycles

Canyon was officially founded in Koblenz, Germany in 2002 (Canyon, 2022). They have more than 1000 employees all over the world with the main part in Germany. They are one of the leading actors on the market and were among the first with direct sales of bikes, meaning that they only sell directly through their website, which they have fully adhered to. They offer all types of bikes, from stylish city bikes, robust downhill bikes to ultralight road racers with electric options in all categories. Their aim is to make the best bikes in the world and offer the customers the best possible riding experience (Canyon Bicycles GmbH, 2021). This project belongs to the gravity department at Canyon that mainly develops mountain bikes for downhill oriented riding. Those types of bikes are so-called full suspension mountain bikes which means that they have suspension that can absorb impacts which are beneficial for that type of riding.

Canyon have a test lab, Figure 1, in their head quarter in Koblenz and on site at their suppliers in Asia where they verify different safety measures of the bikes as well as intended

performance. They have around 20 test benches of which most are testing material fatigue, meaning dynamic testing in long cycles to evaluate material deterioration over lifetime, or in short: the resistance to cracking. For frame stiffness they have two tests that are used for all types of bikes. Most of the test benches have been developed in collaboration with the University of Applied Science in Pforzheim, Germany and identical test benches are used on site at the suppliers as in the head quarter.



Figure 1 Canyon's head quarter and test lab in Koblenz, Germany.

1.3 The problem

Canyon needs a new method of measuring frame stiffness of mountain bikes that can be used, to predict how a bike will feel when riding it, as a tool for the development process as well as for quality control at the suppliers. The background to that need is that the results from the currently used methods for measuring frame stiffness are not corresponding to how the stiffness is perceived when riding the bike. That is based on the perception of development engineers at Canyon. The reason for the mismatch may originate from that the existing methods were developed before full suspension bikes, or even mountain bikes at all, existed and many of the methods focus on pedaling stiffness which are often not of high priority in the development nor when riding many types of full suspension bikes.

To be able to develop a new method where the objective stiffness correlate with the subjective, the perception of stiffness needs to be examined and the main problem is in the end to understand how the stiffness of mountain bike frames affects the riding experience.

1.4 Stakeholders

The main stakeholder to be considered in the project is the company, Canyon. They are both the client and user of the product that the project treats. The larger objective with the project is to improve their effectiveness, through improved processes and in the end also the customer satisfaction, through improved products.

The most important stakeholder within the company is the mountain bike developers that have expressed the need for the new product as a tool to facilitate their work. Their needs and requirements need to be analyzed and prioritized in the development process.

The most important external stakeholder is the end customer, the mountain bike riders, for whom the frames are developed. They are important as they are the ones that will experience the frame stiffness.

1.5 Purpose, aim and expected outcome

The purpose of the project is to facilitate and improve the product development process of full suspension mountain bikes through examining new ways of predicting the riding experience of different frame designs.

The aim with the project is to examine the experience of full suspension mountain bike frame stiffness and determine what forces are causing noticeable deflection when riding and how they can be imitated in a test setup.

The expected outcome of the project is a better understanding of how full suspension mountain bike frame stiffness can be measured in a way that correlates with the riding experience.

1.6 Research questions

The purpose and aim are broken down into three research questions that should be answered during the procedure of the project. The questions relate to each other and need to be examined sequentially to reach the desired result.

To be able to measure frame stiffness corresponding to how the rider feels it the feeling needs to be examined and defined. That is, in what type of scenarios the rider is aware of the level of stiffness of the full suspension frame.

1. When is the rider affected by the frame stiffness when riding a full suspension mountain bike?

The situations in which people seem to be affected by the frame stiffness needs to be examined and quantified into measurable parameters. The potentially critical load cases in the riding situations will be determined and forces estimated.

2. What forces are making the rider notice the deflection of a full suspension mountain bike frame?

To reach the intended outcome of the project the final research question to examine is how the load cases in which the frame stiffness is most noticeable can be imitated in a measuring method that can be used to predict how a full suspension mountain bike frame will be perceived by the rider.

3. What type of measurements can indicate how the stiffness of a full suspension mountain bike is perceived when riding it?

1.7 Delimitations

The project will not treat how the stiffness measurement method could be implemented in a test rig and in that way neither how it can be used in the development process of new full suspension mountain bikes nor for quality control.

2 Frame of reference

This chapter will give an insight into the subject and present the theory for understanding of the rest of the report.

2.1 Full suspension mountain bikes

Mountain bike is a category of bikes developed for terrain riding. There are many different types of mountain bikes with different properties and intended riding styles. The types are usually divided into two categories: hard tails and full suspension mountain bikes. A hard tail has a frame that is made as one piece, like most types of standard city bikes, but with a suspended *fork* which is the part that connects the front wheel and the frame. A suspended fork can be compressed and, in that way, absorb impacts that the front wheel is affected to from the ground. A full suspension bike has, in addition to the fork, also a suspended frame. That means that the frame is divided into a front and rear triangle that are connected by a so-called rear shock absorber, hereinafter referred to as *shock*. The shock allows the frame to compress and absorb impacts from the back wheel as well which improves the riding characteristics for rougher and more demanding terrain. The division into front and rear triangle as well as the placement of the suspension can be seen in Figure 2.

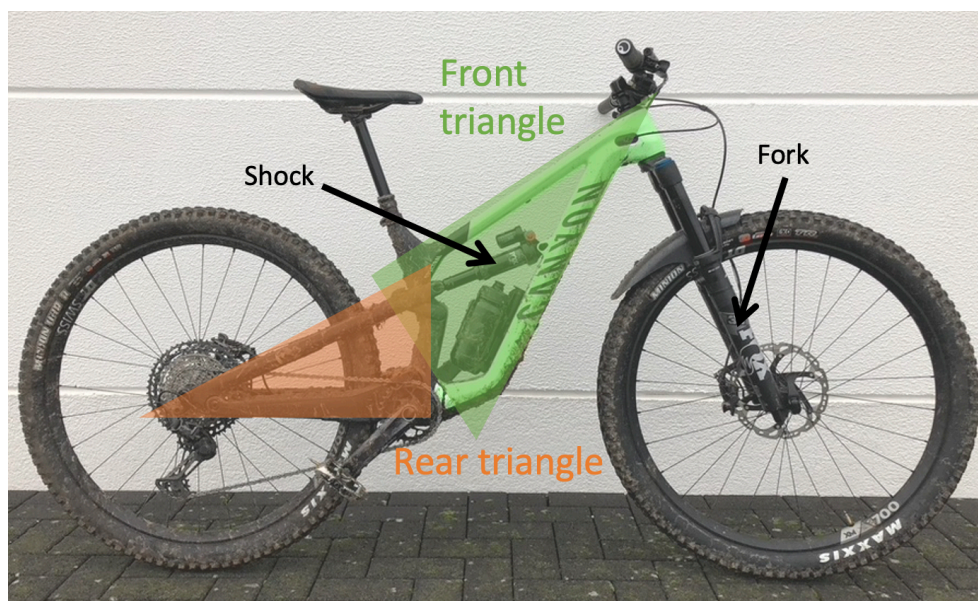


Figure 2 The full suspension mountain bike frame.

There are full suspension mountain bikes for different types of riding. From *Cross Country* which means riding in mixed terrain and often with more high intensity to *Trail* and *Enduro* where the downhill sections are in focus, but the rider still pedals up the hills and *Downhill* that are used in so-called *bike parks*, similar as ski resorts, where no uphill riding occurs and instead ski lifts are used. Full suspension mountain bikes are the most common bike for the three later of the mentioned disciplines as higher speeds and bigger impacts from different obstacles such as jumps, roots and rocks makes the extra suspension beneficial.

The difference in the frame design of full suspension bikes for the different disciplines are mainly related to the geometry and travel length of the suspension, meaning how much the fork

and rear shock absorber can compress and, in that way, how much energy it can absorb. In general, the desired travel increases with the focus on downhill performance where a downhill bike usually has 200 millimeter of travel length and a cross country bike 100 millimeters. Regarding frame geometry, the frame generally gets longer and “slacker” with increased downhill focus. That means a longer wheelbase, the distance between the wheel and ground contact points, and slacker or bigger head tube angle, the angle between the fork and the horizontal plane. These variables increase the stability of the bike but at the same time deteriorates the uphill performance, hence not as desired for cross country bikes.

2.1.1 The parts of a full suspension mountain bike frame

Full suspension mountain bike frames can have varying design but usually have a similar main structure as can be seen in Figure 3. In the front of the front triangle is the *head tube* where the fork is mounted. It is clamped with bearings on both sides, top and bottom, which allow for rotation and in that way steering of the front wheel. The upper part of the front triangle is called the *top tube* and the lower: the *down tube*. On the bike in the picture the front of the shock is mounted on the down tube, but it is also common to have it mounted on the top tube. The top tube ends into the *seat tube* which is where the saddle is mounted. The seat tube end in the seat of the *bottom bracket* which is the bearing assembly the allows for the pedaling motion.

The rear side of the shock is mounted to the *seat stays* that together with the *chain stays* holds the rear wheel and constitutes the rear triangle of the frame. The seat- and chain stays can either be one piece or separate connected with bearings or bushings that allows the parts to pivot. This varies depending on the linkage design, meaning how the parts of the frame moves with the compression of the shock. The different sides of the seat- and chain stays respectively can be connected by a small tube, often called *bride*. Small link arms called *rocker arms*, also connected with bearings or bushings, are common parts of the linkage that affects the kinematics, that is how the rear wheel moves relative the front triangle of the frame when the shock is compressed.

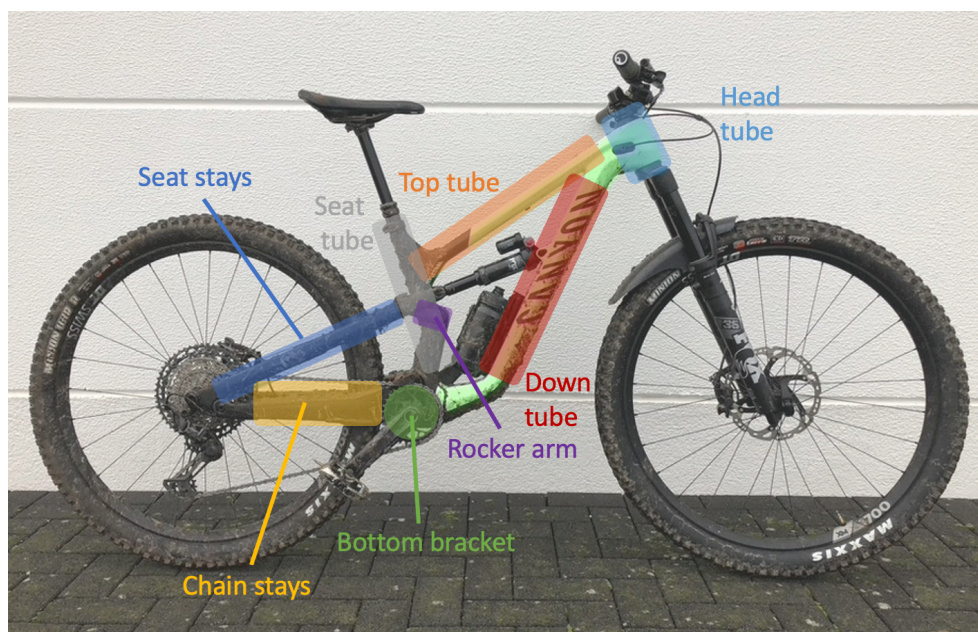


Figure 3 The parts of a full suspension mountain bike frame.

2.2 Bike frame stiffness

Stiffness is a materials resistance to elastic deformation, meaning the amount of force that can be applied without changing the shape of the material i.e., the resistance to bending. Stiffness is measured as how much force is needed to deflect a material a certain distance, that is applied force divided in deflection, either translational or torsional. The ISO unit for stiffness is newton per meter [N/m] for directional and newton meter per degree [Nm/°] for torsional.

On the bike there are several components which stiffness can affect how the bike feels when riding. These components are the contact points in-between the rider and the frame and the frame and the ground and they are generally considered to be the handlebar and stem (mount for the handlebar), the wheels, the *crank arms* (the levers for the pedals) and the suspension on full suspension bikes (Gallardo, 2020). All those components are replaceable and can be exchanged to tune how the bike feels and behaves. That can for example be through changing material of the handlebar, spoke tension or rim width. The frame is the medium in-between the contact points that need to resist the twisting forces that these components create from the rider input (CyclingAbout, 2021). The stiffness of a bike frame is affecting the handling and stability of the bike (Williams, Kaul, & Dhingra, 2015). Unlike most other components, the frame is not tunable and can neither be considered replaceable which makes it important for the manufacturer to optimize it for the intended use.

Bike frames consists of a composition of different hollow, tubular elements either welded together or manufactured as one piece. The stiffness of a bike frame is controlled by the material and the shape. Regarding the shape a thicker wall and bigger diameter of the tubes gives a higher stiffness and for the material a higher *Young's modulus* means more stiffness (Graney, 2012). The Young's modulus, or the modulus of elasticity, is a material specific unit that describes the stiffness as the ratio of stress and strain and in other words how easily it can be stretched (Sheposh, 2017).

Today's full suspension mountain bike frames are usually made of either aluminum or carbon with a few exceptions. Some models also have a combination of a carbon front triangle and an aluminum rear, often by reason of lowering the cost compared to a full carbon frame as that is more expensive than aluminum. Carbon, or *carbon fiber reinforced polymer*, is a composite meaning that it consists of thin fibers held together by a binding material, in this case the fibers are made of carbon and the binder is a polymer. Carbon fiber has become popular for bike frame manufacturing as it can offer high stiffness and strength with a low weight (F. Höchtl, 2012).

The stiffness of a composite depends on the stiffness of the fiber itself, the composition of fiber and binder as well as the orientation of the fibers. The material properties of a carbon frame can in that way be tuned with much more freedom than any metal frame (Graney, 2012). Metals are isotropic, meaning that they have the same material properties in all directions and the stiffness is consistent, determined by the Young's modulus.

Bike frame stiffness has for a long time been a discussed topic in the road bike industry where the general belief has been that a stiffer frame means better pedal efficiency and power output (McEwan, 2020). The accuracy of the idea is being discussed, however what is certain is that for full suspension mountain bikes that often are designed for downhill performance pedaling efficiency is not of highest priority. How stiff a mountain bike frame or the different part of a mountain bike frame should be is similarly a discussed topic. The former engineer and CEO for the American bike manufacturer Santa Cruz said in an interview in 2012 that "*Every time we've*

created a stiffer frame ride quality has increased” and meant that full suspension mountain bike frames could not get too stiff (Graney, 2012). The view of stiffness has changed since then and a common idea is now that some flex of the rear triangle helps the bike to adjust to the terrain instead of bouncing the rider around.

2.2.1 Measuring bike frame stiffness

Laboratory tests of bike frames are generally used by the manufacturers to at first, during the development phase, evaluate their designs and later, when production has started, for quality control. The manufacturers often have their own test laboratories to be able to quickly perform tests and sometimes has equipment designed by themselves to fulfill any special needs. Many of the common tests focus on durability and tests the material fatigue of different parts of the frame, meaning that they it is exposed to continuous repetitions of critical forces during long periods of time. Those types of tests make it possible to examine what will happen with a bike during an entire lifetime in just a couple of hours (Liteville, 2022).

Laboratory testing of performance variables, such as stiffness, can also save a lot of time as it replaces time consuming ride tests. It can also make the evaluation more accurate though limiting unknown variables and standardize the test conditions. When it comes to stiffness tests there is another actor with an interest in laboratory tests of bikes: the press. It is more and more common that bike magazines and other type of medias use stiffness values in their reviews and comparisons of different bikes and components (Ebeling, 2022).

There are commercial test institutes that offer the service of testing to whom the manufacturers can send their bikes. They often test according to existing standards but some of them have developed their own standards with customized tests. Some institutes also sell test equipment, either standardized test benches or customized according to demand. There is an international standard, ISO 4210, that bikes need to fulfill to ensure that they are safe to use (International Organization for Standardization, 2014) and European for different types of bikes (European Committee for Standardization, 2017). They contain requirements for all types of bikes and parts of them as well as for how they should be tested and what forces they should withstand. As frame stiffness is not connected to safety there are no standards covering it and neither any standardized test methods (Vanwalleghem, De Baere, Loccufier, & Paepegem, 2017). However, due to its importance for the performance of the bike it is a common property to measure, and it has been done for several years. In addition to safety testing the bigger test institutes often offer more performance related testing which includes frame stiffness. Some of them also sell their test equipment for in-house use for example manufacturers and bike magazines.

Generally, it seems like most actors doing stiffness tests are measuring in the bottom bracket and head tube area of the frame (Vanwalleghem, De Baere, Loccufier, & Paepegem, 2017). The test benches are often made of modular aluminum profiles in which different parts of the frames are fixed to control what parts that can deflect and not. The load often constitutes classic weightlifting weights that are hung on some sort of fixture mounted on the frame and the deflection is measured with digital gauges in one or many directions. The loading and reading of the gauges are done manually, and the test often includes several cycles of loading and unloading to reach a stable average.

So called dummies are used for replacement of parts of the bike that are needed for the test such as the fork if the frame should be fixed in the front wheel axle or a crank arm if a weigh should

be hung on the pedal position. For full suspension frames the shock can also be replaced with a dummy. Examples of some of Canyon's fork and shock dummies can be seen in Figure 4. The reason for using dummies is to isolate the test to the parts that are being evaluated.



Figure 4 Examples of Canyon's fork and shock dummies.

2.2.1.1 Zedler test institute

Zedler-Institute is a German bike test institute, established in 1994 (Zedler, Zedler testing: State-of-the-art bicycle and e-bike testing technology, 2022). They provide test methods treating almost all parts of the bike. Their tests are divided into the three test systems: *Safety*, *Quality*, and *Performance* where Performance contains their stiffness tests (Zedler, Zedler testing: State-of-the-art bicycle and e-bike testing technology, 2022). They claim that the Performance tests allows them to make “*precise statements as to the riding behavior without time-consuming assembly and long test runs on varying terrain*” (Zedler, Riding characteristics and batch quality – Accurate testing and benchmarking, 2022). They provide five different tests for frame stiffness that measure different parts of the frame and that are designed for different types of bikes. For full suspension frames they suggest the tests *Central frame stiffness* and *Head tube stiffness* (Zedler, Testing services portfolio, 2015). All the tests are available at their test center and for purchase for in-house use.

The two stiffness tests currently used by Canyon is the Head tube stiffness and *Bottom bracket stiffness* tests from Zedler. Despite the recommendation they use the same test on all different types of frames, including full suspension. The head tube test is said to measure the riding stability of the frame and the bottom bracket test: the power transmission stiffness through imitating the forces that the bottom bracket is exposed to when pedaling and shifting the load on the pedals from side to side (Zedler, Testing services portfolio, 2015). The tests were

examined during the start of the project and are presented in detail in section 3.2.4. As pedaling in general is not of highest priority for more downhill oriented full suspension bikes it is understandable that the test is not suitable. The suggested Bike Center Stiffness is instead intended to measure the stiffness in terms of riding stability and steering precision (Zedler, Testing services portfolio, 2015).

Zedler collaborates with the German bike magazine *Tour* and their sister editions *Bike*, *Freeride* and *E-MTB* that do some of the most extensive review testing of bikes with equipment developed together with Zedler. The mountain bike edition, *Bike*, uses the Bike Center Stiffness and the Stiffness-to-Weight ratio for all their tests of full suspension bikes. The Stiffness-to-Weight ratio is the measured stiffness divided in the weight of the frame which is a standard Zedler developed already in 1994 and still uses (Zedler, Testing services portfolio, 2015) (Zedler, Riding characteristics and batch quality – Accurate testing and benchmarking, 2022). All the *Tour* sister-magazines publish the measured stiffness values from the tests in the magazines.

2.2.1.2 EFBE Prüftechnik

EFBE Prüftechnik is another German bike test institute, established in 1995 (Ebeling, 2022). Their tests comply with the international and European standards, but they also have their own, more extensive “TRI-TEST” standard. They perform tests themselves in their laboratories as well as offer equipment and production process support for manufacturers. Their tests are divided to the categories: fatigue/dynamic, static, impact and stiffness (EFBE, 2022). Their stiffness tests measure head tube and bottom bracket but are not presented more in detail.

3 Method

The chosen method for the project was inspired by a heavily stripped-down product development process. Unlike most product development projects, this project was not carried out as an interdisciplinary activity but rather solely by the design function (Ulrich & Eppinger, 2016). The reason for that was that the focus was not a commercial product but rather a customized installation for internal use within the company and their suppliers. That meant that neither any market nor production aspects were relevant to consider. The usual preceding planning phase were neither included in the process as that company already had stated the project idea (Ulrich & Eppinger, 2016).

The project was carried out solely by one individual which also is rare for product development (Ulrich & Eppinger, 2016). Even though there were no project team, and the work structure could be compared to consulting assignment, it was still carried out on site at the company and other functions and competences were consulted. The product development process used for inspiration was what was suggested in the advanced level courses in product development at Chalmers University of Technology during 2020 and 2021 and the book “Design and Product Development” by Ulrich and Eppinger that was the main reference literature for the courses and for the general method of the project (Ulrich & Eppinger, 2016).

3.1 Project structure

As shown in

Figure 5 the process of the project was divided into three phases: *Pre-study*, *Idea exploration* and *Testing*. The aim with the first phase was to form a better understanding of the problem with the existing test methods and gather information about people’s perception of frame stiffness. The insights from the pre-study were further examined in the second phase where potential load cases causing deflection of the frame were studied. The initial plan for the second phase was to do a more traditional concept generation with iterations of generating and evaluating different ideas with the help of finite element simulations. Unfortunately, no usable result could be reached with the simulations and the process had to be changed so that a smaller number of promising load cases was evaluated solely through experimental testing instead.

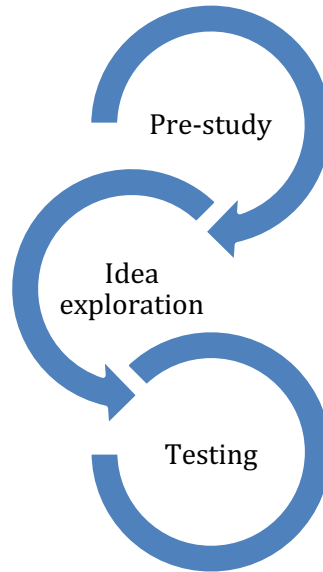


Figure 5 The activities included in the Concept development phase of the project

3.2 Pre-study

The first phase of the project served as a pre-study. The focus was on forming a better understanding of the problem and the purpose of the project. Despite being a critical aspects of bike frame design there is a lack of research about frame stiffness. Nevertheless, is it a frequently discussed topic among as well manufacturers and mechanics as riders on different levels. The project started with a wide information search about the topic in general to get an idea about what would be promising to examine further. Part of the gathered information was summarized into what is presented in the preceding Frame of reference chapter.

3.2.1 Customer need mapping

To clarify the aim with the project the company's needs and expectations were discussed in unstructured interviews in the beginning of the project with employees involved in the development at Canyon. The findings, i.e., their needs, presumptions and constraints were summarized into a so-called mission statement that is a tool suggested for communicating information from a pre-project phase to the concept development (Ulrich & Eppinger, 2016).

3.2.2 Evaluation test

As the topic of the project was to quantify a feeling a simple exploratory test was carried out early in the project for the author to experience the said feeling and get a better personal idea about it. A bike was modified to reduced stiffness through cutting off the bridge in between the chain stays, meaning the tube connecting the two sides. The intention was to create a less stiff rear triangle and test how and when that was noticed when riding. A short trail section of approximately 200 meter was chosen for the test. It was started with five runs with intact chain stays which then was switched to the modified and the difference in feeling was observed. A camera was mounted under the saddle to check for any visual differences.

3.2.3 Survey study

As there were no existing research about how people perceived frame stiffness when riding mountain bikes new information was needed. A survey study was the choice for gathering data. The study was divided into two parts: an internal, only aimed at people working at Canyon and an external for the general mountain bike rider. The data from the both groups of stakeholders were collected with web-based questionnaires.

3.2.3.1 Internal survey

The first part of the study was based on two questionnaires: a main and a short follow up. It had two purposes: firstly, to examine the experts on the topic thoughts about frame stiffness in general and their opinions about the existing test methods. The second purpose was to create a subjective ranking of Canyon's existing full suspension mountain bike frames to use as reference in the project.

The main questionnaire was sent out with email to 56 Canyon employees which included everyone in the different mountain bike departments and some others either working with full suspension mountain bikes or that were known to have much riding experience. It consisted of 16 questions of which the majority were answered with either a scaling between positive/negative or agree/disagree or with multiple choice alternatives. The most important questions were answered in written text, such as in what situations they perceived frames stiffness as most noticeable. The questionnaire was concluded with a free text field where the respondents got to express any ideas, thoughts, or concerns regarding the topic.

The grading of the frames was made on a scale from 1-9 in increasing stiffness. The respondents were instructed to skip the frames that they had not ridden. In addition to the grading, they also got to assess their confidence in the grading on a scale from 1-5 where 1 meant "not confident" and 5: "very confident".

A trial run of the questionnaire was carried out before it was published, and it was adjusted according to feedback and finding when analyzing the answers. No thorough analysis of the results was carried out until after the follow-up questionnaire were finished.

3.2.3.1.1 Follow-up

The first questionnaire was complemented with a follow up of the frame grading. It was sent out a couple of weeks later so that the respondents should have forgotten what they answered. The purpose was to examine how much the grading differed and to increase the reliability of the grading. According to the Delphi method the old result, both average and all the individual responses, anonymized, were shown in the beginning of the survey (Karolinska Institutet, 2022). The reason was to make the respondents affect each other's opinions and decrease the deviation of the grading. The follow up questionnaire was sent out to everyone that participated in the first part of the internal survey.

The results from the follow-up survey were used to create the subjective grading of Canyon's frames. To increase the reliability the responses were filtered. Respondents with confidence lower than four and fewer graded frames than two were considered unreliable and were removed.

3.2.3.2 External survey

The second part of the survey was aimed at examining the general perception of mountain bike frame stiffness. It targeted all types of mountain bike riders, not only people riding full suspension bikes, to check if there was a difference in their respective perception. It was sent out on social media and in different bike forums.

The questionnaire consisted of 39 questions, all with preset options, but some possibilities for the respondents to add their own alternatives. The reason for not letting them to write down their own answers was to facilitate analyzing the result. The beginning part of the questionnaire treated mountain bikes and riding in general to examine the profile of the respondents as well as how aware they were about frame stiffness and how important they thought it was compared to other aspect of the bike. The ending of the questionnaire was more focused on frame stiffness specifically and aimed to gather information about how and when people noticed it to use for examining different load cases.

The purpose of the survey was presented to the respondents as to examine mountain bike riding in general and the project's focus on frame stiffness was not mentioned to avoid people thinking about it more than what they otherwise would have. In the very end of the survey the topic of the project was revealed, and the respondents were welcomed to share any ideas, thoughts, or concerns about the topic in a text field.

A couple of iterations of trial runs of the questionnaire was carried out with different people both at Canyon and other mountain bike riders at varying level to get feedback and check if the questions were interpreted in the right way in the answers.

3.2.4 Evaluation of the current state

Canyon's existing methods for measuring frame stiffness were tested to obtain experience of the procedure. Canyon wished for a new method to follow the same material and workflow as the existing, hence that needed to be examined. Other test benches in the lab were also observed for inspiration.

The subjective grading of Canyon's frames from the survey study was used to evaluate the existing methods through comparing the results. The results from a previous study on the topic carried out by Canyon was also compared to the subjective grading and bike magazine results to examine the magnitude of the mismatch between subjective and objective stiffness.

3.2.5 Competitor analysis

As part of the evaluation of the current state, was a competitor analysis carried out. It was aimed to provide inspiration. Many of the bigger bike manufacturers develops their own test methods to be able to fulfill their needs. There might be of interest to keep the ideas secret if they can mean an advantage in the development process, but sometimes test labs and methods are shown or can be spotted in for example factory tour reports on different medias. An unstructured internet search was conducted to find any interesting information.

3.3 Idea exploration

The initial idea for the second phase was to do quick iterative idea generation and evaluation loops with the help of simulations of deflection. Due to the simulations being unusable no evaluation could be carried out at this stage. Instead, the evaluation had to be carried out as experimental testing. Physical testing was included in the plan from the beginning as simulations implies simplifications and could not be considered as reliable, but at a later state when more knowledge existed. The focus on this phase was thereby instead to theoretically explore different ideas to decided what to test physically. Physical testing required building of prototype test rigs which limited the amount of test possible to carry. Hence not as many different ideas would be possible to evaluate.

3.3.1 Examination of load cases

The idea behind laboratory testing of bikes is to imitate riding scenarios that might deform the frame. The key to design a well-functioning test bench is thereby to know what scenario to imitate. To be able to understand how the frame then deflects in those situations it was necessary to understand what forces they it is exposed to. Forces acting on the frame originate from the rider's weight and depend on what the rider is doing as well as the character of the ground (Vanwalleghem, De Baere, Loccufier, & Paepegem, 2017). The results from the pre-study were broken down into load cases that were likely to cause noticeable deflection of the frame and the forces involved were studied for what would be most promising to test.

There is a lack of research on the topic but since it is about riding technique there is a big interest among riders and there are a lot of videos and articles about it. These sources are not science based but since they reflect how people ride those types of sources were used for this exploratory examination.

3.3.2 Finite element simulation

Since bike frames are hollow asymmetrical objects with a lot of complex surfaces it would be impossible to theoretically calculate the stiffness. Instead, the simplest and fastest way of evaluating their stiffness was assumed to be finite element simulations. The aim was to make simulations of frames with different perceived stiffness according to the subjective reference and test different load cases and then compare the results and check for correspondence with the subjective reference.

At the time of the project Canyon mainly used simulations for parts of frames or separate components. Though, a new procedure for full frame simulations in the software SolidWorks was recently developed. It included guides for simulating most of the test that were performed in the test lab. The simulations made in this project followed that procedure starting with the final 3D models of different frames. Three frames were chosen as a start, and they were worked on in parallel.

3.4 Experimental testing

Due to experimental testing being time consuming and limited by the access to equipment the scope of examination was narrowed down to the most promising findings from the idea exploration phase. One of Canyon's existing test benches, the so-called *scrub load fatigue test*,

was used for the base fixation of the frame but modified for testing other load cases. It was chosen because it was most similar as what was going to test and thereby fixed the bike in a suitable position. Another benefit was that it was relatively new and was still under evaluation and due to that that not used as frequently as the other test benches.

The design of the test setup and the test procedure was carried out in an exploratory way where discoveries lead to adjustments and the whole process, method, and result, is described together in section 4.3.

4 Result

This chapter presents and explains the results from the study.

4.1 Pre-study

The following section presents the results from the pre-study.

4.1.1 Canyon's perception of mountain bike frame stiffness

In short, Canyon's general idea about frame stiffness of full suspension mountain bike frames seemed to be that it is important to separate the front and rear triangle where the front should be stiffer than the rear. The stiff front makes the bike precise in terms of steering and keeping the line in rough terrain and the flexier rear should help absorb shocks in lateral direction that cannot be absorbed by the suspension also in that way help keeping the bike on the line.

4.1.1.1 *Mission statement*

Canyon wanted a new measurement method for mountain bike frame stiffness that would give values that correspond to the riding perception. The focus on only full suspension bikes was not defined initially but as the structural differences, the shock and linkage, in the frame are big and the project belonged to the gravity department than was perceived as the primary need and focus of this project. The product idea was summarized into a mission statement that was used as the starting point of the project. It can be seen in Table 1.

Table 1 The companies needs and expectations on the new product summarized into a mission statement for the project.

Mission statement: Measurement method for frame stiffness	
Product Description	• Measurement method for frame stiffness of full suspension mountain bike frames for which the measured values correlate with the perceived stiffness
Benefit Proposition	• Reliable and repeatable measurements • Easy to use • Possible to use for multiple different types of bike frames and wheel diameters
Key Business Goals	• Support the development of mountain bikes by giving a better indication of how the final frame will feel on the trail in terms of traction, confidence, harshness, etc.
Primary Market	• Full suspension mountain bike frames • Electric full suspension mountain bike frames
Secondary Markets	• Hardtail mountain bikes • Rigid bikes
Assumptions and Constraints	• Measuring the stiffness of mountain bike front- and rear triangles separately • Possible to install both in Canyon's test lab and at the suppliers • Follow the same material as the already existing Canyon stiffness test-rigs • Follow a similar workflow as the already existing Canyon stiffness test-rigs • It is necessary to validate the method by benchmarking frames so that the measurement correlate with riding impressions
Stakeholders	• Developer engineers • Test lab personnel • Suppliers

4.1.2 Test ride with flexy frame

The modified frame used in the test can be seen in Figure 6.



Figure 6 A rear triangle made less stiff through cutting off the bridge in between the chain stays.

The main insight from the test ride with the flexy frame was that the modified chain stays gave the bike a similar feeling of having too low pressure in the rear tire which makes the bike unstable and unpredictable. It was mostly felt when changing directions of the bike and especially in short corners entered with higher speed. It was difficult to see any big differences in the video mainly because the camera came too close to the tire when the suspension was compressed. A videoframe comparison example can be seen in Figure 7. The test gave the author an idea about how lack of stiffness can feel and an insight that it most likely easily can be confused with wheel stiffness.



Figure 7 Video caption for the test ride, intact frame to the left and modified to the right.

4.1.3 Survey study

The following sections presents the result from the survey study. Starting with the internal and followed by the external.

4.1.3.1 Canyon employee thoughts of frame stiffness

The internal survey got 27 responses. A reminder was sent out about a week after the initial email. Several people answered that they were too unsure or unexperienced of the topic to be able to contribute and hence chose not to answer at all. Due to that the number of responses was considered acceptable and no more reminders were sent out.

The biggest part of the respondents were engineers working with development of bikes and the distribution of the rest can be seen in Figure 8.

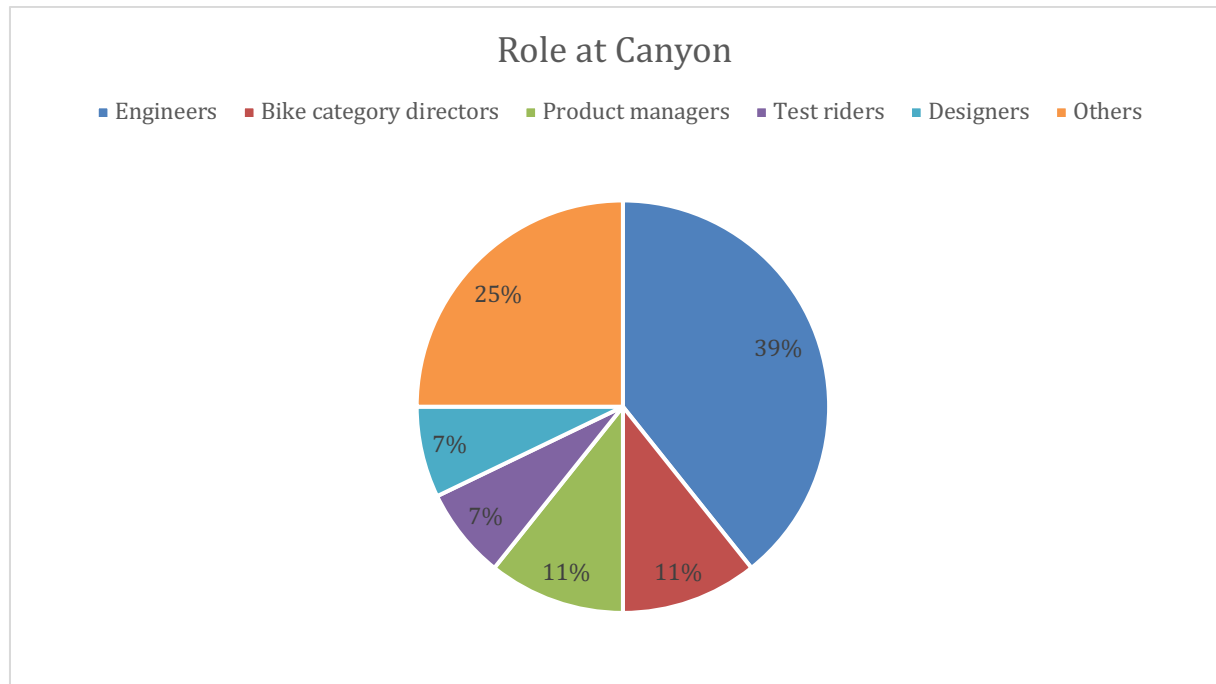


Figure 8 The respondents' role at Canyon.

When grading their experience of mountain bike riding on a scale from 1-5 where 5 was the most advanced, all the respondents placed themselves in the upper half of the scale with a majority (52%) on grade 4.

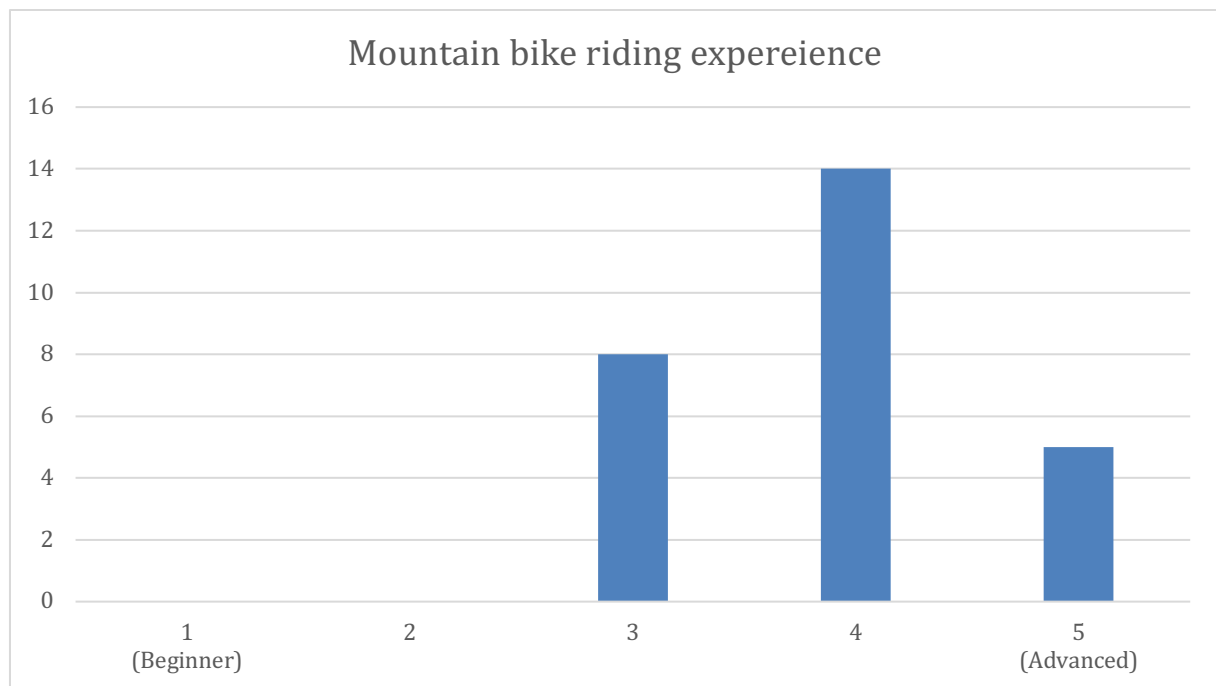


Figure 9 The respondent's mountain bike riding experience.

Their preferred type of mountain bike riding was quite evenly spread out over cross country, trail, enduro and downhill as can be seen in Figure 10.

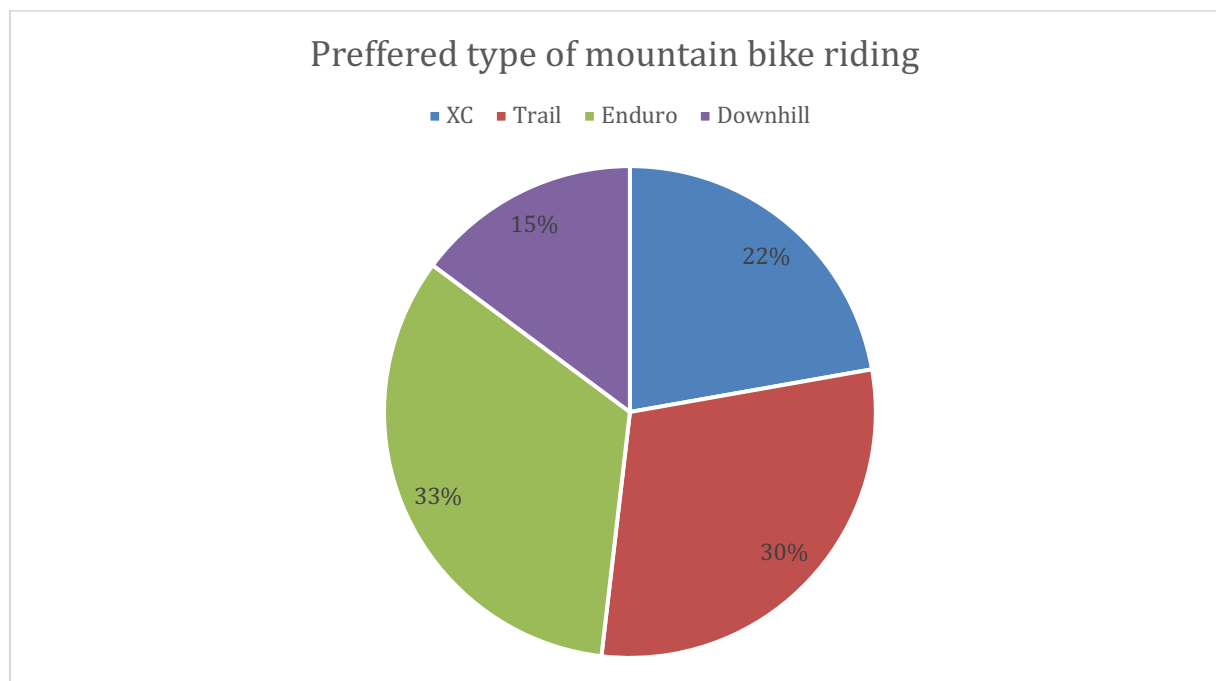


Figure 10 The respondents' preferred type of mountain bike riding.

74% of the respondents thought that they had felt a significant difference in stiffness of full suspension mountain bikes that they had tested in the past and 63% claimed they had a clear personal preference.

On a scale increasing from 1-5 of how much frame stiffness affects their riding experiences the majority (59%) chose 4. The rest of the distribution can be seen in Figure 11. Of the respondents choosing below 4 was 60% cross country riders and the rest trail riders. When comparing the average grading of the importance of stiffness for the different disciplines it was sinking from 4 for downhill and enduro to 3 for trail and cross country.

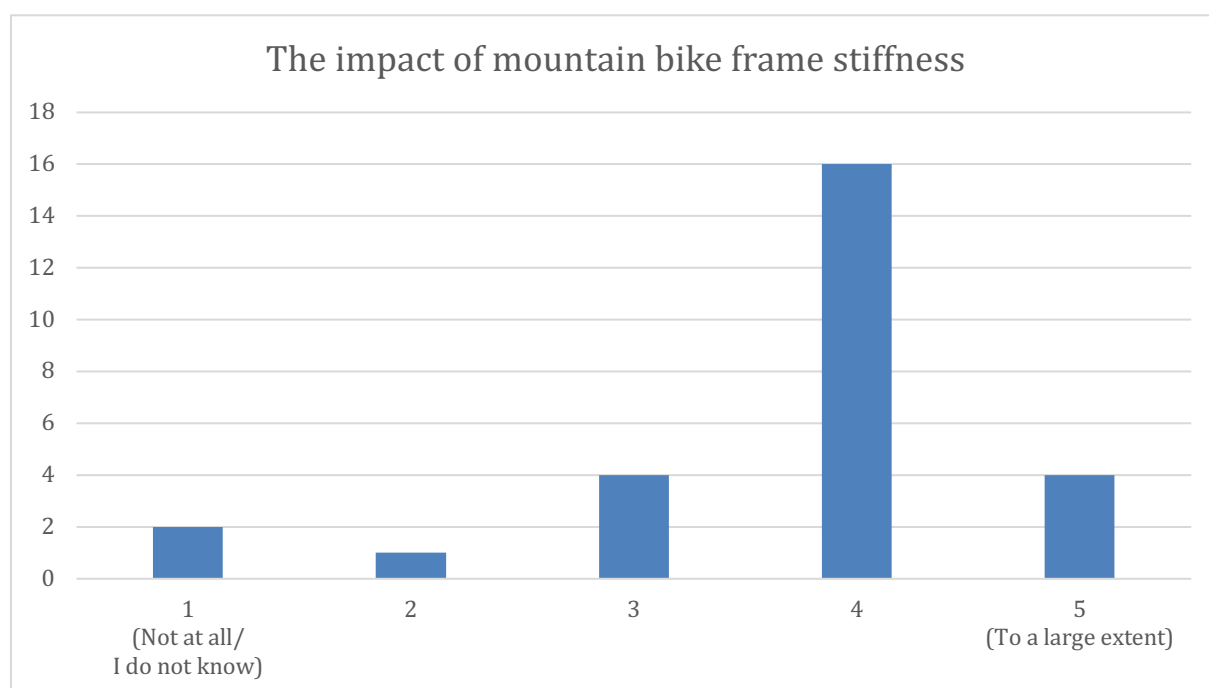


Figure 11 The respondents' perception of the impact of frame stiffness on mountain bike riding.

The respondents thought that the level of frame affected the riding experience mainly in terms of control followed by traction and confidence. The full result can be seen in Figure 12. All alternatives were predefined options apart from power transfer that was added by three of the respondents. The answers were similar when comparing respondents with different level of riding experience and different prefer bike discipline apart from that everyone adding power efficiency was cross-country riders.

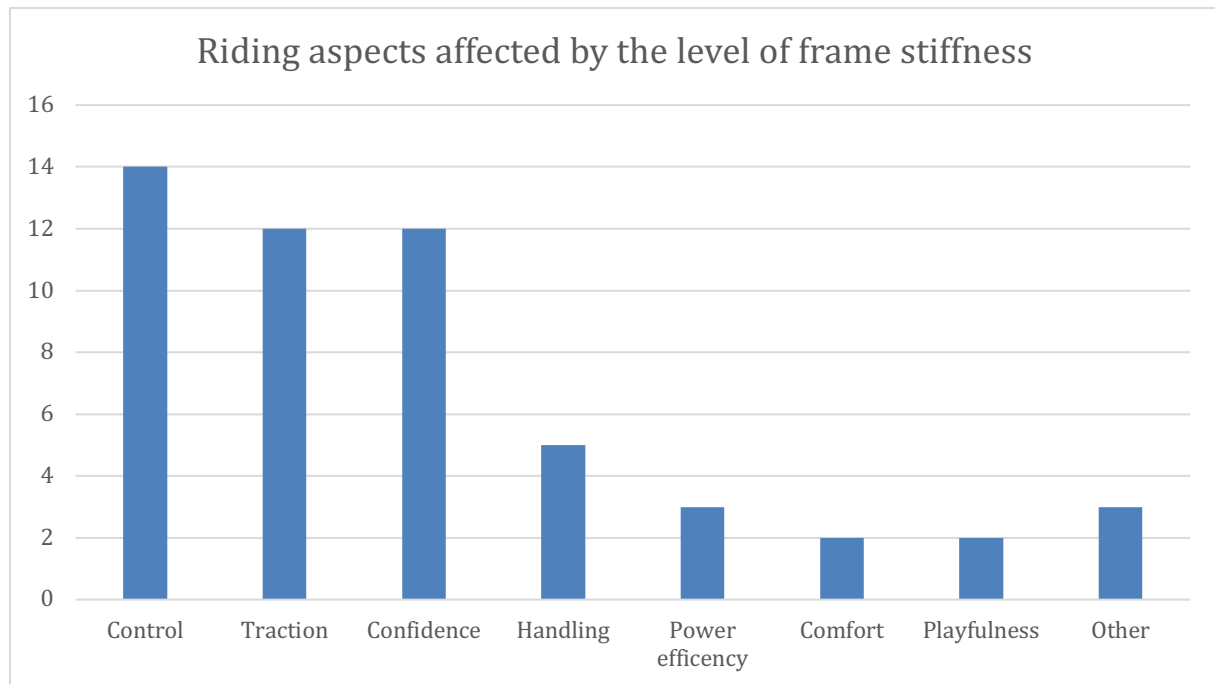


Figure 12 The riding experience aspects that were most affected by frame stiffness according to the respondents.

The most important question of the survey was about in what type of terrain, trails or obstacles frame stiffness of full suspension mountain bike frames is most noticeable. To get as much as possible out of it and not lead the respondents to an answer the question was answered in written text. The most common answers are summarized below:

- High speed direction change/aggressive cornering.
- *Berms* (inclined corners)/bike park-styled trails with big compressions/high G-forces.
- High speed on rough and rocky trails.
- Off-camber sections.
- When need for precise steering.

It seemed that the perception of when stiffness is noticeable was somewhat independent on the experience of the rider and was also similar in the different bike disciplines where only cross-country distinguished a little with answers such as sprints and uphill sections.

The survey also contained a couple of questions about Canyon's currently used measurement methods for frame stiffness and how reliable the respondents thought the methods were. None of the respondents thought that the currently used methods worked "very well". The distributions of the answers were analyzed for engineers separated from the others as they were the most important stakeholder cover by the respondents. Half of the developer engineers thought the currently used stiffness measurement methods worked somewhat okay. Among the other respondents the majority (53%) did not know. A majority (60%) of everyone choosing "poorly" was working in the gravity bike department. The distribution on the engineers and the others respectively can be seen in Figure 13 and Figure 14 below.

Developer engineers opinion about the currently used stiffness measurement methods

■ Somewhat okay ■ I do not know ■ Poorly

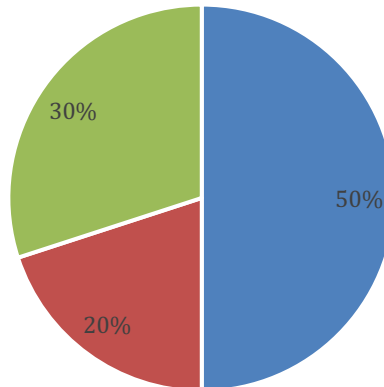


Figure 13 The developer engineers' opinion on the currently used frame stiffness measurement methods.

The others opinion about the currently used stiffness measurement methods

■ Somewhat okay ■ I do not know ■ Poorly

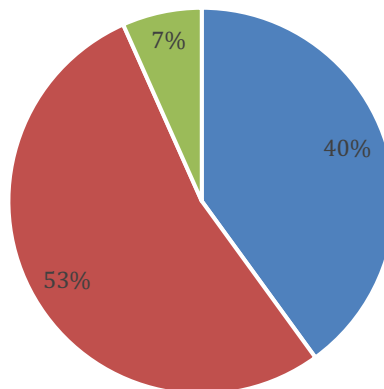


Figure 14 The other respondents' opinions about the currently used stiffness measurement methods.

The respondents were also allowed to mention any specific frames or methods in which the stiffness measurements corresponded particularly good or bad with the perceived stiffness. There were no obvious patterns in the answers, some models were mentioned but only once, but some other interesting statements were the following:

- The head tube stiffness test is the least bad, it works quite well for measuring carbon front triangles.

- The existing stiffness test works well for cross country and down country bikes.
- The bottom bracket stiffness test works for hardtail and road bike frames but is questionable for full suspension frames.
- For cross country bikes the bike center stiffness is the most used test nut it measures lower stiffness than the developers and athletes' subjective opinion when comparing to other bikes. Bottom bracket and head tube stiffness is more reliable.

A second purpose of the survey was to create a subjective grading of Canyon's full suspension frame supply to be able to use that as reference during the project and to choose what frames to test. The respondents got to grade their perceived stiffness of 14 Canyon full suspension frames as 1-9, where 9 was the stiffest. The frames were chosen to cover most of the contemporary supply of which samples for testing would be accessible. The selection covered cross country, trail, enduro and electric full suspension bike frames.

The result of the grading can be seen in Table 2. The model designations are hidden due to confidentiality. The frames are sorted in increasing level of perceived stiffness from left to right where red means soft and green stiff. The average deviation is shown in the second row where the darkest red indicates biggest deviation. The last row indicates the number of respondents grading each frame, darkest red shows least responses.

Table 2 Subjective grading of some of Canyon's existing full suspension mountain bike frames based of the survey results.

	Frame N	Frame M	Frame K	Frame J	Frame L	Frame I	Frame F	Frame G	Frame H	Frame B	Frame E	Frame A	Frame C	Frame D
Average	3.9	4.3	4.4	4.7	4.7	4.9	5.0	5.3	5.5	6.5	6.8	6.8	6.8	7.0
Average deviation	1.8	1.8	1.4	1.2	1.8	1.3	1.7	1.5	1.1	1.2	0.6	1.5	1.2	0.5
Number of gradings	14	12	12	16	11	15	13	12	8	11	20	13	6	8

The maximum difference in the grading of a frame was 7 which gave an average deviation of 1.8 and the average deviation for all frames was 1.33. The average numbers of grading of each frame were 12.2 which means 45% of the respondents. The average confidence in the grading was 3.4 on a scale from 1-5.

4.1.3.2 Perceived stiffness of Canyon's full suspension frames

The follow up questionnaire was, despite three reminders, answered by 12 of the initial 27 respondents. The old grading for the 12 respondents was exchanged with the new and the rest were kept as it was. It had a stabilizing effect on the result. The total changes in the grading with the new responses added were the following:

- The average stiffness grading decreased with 2%.
- The average deviation decreased with 4% to 1.27.
- The average number of gradings per frame decreased with 5% to 11.6 (meaning that some of the respondents omitted some of the frames from the first grading).
- The average confidence decreased with 8% to 3.1.

The new average stiffness grading and the percentual change per frame can be seen in Table 3.

Table 3 Changes in the subjective stiffness grading after the verification questionnaire.

	Frame N	Frame M	Frame K	Frame J	Frame L	Frame I	Frame F	Frame G	Frame H	Frame B	Frame E	Frame A	Frame C	Frame D
Average	3.7	4.0	4.4	4.3	4.3	4.8	5.2	5.4	5.9	6.7	6.6	6.6	6.5	6.4
Change of average	-5%	-6%	-1%	-9%	-10%	-2%	4%	2%	6%	4%	-2%	-2%	-5%	-9%
Change of deviation	-14%	5%	-6%	-8%	9%	-9%	14%	-8%	-6%	-16%	1%	-20%	-14%	20%
Change of gradings	0%	0%	-8%	-25%	9%	-13%	8%	-8%	-13%	0%	-10%	-15%	0%	25%

After filtering the responses, the average deviation of all frames was decreased to 0.99. The final grading can be seen in Table 4.

Table 4 Subjective grading of Canyon's full suspension mountain bike frames.

	Frame N	Frame M	Frame L	Frame K	Frame J	Frame I	Frame H	Frame G	Frame F	Frame E	Frame D	Frame C	Frame B	Frame A
Average	2.9	3.0	3.5	4.0	4.3	4.6	5.3	5.5	6.0	6.5	6.7	6.8	7.0	7.1
Average deviation	0.6	1.3	1.7	0.6	0.6	1.2	1.3	1.4	1.6	0.7	0.4	0.9	0.9	1.0
Number of gradings	9	6	6	7	8	9	4	8	9	10	6	4	7	7

4.1.3.3 The general mountain bike riders thought about frame stiffness

The external survey got 3500 responses. Before analyzing the results, they were checked and briefly filtered. In the questionnaire tool used it was not possible to allow input of both metric and imperial units, so default was chosen as metric and a link to a convertor from imperial was included in the applicable questions. Despite that there seemed to have been some miscalculations and the first step of the filtering of the responses was to remove all unreasonable low and high BMI values that were outside the limits for extreme underweight and extreme obesity (16-40) as that could be assumed to be faulty. The respondents were however kept in the results, just their body measures removed.

The respondents with body measures that were outside the limits for Canyon's and many other bike brands were removed which meant people under 152 centimeters (Canyon Bicycles, Women's Bikes, 2022), above 200 centimeters (Canyon Bicycles, Bikes for tall people, 2022) and above 120 kilograms (Canyon Bicycles, FAQ & Support Articles, 2022). In addition to that the extreme values of some of the different questions were checked, and some unserious respondents were removed where the answers could be considered obviously unreasonable. In total 52 respondents were removed because to body measures outside the scope or lack of seriousness and the number of respondents included in the full analysis was thereby 3448. After filtering, the average height was 178 centimeter and average weight 80 kg.

The most popular main mountain bike discipline was trail followed by enduro/all mountain and cross country as can be seen in Figure 15. Dirt/slopestyle was the main discipline of just 0.4% or the respondents.

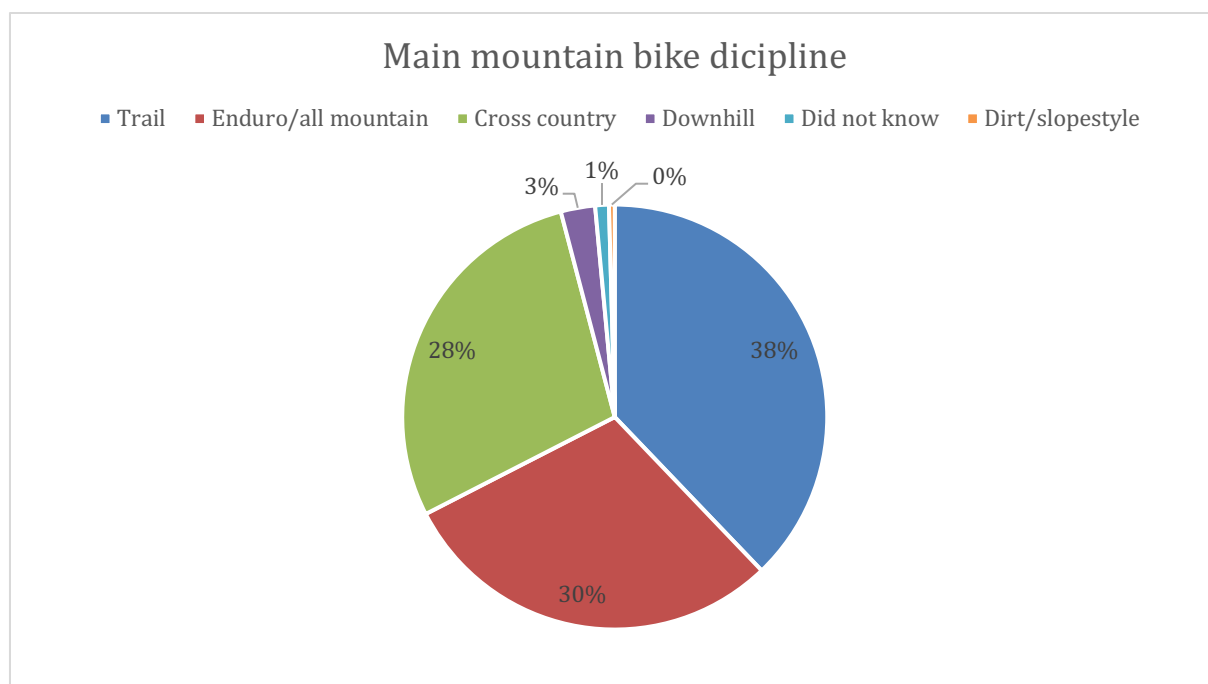


Figure 15 The respondents main mountain bike discipline.

The average mountain bike riding level on a scale from 0-10 where 0 was described as beginner and 10 professional athlete was 5.4 with the biggest part (28%) on level 6. The full distribution can be seen in Figure 16. The number above the columns show the number of respondents. Regarding level of aggressiveness in their riding style on the same scale the average was the same (5.4) and the distribution similar with the biggest part (25%) on level 6.

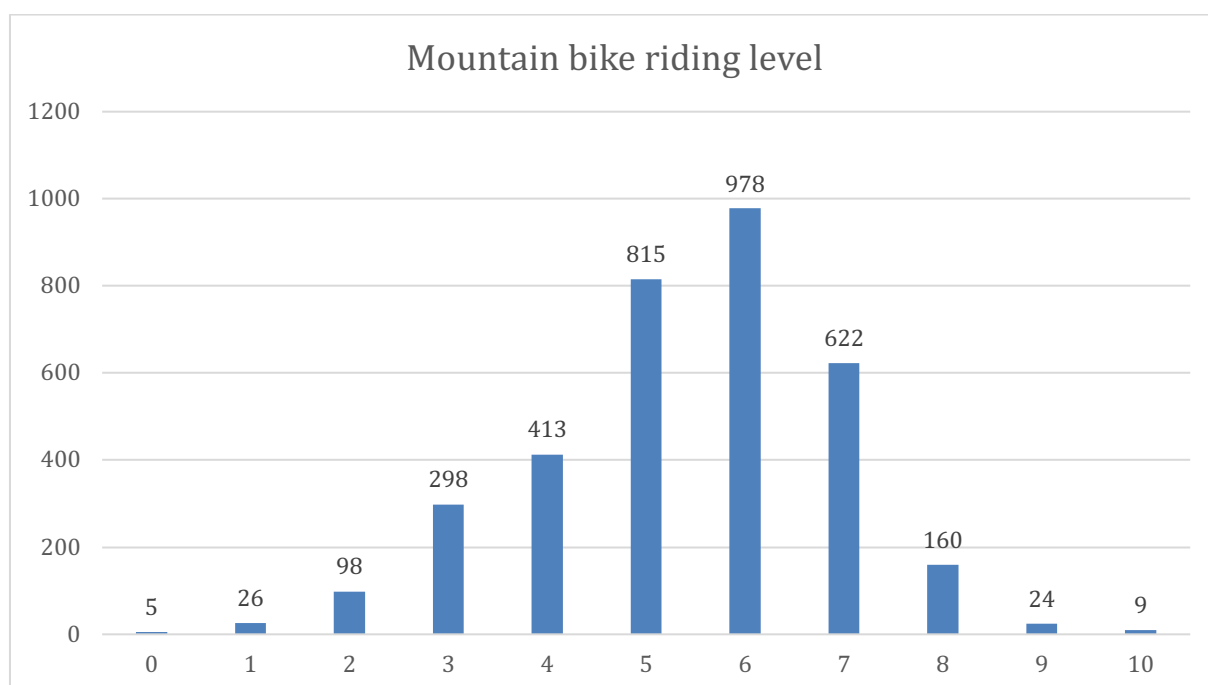


Figure 16 The respondents mountain bike riding level.

46% of the respondents had competed in mountain bike riding, 26% just tried it a couple of times and the rest regularly, in decreasing amount on higher level with 66 persons on elite level

and 6 professionals. Most of the respondents (53%) rode mountain bikes several times every week, 6% almost daily, 26% once every week and the rest more seldom. The full result can be seen in Figure 17.

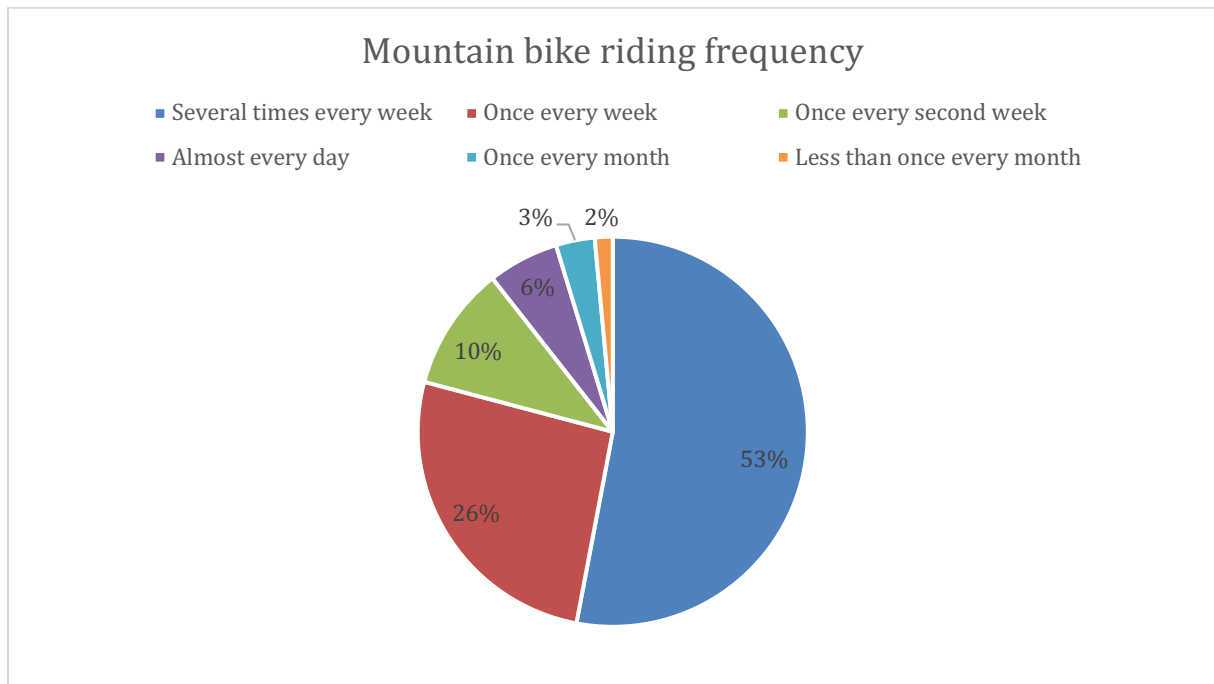


Figure 17 The respondents' frequency of mountain bike riding.

For the main part of the respondents (31%) the most common trail condition on a scale from 1-10, where 1 meant hardpack and 10 soft, were in the middle of the scale (5). 40% usually rode conditions more towards hardpack and the rest softer. 51% of the respondents did never visit lift supported downhill bike parks and of those who did were 30% doing it 1-5 days per year and the rest more seldom.

The most popular style of trail was natural single tracks with 59% of the responses and after that came technical trails (23%) and machine build flow trails (9%). The average number of owned mountain bike so far for their main discipline was 3.4.

When ranking the riding experience impact of the choice of different components the tires, brakes and suspension got the highest ranking and for other aspects of the bike tire pressure, suspension settings, and geometry was on top. Frame stiffness and wheel stiffness got the lowest ranking but also the biggest share of people not knowing.

More respondents had not experienced how different levels of stiffness of a mountain bike frame feels than claiming to be sure about it as can be seen in Figure 18.

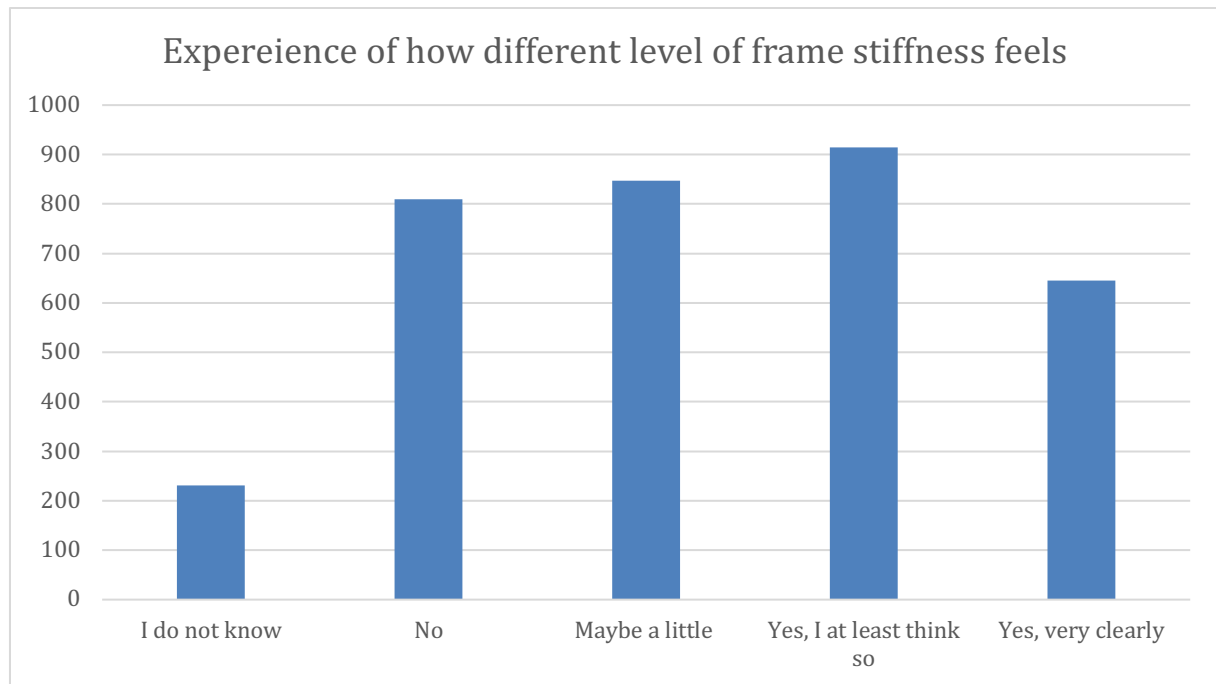


Figure 18 Many respondents had not experienced how different levels out frame stiffness feels.

56% were either sure that they were affected by frame stiffness when riding or thought that they were as can be seen in Figure 19.

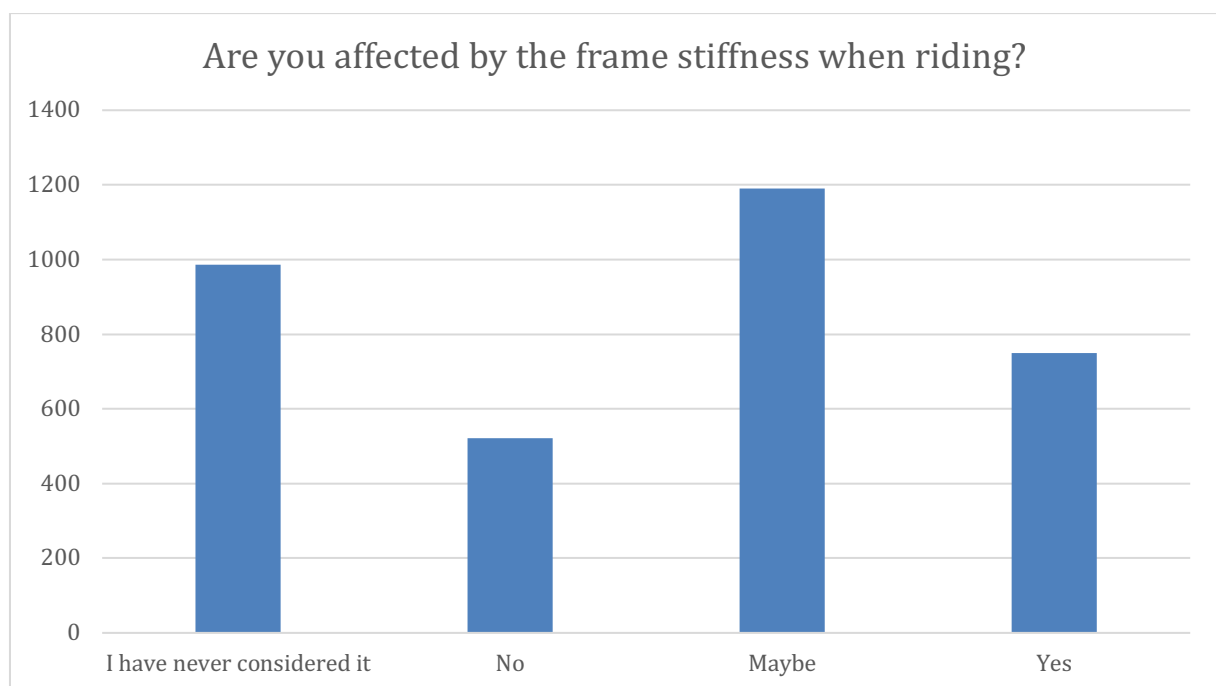


Figure 19 56% of the respondents were or were maybe affected by frame stiffness when riding.

The riding situations in which the respondents perceived frame stiffness as most noticeable was “rough sections” tightly followed by “technical section”. A couple of filters were tried to search for different patterns:

- only including respondents that were surely affected by frame stiffness when riding
- cross country riders excluded
- only including riders of full suspension bikes with 150 mm or more suspension travel (more gravity-oriented riders)

All filters showed an almost identical distribution of the responses as can be seen in Figure 20 where all respondents were included.

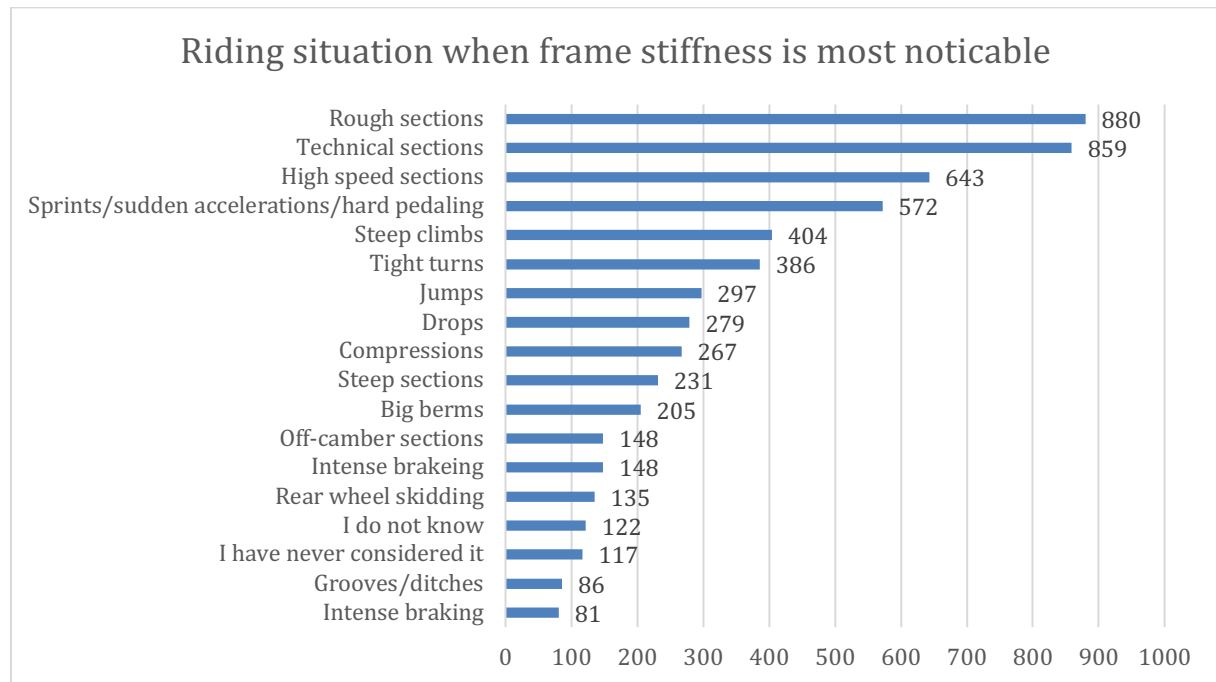


Figure 20 Riding situation when the respondents perceived the frame stiffness as most noticeable.

4.1.4 Canyon's existing frame stiffness measurement methods

Canyon's two existing stiffness measurement methods were tested to get better understanding of the procedure and to examine its material and workflow as it was required by Canyon that a new stiffness measurement method should follow the same.

4.1.4.1 Head tube stiffness test

In the head tube stiffness test the frame was placed horizontally with the non-drive side up, meaning the opposite side to where the drive train is. The setup can be seen in Figure 21. It was fixed with the rear wheel axel and supported under the side of the head tube as well as on the side of the bottom bracket to avoid rotation. The test was performed with a fork and shock dummy. The fork dummy was a metal rod clamped into the head tube that worked as a lever for the weight of 10 kilogram that was 's hung approximately 1 meter away from the head tube. The vertical deflection of the rod was measured with a digital gauge at a flat surface 40 centimeter from the center of the head tube.



Figure 21 Zedler's head tube stiffness test performed in the manufacturers test lab.

The test procedure followed the template in Figure 22 with two test runs affecting the result and an additional test run for verification. Each test run consisted of three cycles where the loaded state first was measured and then the unloaded to calculate the actual deflection. The load was a 10-kilogram weightlifting weight hung in a strap that carefully was hung and removed from the rod to not cause any oscillation. The value shown in the gauge was noted down when no big changes longer appeared. The average deflection was then calculated, and the result was presented as newton meter per degree, i.e., how much torque that is needed to bend the headtube one degree. The green cell in the test template showed the average difference in the measurements and the acceptable limit was 0.2 mm regardless of the magnitude of the deflection.

1. test run	↓	11.41	10.31
	-	1.08	
	↓	11.43	
	-	1.13	
	↓	11.47	
	-	1.16	
2. test run	↓	11.48	10.31
	-	1.18	
	↓	11.50	
	-	1.19	
	↓	11.50	
	-	1.19	
Ø	mm	10.31	
Δ	mm	0.03	
S	Nm/°	68	
additional 3. test run	↓	11.51	10.31
	-	1.21	
	↓	11.54	
	-	1.23	
	↓	11.54	
	-	1.23	

Figure 22 Test template for head tube stiffness.

4.1.4.2 Bottom bracket stiffness test

The bottom bracket stiffness was measured with the frame in an upright position, slightly tilted towards the non-drive side. The test set up can be seen in Figure 23. A fork, shock as well as *crank set* dummy were used for the test, i.e., the front gear on which the chain is mounted that is rotated with the pedals. The crankset dummy was, similarly to a normal, mounted with an axle through the bottom bracket from the drive side. It consisted of a crank arm mounted at 45° forward from the bottom position. A shaft with a flat surface on the end of the crank arm constituted a pedal dummy onto which an 80-kilogram load was hung. A link arm that ran from the top of the crank set towards the rear wheel axle, mounted on the test bench imitated the chain and the effect of chain force.

Two digital gauges were used to measure displacement vertically one on top of the pedal dummy, above where the load was hung and one on the backside of the crank arm measuring horizontal displacement.



Figure 23 Zedler's Bottom Bracket Stiffness test bench and set up with a full suspension mountain bike frame

The test was carried out similarly to the head tube test with two test runs and one additional for verification as can be seen in Figure 24. The values from the two gauges were noted both in loaded and unloaded state when big changes had stopped occurring. The load was hung with a chain with a hook in the end on the bottom of the pedal dummy and was loaded with the help of a jack mechanism.

The stiffness was calculated as the average of the two directional stiffness, vertical and horizontal, in newton per millimeter. Like for the head tube stiffness, the limit for acceptable average difference in the measured deflection was 0.2 millimeter in both directions.

1. test run	I	→	7.16
	II	↓	6.14
	I	-	0.06
	II	-	0.21
	I	→	7.16
	II	↓	6.14
	I	-	0.07
	II	-	0.22
	I	→	7.18
	II	↓	6.15
	I	-	0.07
	II	-	0.25
2. test run	I	→	7.17
	II	↓	6.15
	I	-	0.08
	II	-	0.26
	I	→	7.18
	II	↓	6.18
	I	-	0.08
	II	-	0.27
	I	→	7.17
	II	↓	6.18
	I	-	0.08
	II	-	0.28
Ø	I	mm	7.10
Ø	II	mm	5.91
Δ	I	mm	0.02
Δ	II	mm	0.04
S		N/mm	86
additional 3. test run	I	→	7.18
	II	↓	6.19
	I	-	0.07
	II	-	0.28
	I	→	7.18
	II	↓	6.19
	I	-	0.07
	II	-	0.28

Figure 24 Test template for the bottom bracket stiffness test.

4.1.4.3 Visualization of the mismatch of measured and perceived stiffness

Test results from the two existing stiffness measurement methods were compared with the perceived stiffness from the subjective ranking of eight frames. The mismatch of both methods was obvious as can be seen in Figure 25. All values, grading, and stiffness were normalized into percentages of the highest values of the different types. The reason for that conversion was to be able to compare the different tests, despite different units, with the graded perception of stiffness.

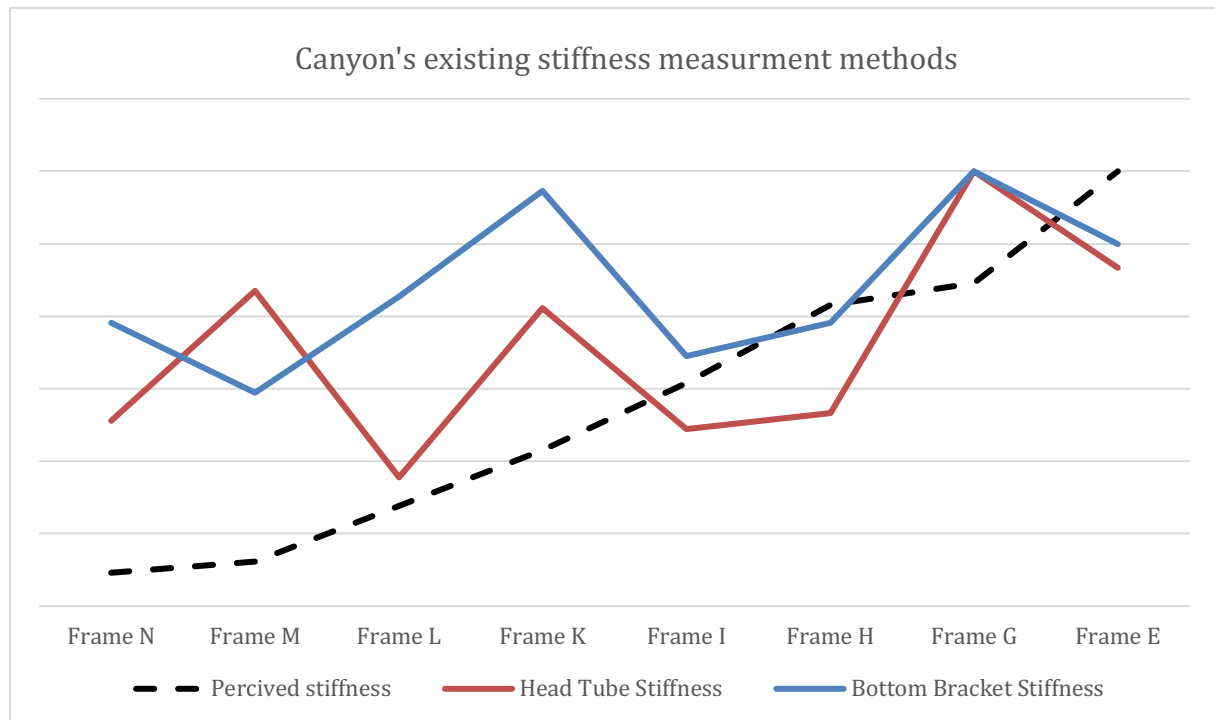


Figure 25 Comparison of the perceived and stiffness with Canyon's existing measurement methods.

The other two of Zedler's stiffness measurement methods, Bike Center Stiffness and Stiffness-to-Weight ratio, that the German magazine BIKE used as standard in their mountain bike reviews were also examined though a comparison of the results. Test results from magazine reviews could be found for five of the frames included in the subjective grading. The results had a bad correlation as can be seen in Figure 26.

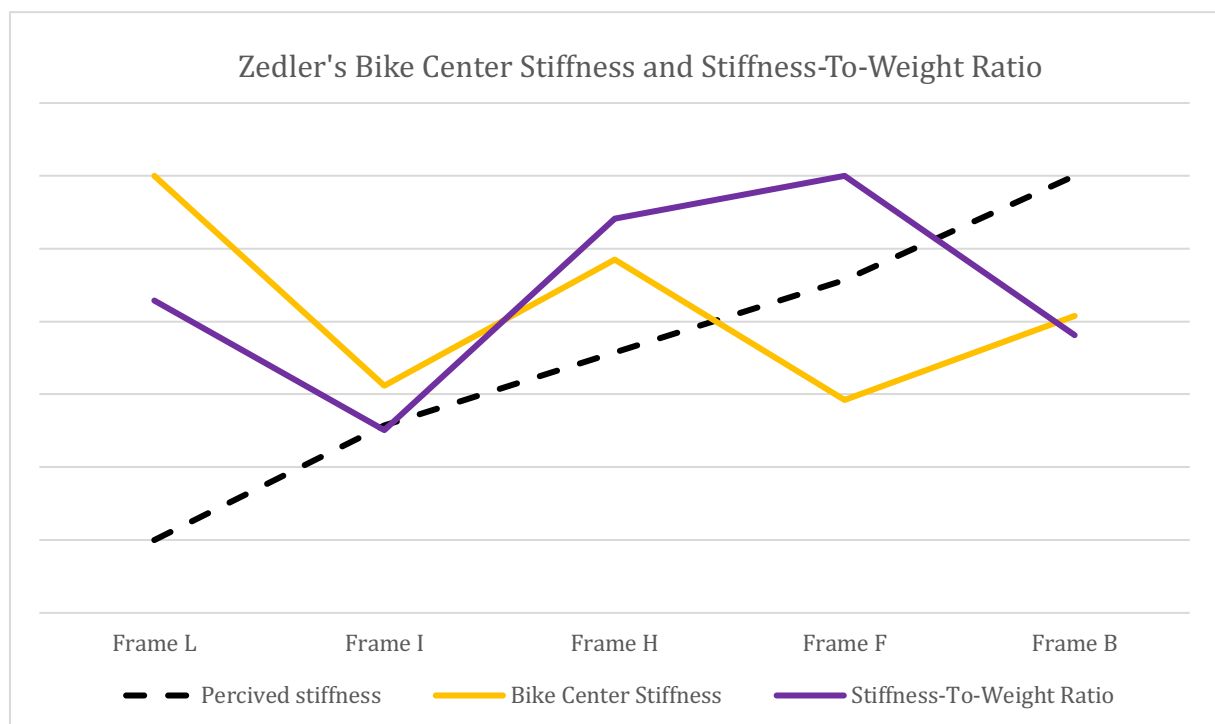


Figure 26 Comparison of two of Zedler's stiffness measurement methods that are used by the BIKE magazine.

4.1.4.4 Summary of existing measurement methods for frame stiffness

A new stiffness measurement method was required to follow the same material and workflow as Canyon's the existing ones. To copy as many already existing solutions as possible would also facilitate the experimental testing in this project. The general material and workflow for the existing measurement methods were thereby observed.

Material

- Test rig built up by aluminum profiles.
- Normal weightlifting weights as load.
- Digital gauges for measuring displacement held in place by jointed holders mounted with magnets on steel plates on the test benches.
- Jack mechanism for lifting heavy weight.
- Rigid shock and fork dummies.

Workflow

- Aligning the frame with the help of spirit levels.
- Manually loading and unloading and reading deflection.
- Load let hanging until no more big changes occurred in the digital gauges.
- Two iterations with three cycles and an additional test run for verification.
- Measuring translational or torsional stiffness.

4.1.4.5 Other interesting test benches

Other test benches in the lab were examined for inspiration. The most interesting was a test called "Scrub load fatigue" in which the rear triangle was affected to a lateral force. The test bench was quite new and still under evaluation at the time of the project. The force was applied by a pneumatic cylinder perpendicular to a rear wheel dummy mounted on a linear bearing. The linear bearing could raise vertically, and the force could in that way create torsion around the center of the wheel. The test was intended to simulate rear wheel skidding, or scrubbing, meaning drifting in the lateral direction. The test was a fatigue test meaning that the frame was affected to continuous force pulses during a long period of time to evaluate for the occurrence of permanent deformation.

4.1.4.6 Previous work on the topic

In a previous study at Canyon, they tested the idea about separating front and rear triangle stiffness with an isolated rear triangle stiffness test. An experimental test setup as can be seen in Figure 27 was build up. The frame was positioned sideways fully fixed in the bottom bracket and with a support in vertical direction close to the headtube. A 30-kilogram weight was hung onto a back wheel dummy consisting of a wheel axle with a 355-millimeter perpendicular rod corresponding to the radius of a 27.5" wheel. The rod was angled so that it was in position of the ground contact patch. The deflection of the wheel dummy was measured vertically on top of where the load was hung.



Figure 27 Test of conceptual test rig for measuring rear triangle stiffness. Reproduced with permission.

The result from the study was said to not correspond to the subjective stiffness. To verify that the results were compared with the subjective stiffness grading of the frames, in the same way as previously described, converted into percentages. The comparison can be seen in Figure 28. The comparison had a better match than the other methods where the four subjectively stiffest frames corresponded well with the measured stiffness.

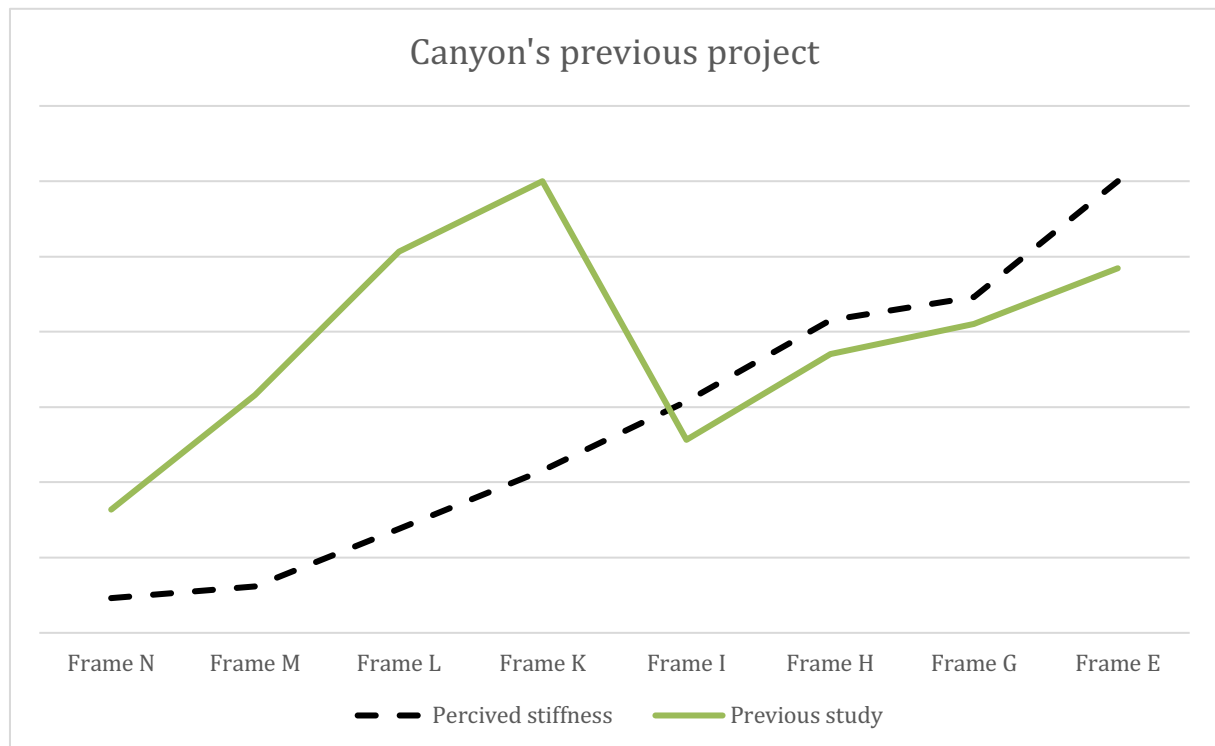


Figure 28 Comparison between the subjective and measure stiffness from a previous Canyon project.

4.1.5 Interesting insights from the competitors

Competitors were examined for inspiration. An internet search was carried out for new ways of testing stiffness as well lateral forces on the rear triangle similar as Canyon's scrub load fatigue test. Most of them seemed to keep those things to themselves and the information found was in general old, but some interesting insights was gathered.

4.1.5.1 Specialized

In a factory tour report from the American bike manufacturer Specialized from 2014 a stiffness test setup could be viewed in which the front triangle was isolated (Sicklines, 2014). A full suspension frame with a real shock was mounted sideways flat on a table. It was fixed in the head tube and supported under the bottom bracket. A long metal rod was mounted in the seat tube with a digital gauge measuring the vertical deflection of the rod a couple of decimeters away from the frame. The load was hung onto the rod and the torsional stiffness of the seat tube was tested similar as Zedler's head tube stiffness test. In another factory tour from 2018 a Zedler's headtube stiffness test bench was shown in which the frame was also mounted with a normal shock (Benedict, 2018).

4.1.5.1.1 Cube

In another factory tour report from 2014, but from the German manufacturer Cube, a stiffness test rig was shown. A frame was mounted upwards, fixed in both the front and rear wheel axle with a metal rod mounted horizontally in the bottom bracket (Gierulski, 2014). A weight was

hung on the edge of the rod and the vertical deflection was measured on the rod a couple of decimeters from the frame. The rig tested in this way the torsional stiffness of the full frame.

The frame mounted in the stiffness test rig was rigid but all full suspension frames in other test rigs shown in the report had real shocks mounted (Gierulski, 2014).

4.1.5.2 Propain

The German bike manufacturer Propain showed their test lab in a video from 2017 (Propain, 2022). They did not include any stiffness tests but showed a test of lateral forces on the rear triangle. They said that it tested forces that riders would feel when cornering, drifting, or landing a jump slightly sideways. Their setup was similar as Canyon's scrub load fatigue test with a fork and bottom bracket fixture and a pneumatic actuator pushing a wheel dummy horizontally following a rail. The only difference was that the rail did not have the possibility to rise as Canyon's (Propain, 2022).

4.1.5.3 EFBE Prüftechnik lateral load tests

The test institute EFBE Prüftechnik, introduced in section 2.2.1.2, did not present much info about their test equipment themselves but some information could be found from bike manufacturers using their tests. They had a mountain bike specific "Lateral loads rear" test that was intended to *"simulate cornering and bad landings after jumps"* (77designz UG, 2019). The frame was fixed like in Canyon's scrub load fatigue test, but with the bottom bracket not fully fixed so that it could move a bit laterally and, in that way, also move the front triangle (Kavenz, 2019) (77designz UG, 2019). That differed from Canyon's lateral test as not being an isolated rear triangle test. The force was applied horizontally on a fork dummy sliding on a rail that were fixed on the bench and thereby could not raise with rotation of the frame. A rigid fork and shock dummy was used with compression set to 100% and the applied force was 400 newtons in 20000 cycles (Pole Bicycles, 2021). Three bike manufacturers that were using the test and showed it in different reports described in as it was testing:

- *"simulates riding berms"* (Kavenz, 2019)
- *"high-speed berm where a change of direction happens very fast"* (Pole Bicycles, 2021)
- *"simulates lateral loads (when cornering or landing at an angle)"* (Zimmerman, 2016).

Another test that could be related to lateral loads was the "Maximum load test pedal load" that was a test where a large static force of 2500 newtons was applied during 10 seconds to a single sided crank dummy in the bottom position with the force angled 26° laterally downwards (Pole Bicycles, 2021). The frame was tested for visible cracks, but deformations was considered okay. It was not described what the test was intended to simulate, but it was at least creating a lateral deflection of the whole frame.

4.1.5.4 Commencal

The Andorran manufacturer Commencal launched a new downhill bike in 2022 with tunable rear triangle stiffness through replaceable meatal seat stay bridges, meaning the connection between the two sides of the seat stays (COMMENCAL bicycles, 2022).

4.2 Idea exploration

The findings from the pre study were examined more thoroughly in the following phase of the project. The examination was solely theoretic as the intended simulations could not be used. The simulation process is anyway described in the report.

4.2.1 Mountain bike riding breakdown

The results from the pre-study indicated that the scenarios in which most people seemed to notice frame stiffness could be generalized to when cornering and when riding through rough terrain.

4.2.1.1 Initial assumptions

The suspension of full suspension mountain bikes works in the vertical direction and for it to be able to handle the vertical movements of the frame it is desirable for the rest of the frame to be stiff in that direction (Starling Cycles, 2018). If the suspension does handle all vertical movement, it should be difficult to notice any deflection in that direction apart from when the suspension reaches its bottom, but the feeling in those situations were not assumed to affect the overall perception. The principle of the bike having two big wheels in line and the rider sitting straddled over it restrains the frame to have a long and shallow shape. If seen as a beam, it is obvious that the frame is stronger and stiffer in the vertical direction than in the horizontal.

In addition to being stronger vertically, the suspension most likely makes it difficult to feel the vertical stiffness of the full suspension frame. There are in that way reasons to believe that lateral forces are more likely to cause noticeable deflection of a full suspension frame. This was not verified but to limit the scope and narrow down to possible forces to test, fully vertical forces were excluded from the examination already from the beginning.

It is assumed that the rider is more likely to notice a lack of stiffness than when it is enough or too much. Mountain bike frames are generally designed to have a stiffer front than rear triangle. As Canyon wanted a new measurement method for front and rear triangle separately the initial focus was aimed at the rear triangle.

4.2.1.2 Mountain bike riding position

Full suspension frames give better performance in rough terrain and when exposed to big impacts which is why they are suitable for downhill oriented riding where the speed and, with that, forces are high. The riding position for that type of riding differs from others. The biggest difference is that the rider is not sitting on the saddle but rather stands up, especially in the most critical terrain (Warner, How To Corner A Mountain Bike : Bermed Corners - Better Berms In 1 Day, 2020). The reason for that is to let the bike move separated from the body to be able to shift position to stabilize the bike, dampen shocks or let the bike lift from the ground. The contact points where the force from the rider is applied to a mountain bike when riding downhill is thereby limited to the pedals and handlebar.

The shifting of the body weight, or *center of gravity*, is an important aspect of mountain bike riding with the aim to keep the weight distributed over the wheels (Downhill body position, 2022). When riding on flat terrain the center of gravity should thereby be in the middle of the

bike, when going uphill it needs to be shifted forward and when going downhill: moved backwards to keep it over the midpoint in between the wheels as can be seen in Figure 29.

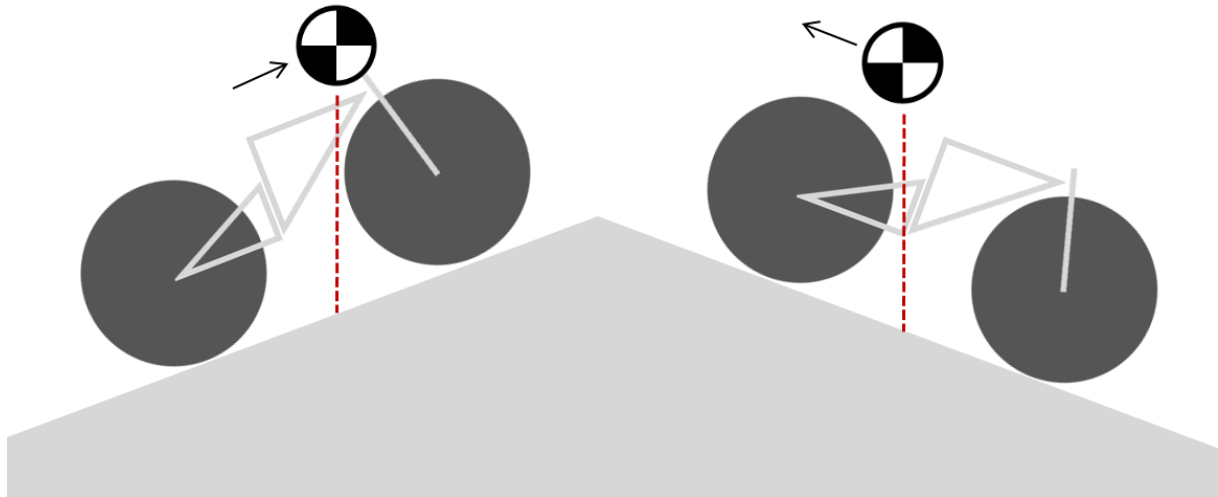


Figure 29 Illustration of how the center of gravity needs to move to keep the weight distributed over the wheels.

Having an even weight distribution helps keeping both wheels on the ground and improves the grip. Where the center of gravity is on the rider depends on the body shape and riding position but as a simplification for this examination it is considered to be in position of the belly button, which corresponds relatively well to where it is when standing up (J. C. Le Huec, R. Saddiki, J. Franke, J. Rigal, & S. Aunoble, 2011).

To achieve stability the center of gravity needs to be centered over the bike in the lateral direction as well to not fall over. That is not true when cornering due to the occurrence of centripetal force. The bike needs to be tilted and the center of gravity shifted to the side to compensate for the additional force and the riding position needs to change. Cornering was one of the most mentioned situations in which people noticed frame stiffness in the survey study and was thereby examined further.

4.2.1.3 Cornering with a bike

To examine the motion of cornering with a bike it is viewed as a statical load case where the rider travels with constant speed and the corner has a constant radius on flat ground. The center of gravity for the whole system, rider and bike, is assumed to be collinear with the height of the bike.

As shown in Figure 30 the forces acting on the bike are the gravitational force from the rider's mass (F_g) and the corresponding normal force from the ground (F_N), the centripetal force from the lateral acceleration (F_C) and the corresponding frictional force acting on the tire (F_μ).

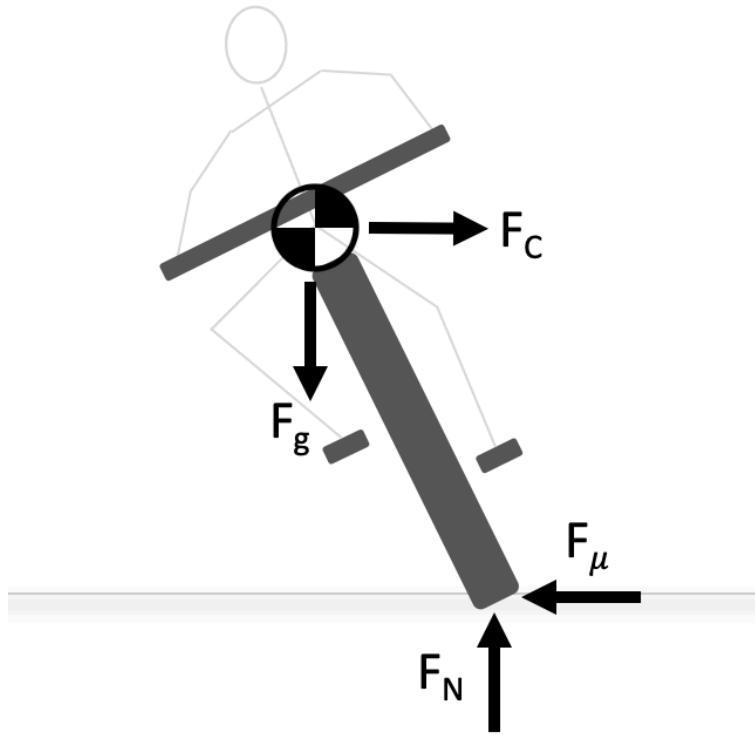


Figure 30 Simplification of forces acting on a bike when cornering, viewed from the front.

If the rider manages to make the turn without falling over the system is in equilibrium, meaning that the sum of all forces equals 0. The gravitational force from the rider is the mass (m) in kilogram multiplied with the gravity acceleration (9.81 m/s^2). The centripetal force for an object, moving with constant speed (v) in meter per second along a constant radius (r) in meter, is the mass multiplied with the speed squared, divided with the corner radius. The forces acting on the bike when cornering as described are thereby the following:

In vertical direction: $F_N = F_g = mg$

In horizontal direction: $F_\mu = F_c = \frac{mv^2}{r}$

If the center of gravity is collinear with the bike it must lean with the same angle (λ) as the resultant from the normal force and frictional force from the ground to compensate for the centripetal force. As shown above the normal force from the ground is equal to mg and the frictional force to $\frac{mv^2}{r}$ in the state of equilibrium as can be seen in Figure 31. The two perpendicular forces from the ground will act on the bike with the collinear resultant force (F_R). The lean angle of the bike depends on the speed and radius as can be seen in the equation below.

$$\lambda = \tan^{-1} \frac{\frac{mv^2}{r}}{mg} \Rightarrow \tan^{-1} \frac{v^2}{gr}$$

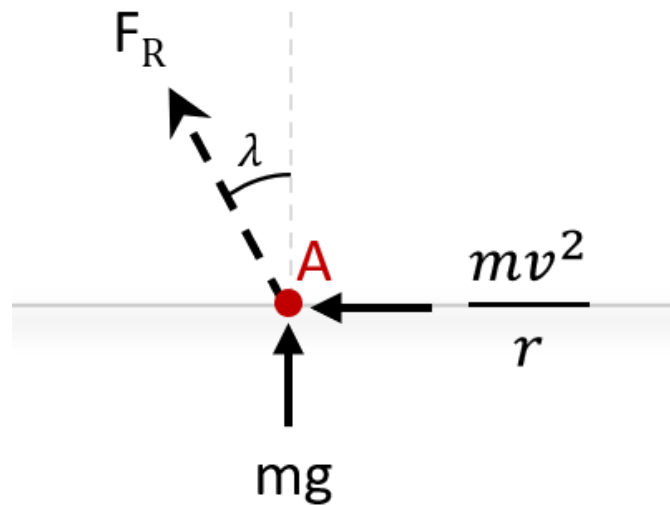


Figure 31 The resultant force acting collinear on the leaning bike.

A Japanese research team could confirm that the calculated lean angle did correspond with the actual lean angle when cornering a road bike in a downhill segment (Sakai, o.a., 2020). They used different sensors for measuring the corner radius, lean angle, and velocity which they regulated to a constant speed with an automatic break actuator on the bike. Nevertheless, when cornering with a mountain bike, the conditions are less ideal, and this calculation would most likely not be as accurate for example for a muddy corner filled with roots in the forest. On top of that this type of cornering technique does not cause any lateral forces on the bike since the resultant is collinear with the lean angle.

4.2.1.4 Mountain bike cornering

The flat corner technique of mountain bikes compared to road bikes differ in many ways. That is due to differences in the bikes which in turn depends on the differences in the intended riding terrain. The ground when cornering a road bike is most often tarmac or some similar hard and flat material and for mountain bikes it is not uncommon that it is the opposite, with no limit for how soft or rough the terrain can be. Mountain bike riding is less predictable, and the bikes are designed for that regard. The seemingly two most affecting differences when it comes to cornering are the frame design and riding position as well as tire design and pressure.

Road bikes have higher frames and fixed seat post which makes the space for the rider to move around on the bike limited compared to mountain bikes that are designed specifically to maximize the space for shifting the body position in different directions. That also depends on the fact that road bike riders sits on the saddle most of the time and whereas mountain bike riders stand up. Road bike tires are narrow with little pattern and high pressure for optimal rolling efficiency and mountain bike tires are often wide, with rough pattern and lower pressure for optimal grip.

When making a flat corner with a mountain bike there is a general idea of so called body and bike separation which means that the bike and body do not lean together but rather separated with the bike leaning more than the body as illustrated in Figure 32 (Warner, How To Corner

A Mountain Bike - Better Flat Turns In 1 Day, 2020). Why that is beneficial is not obvious, especially when comparing to motorcycle riding where the rider does the exact opposite: leaning the body more than the bike, sometimes even with the knee touching the ground. Even though bikes and motorcycles share the property of being two wheeled vehicles there are differences justifying the difference in cornering technique. In an interview with four experts within both the mountain bike and motorcycle business no clear reason is presented but rather a lot of different factors such as the predictability of the ground surface, the weight ratio of rider and vehicle, the speed, and the corner radius (Morgan, 2021). It might be the case that the two sports are too different to compare even though they share the same basic principle.

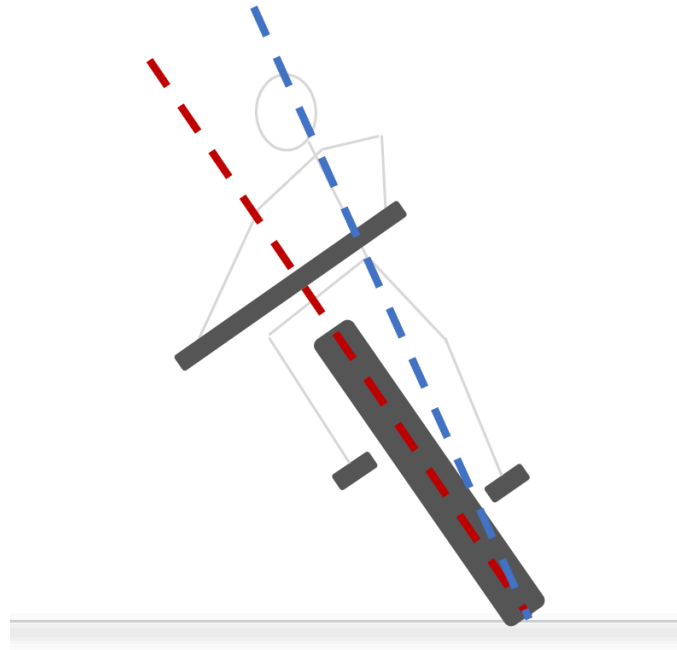


Figure 32 Illustration of bike and body separation when cornering a mountain bike.

The purpose with the so-called bike and body separation is to tilt bike to get a particular area of the tire contact the ground. Mountain bike tire usually have a profile with knobs in the middle and on the sides and an emptier space in between on both sides. The middle knobs add grip when the bike is in an upright position and when braking. They are usually a bit smaller than the side knobs to decrease the rolling resistance. The empty channels are intended for leading away dirt and mud from the knobs. The side knobs are intended for giving grip when cornering and since they do not affect the rolling resistance as much, they are usually bigger. To get use of them when cornering the bike needs to be tilted and that is one reason for the bike and body separation technique.

The common riding position for flat corners with mountain bike is to lower the outside foot and bend both knees to move the hip outside of the turn to create space for tilting the bike. Through straighten the inside arm and keep the outside bent the shoulders can be kept in a stable position, together with the hips, in parallel with the handlebar and slightly rotated towards the direction of the corner (Warner, How To Corner A Mountain Bike - Better Flat Turns In 1 Day, 2020). Apart from being able to tilt the bike the separation of body and bike goes in line with the general principle of letting the bike move and use the body to stabilize it and dampen impacts from the terrain.

4.2.1.5 Bike and body separation

To examine the forces in the bike and body separation cornering technique a new calculation was set up where the bike's and rider's center of gravity do not coincide. The forces were unchanged, but the mass was separated into m_b for the bike and m_r for the rider.

$$\begin{aligned}\uparrow : F_{gtot} &= (m_b + m_r)g \\ \rightarrow : F_{ctot} &= \frac{(m_b + m_r)v^2}{r}\end{aligned}$$

The resultant force (F_R) will always act in the direction of the common center of gravity and since that is no longer in line with the bike it will be affected by a lateral force component (F_{RX}) as can be seen in Figure 33. If the bike is tilted with the additional angle α as shown in the figure, the lateral force can be calculated as follows:

$$F_{RX} = F_R \times \sin \alpha = \left(\sqrt{\left(\frac{(m_b + m_r) \times v^2}{r} \right)^2 + ((m_b + m_r) \times g)^2} \right) \times \sin \alpha$$

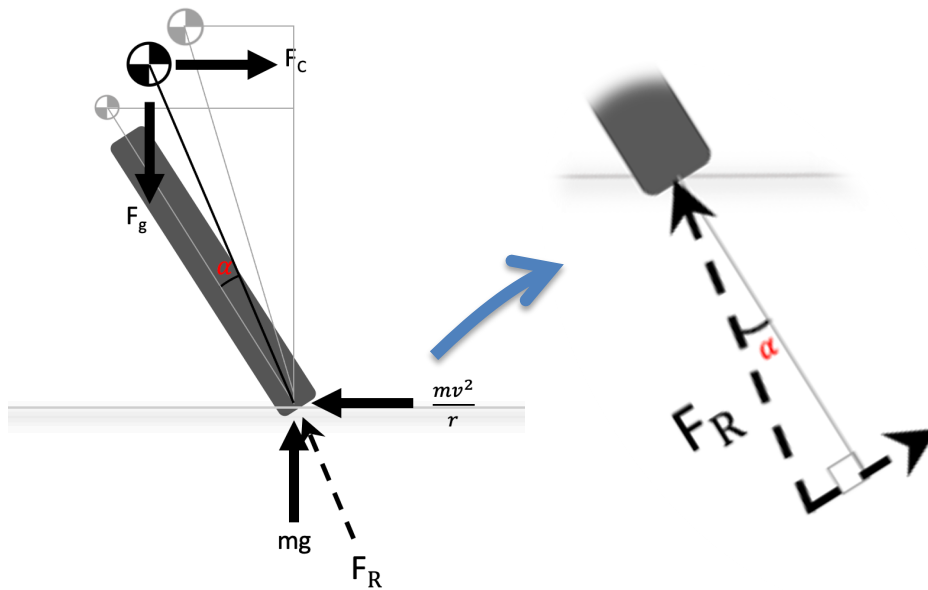


Figure 33 Lean of bike compared to lean of rider.

If using the most common weight from the external survey: 80 kilogram and assuming a bike weight of 15 kilogram, $\alpha = 7^\circ$, a corner radius of 4 meter and a speed of 4 meter per second which were suggested as a suitable size for flat mountain bike corners by a trail building firm (Trailism, 2022) the lateral force would be:

$$F_{RX} = \left(\sqrt{\left(\frac{(80 + 15) \times 4^2}{4} \right)^2 + ((80 + 15) \times 9.81)^2} \right) \times \sin 7 \approx 120 \text{ N}$$

The calculation includes a lot of assumptions, and it is difficult to determine how big the lateral force can be and how likely it is that it causes noticeable frame deflection for the rider. Especially, since it most likely slowly increases and then decreases with the shape of the corner. It seems more reasonable that a suddenly appearing force would cause a noticeable deflection of the frame.

4.2.1.6 Riding berms

Bike park-styled trails and so-called berms were some of the most mentioned aspects in the questionnaire. A berm is a corner in which the ground is inclined, rising towards the outside of the corner and what is meant with a bike park-styled trail is a trail with a lot of those kinds of features, built to make it possible to ride with high speed. The berm reduces the risk of losing grip by decreasing the need to tilt the bike in relation to the ground as can be seen in Figure 34.

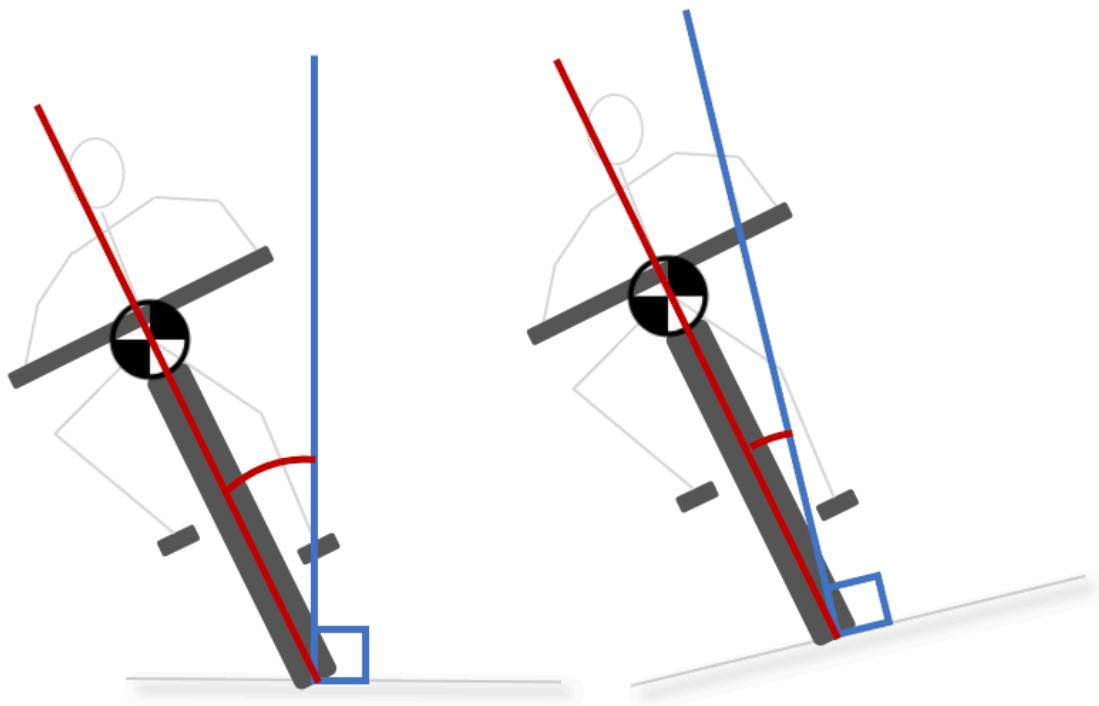


Figure 34 Comparison of cornering on flat and inclined ground.

The reason that many riders seemed to notice frame stiffness in those types of situations is most likely because the berm makes it possible to corner with high speed and small radius which increases the centripetal force and in turn the resultant force acting on the bike. If the center of gravity is in line with the bike the bigger force resultant will only cause the suspension to compress more of the increased force from the rider, but if the rider's center of gravity does not coincide with the bike's there will be a lateral force component acting on the bike similar as what was described in the previous section. A bigger centripetal force will mean a bigger lateral force which might result in deflection of the frame big enough for the rider to feel it. The lateral force will however be a component of the angled resultant force that will have a bigger vertical than lateral component (if the bike is not leaned more than 45°), hence the suspension will be compressed at the same time.

Another potential cause of lateral forces in the cornering scenario is if the centripetal force becomes bigger than the frictional and skidding occurs. That could happen if the speed is too high, the radius too small or if the ground surface has low friction. The bike will most often be leaned when skidding occurs in a corner since otherwise it would tilt over to the outside instead. Hence, the force on the bike will not be perpendicular. The skidding itself will not cause any big forces but rather when it stops and a counteracting force arises, which might be caused by an obstacle on the ground. If the speed in the corner is high the force when skidding occurs can be big and might cause noticeable deflection of the frame.

4.2.1.7 Riding in rough terrain

The other riding scenario that was most mentioned in the survey study was riding through rough terrain. Rough terrain is interpreted as uneven ground with obstacles that are unavoidable to cross. A typical kind of rough terrain are so called rock gardens that are shorter trail sections covered with rocks of different sizes. Higher speed can usually make those kinds of obstacles easier to ride as the momentum gives stability through keeping the bike skipping over some of the unevenness rather than follow the contour of every rock and risk getting stuck. An illustration can be seen in Figure 35. The suspension is usually also working better in higher speeds as any static friction will have smaller impact when the forces are bigger. In addition to keep high speed in rough sections the center of gravity is usually shifted backwards slightly to unload the front wheel and to be able to lift it up when necessary.

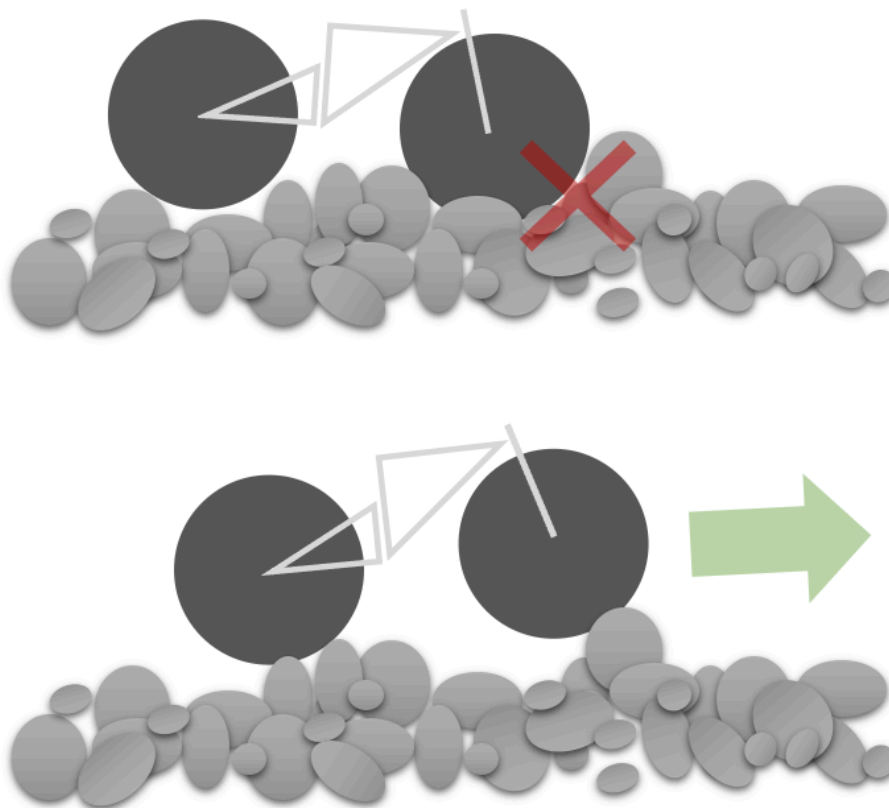


Figure 35 The difference between low and high speed in rough terrain.

High speed will make it easier to ride through rough terrain, but it will also make the forces acting on the bike bigger. The forces are most likely biggest in the vertical direction, because of gravity, and those forces will largely be absorbed by the suspension. When riding with high speed on uneven and unpredictable ground there is a risk that the bike will bounce around and hit things sideways, especially the back wheel that is less controllable as it follows the steering of the front wheel. When one of the wheels hit something sideways the bike will be affected to a corresponding reaction force and if the speed is high the force can be big. The lateral reaction force will not be absorbed by the suspension and might instead cause a deflection of the frame that can affect the riding feel for the rider.

4.2.1.8 Development of a new shock dummy

A discovery from the competitor analysis was that some of them used a normal shock in their tests. A reason for that could be that they had observed differences in the measured frame stiffness when comparing a normal shock with a dummy. That was examined further, and a new shock dummy was developed to use in the experimental testing. The reason for that could be a difference in stiffness of a real shock and a dummy, but also the fact that the two so called eyelets, that are the holes used for mounting, can rotate relative each other on an air shock which is the most used.

A mountain bike air shock consists of two main parts as can be seen in Figure 36: the air can and the shaft. The air can constitute a pressurized air chamber with a piston in the middle on which the shaft slides when the shock is compressed. The shaft can rotate limitless in the air can.



Figure 36 The main parts of a mountain bike rear shock.

A lateral force on the wheel of a bike will create a torque around the center of the wheel which in turn will act bending on the frame, see Figure 37. As the rear triangle of the frame is connected to the shock the bending might be propagated and rotate the shaft in the air can.

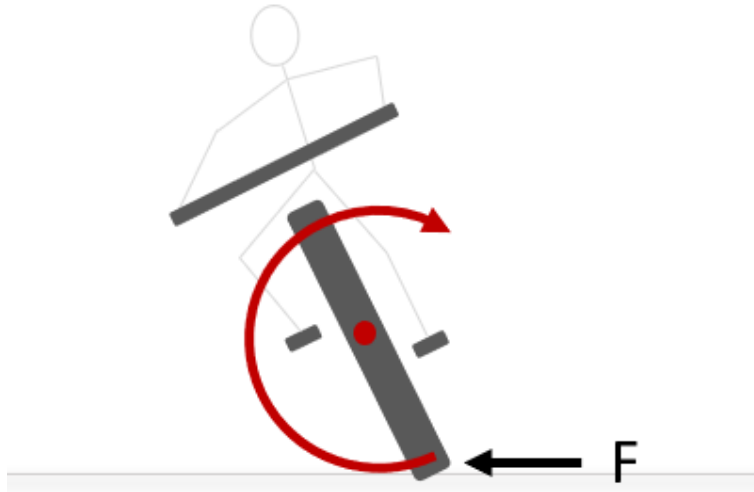


Figure 37 A lateral force creating a torque around the center of the wheel.

If, and to what extent, that happens while riding was not known, but replacing the shock with a rigid rod might make a frame stiffer than what it is with a normal shock. Especially for the rear triangle which was in focus.

A reason for using a shock dummy was to be able to adjust the length as it was considered more reasonable to measure the stiffness in a compressed state. This idea was intended to be tested with simulations, but as that was not possible it had to be tested practically. A new shock dummy was designed that was rotatable and had adjustable length. A simple version that can be seen in Figure 38 was designed to test the hypothesis.

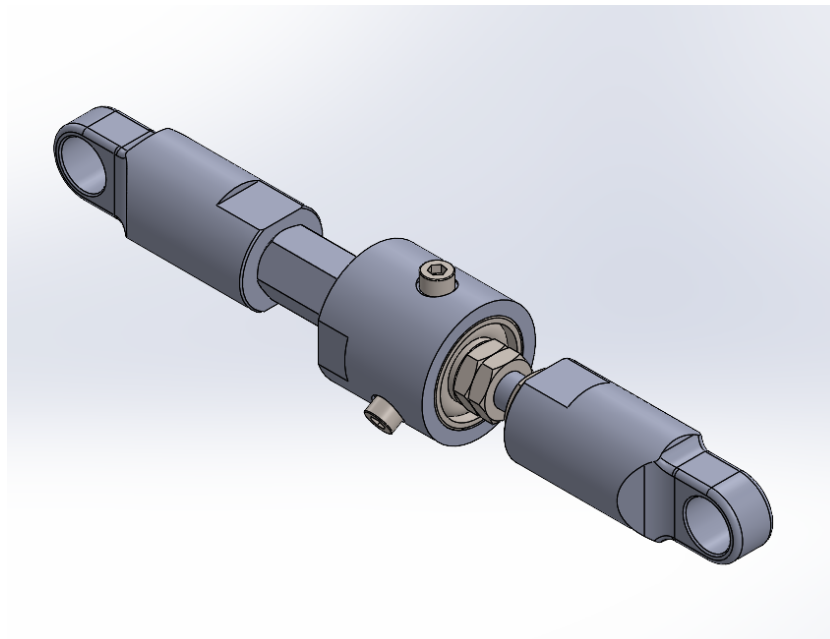


Figure 38 Rotatable and length adjustable shock dummy.

The new shock dummy was made compatible with the existing eyelet nuts, the parts used for mounting on the frame, to reduce the number of new parts needed to be machined. The dummy consisted of a threaded shaft on which two angular ball bearings and a spacer in between was fixed by two nuts as can be seen in the cross section in Figure 39. The spacer had three threaded holes with which it was fixed with screws inside a socket. On the top of the socket there was a short, threaded axle. The two eyelet nuts were screwed onto the short socket axle and the shaft respectively. For longer shock dimensions was a coupling nut and a short, threaded rod added in between the socket and eyelet nut, see the lower configuration in the figure. The shock dummy could be adjusted to the length of 50% compression of all Canyon's existing full suspension mountain bike shocks. The three parts that needed to be machined was ordered from a CNC firm and can be seen in Figure 40.

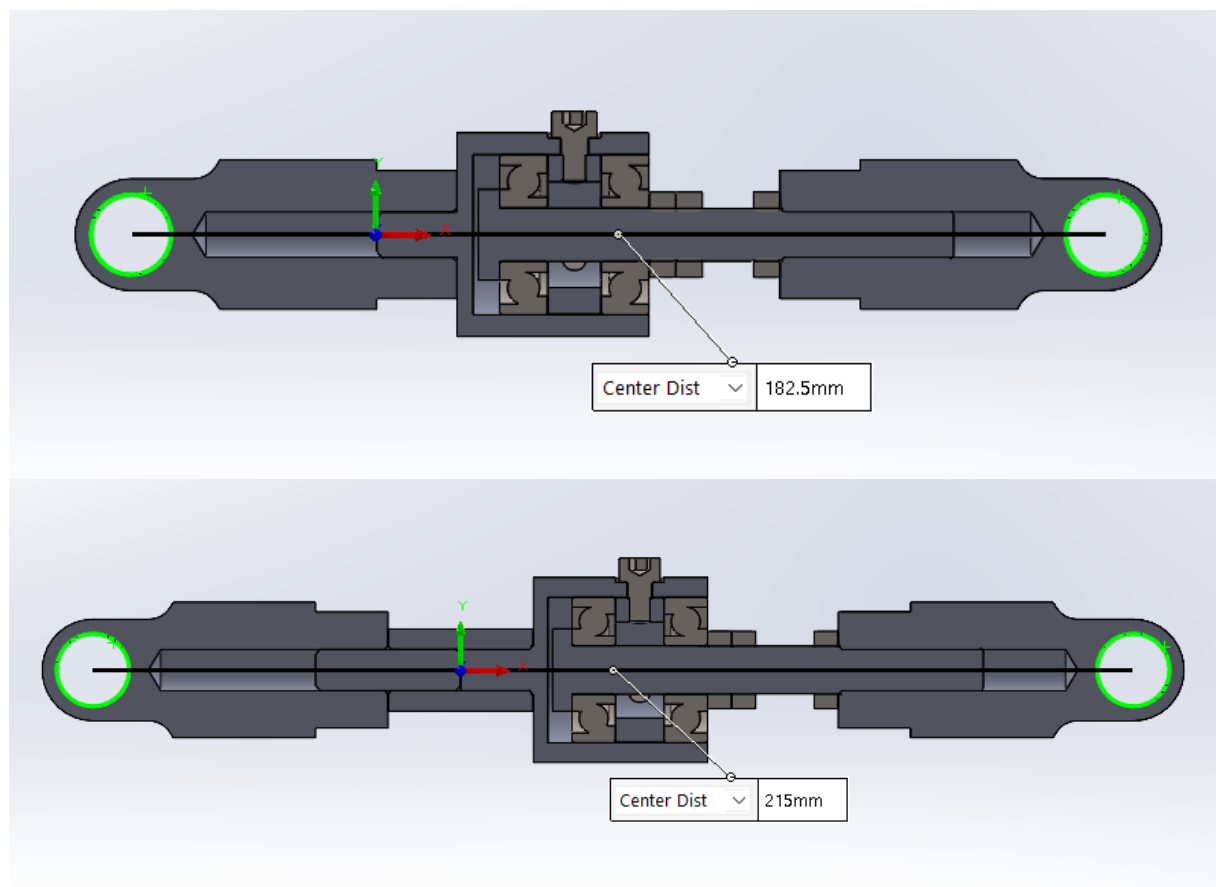


Figure 39 Cross section of the rotating shock dummy. Short configuration on top and long below.



Figure 40 Parts machined for the rotating shock dummy.

4.2.1.8.1 Improved version

After using the rotating shock dummy in different tests some possibilities for improvement as well as to be able to do a proper evaluation of the effect were identified. A new version was designed with better strength, usability, and compatibility. It can be seen in Figure 41.

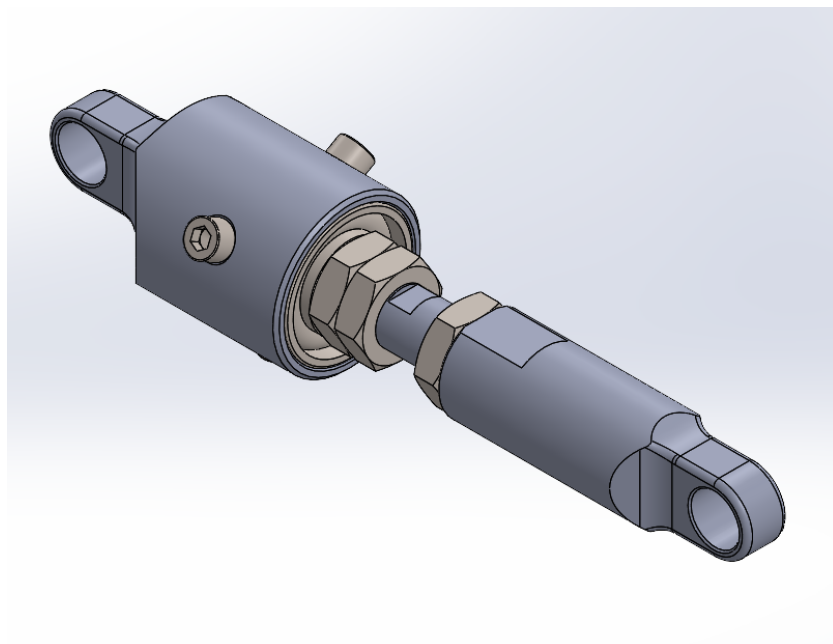


Figure 41 Improved version of the rotating shock dummy.

The adjustments made in the second version were the following:

- The diameter of the threaded rod was increased to 16 millimeters.
- One of the eyelets was integrated in bearing housing to reduce the number of parts and making the fixed length of the shock dummy shorter.
- The other eyelet was part of a nut long enough to make the shock dummy adjustable for all of Canyon's different shock dimensions without removing or adding anything. The longest and shortest length setting can be seen in Figure 42.
- The size of the bearings was increased and the spacer in between them had double the width to reduce the risk of any play. The tolerance on the drawing were also decreased for the same reason.
- A cutout for a 14-millimeter wrench was added to the threaded rod to be able to tighten the bearing assembly while still being in the housing.

The manufacturing time was too long for it to arrive in time for this project.

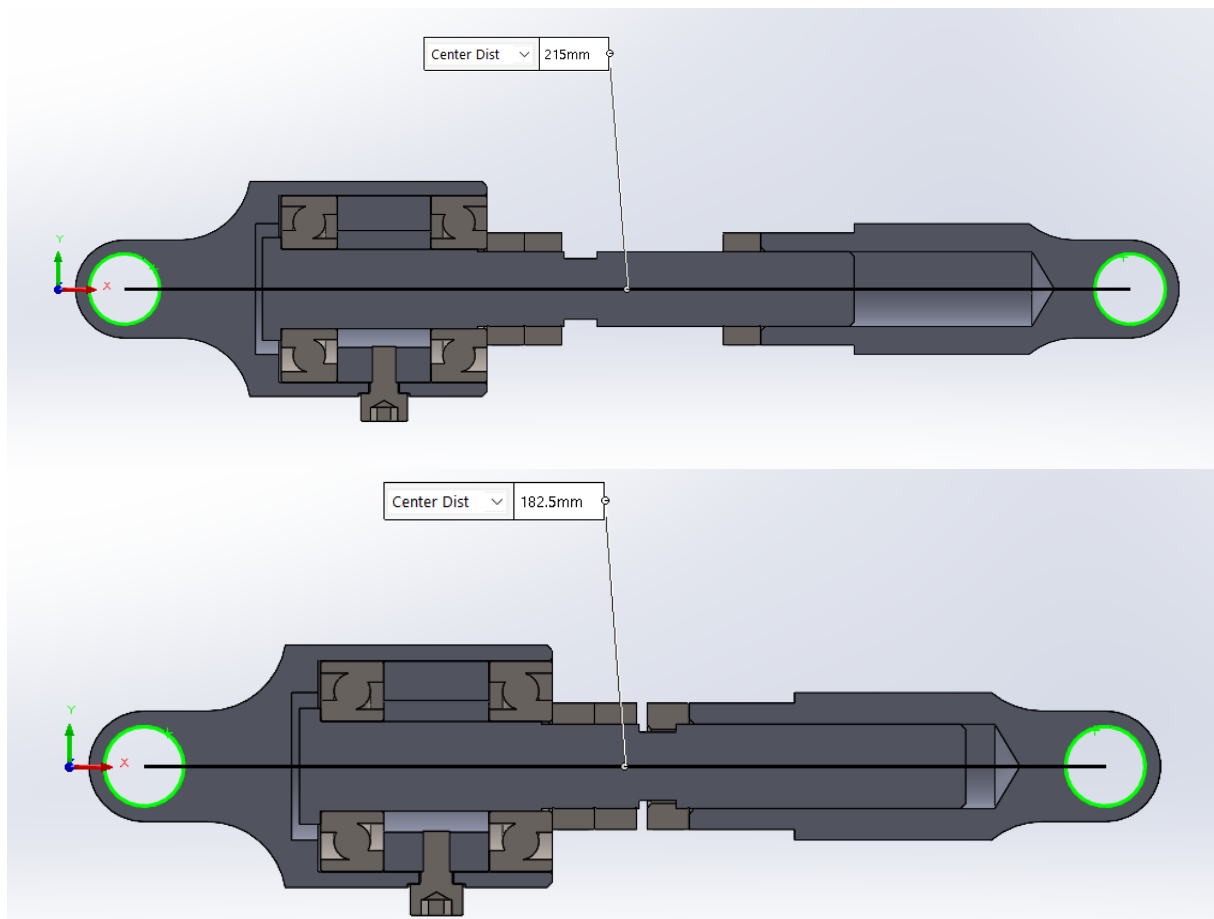


Figure 42 Length adjustment of the improved version of the rotating shock dummy.

4.2.2 Finite element simulations

Three frames were chosen for the initial simulations. They covered both carbon and aluminum as well as 27.5" and 29" wheels and had a big spread on the subjective grading scale.

The simulations were made with the final 3D-models of the chosen Canyon frames. Even though the models already existed some processing was needed to prepare them for the simulations. An initial sample of three frames with different perceived stiffness according to the subjective grading was chosen.

The first step was to separate the parts that would be included in the simulation from the rest of the frame assembly. Meaning the front triangle, chain stays, seat stays, rocker arm and shock extension if part of the frame design. That was saved as a new assembly to make the file slightly more manageable for the software. The transition from the original to the simplified model can be seen in Figure 43.

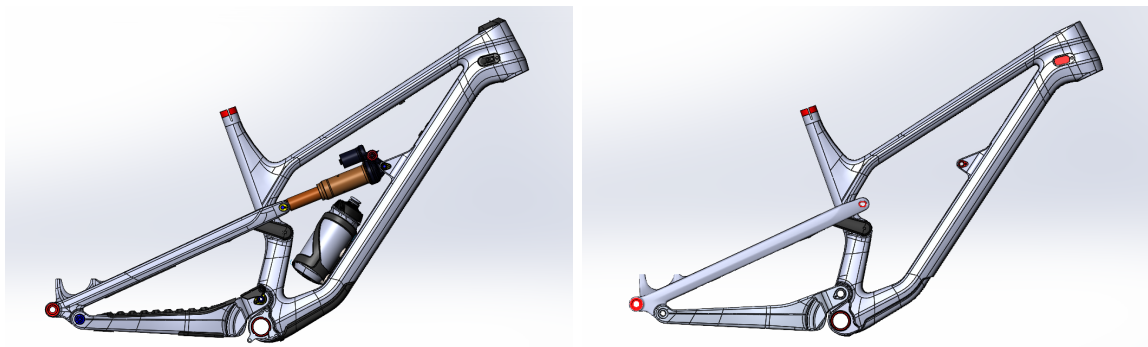


Figure 43 Original 3D model of one of the frames to the left, parts separated to be included in the simulation to the right.

The next step was to make surfaces bodies of all hollow parts of the frames that originally were solid. The procedure differed between the different frame materials.

For the carbon frames, that are manufactured and modeled as one piece the solid parts could be transformed to surfaces just by removing one face of the parts such as in the head tube. The transformation as can be seen in Figure 44.

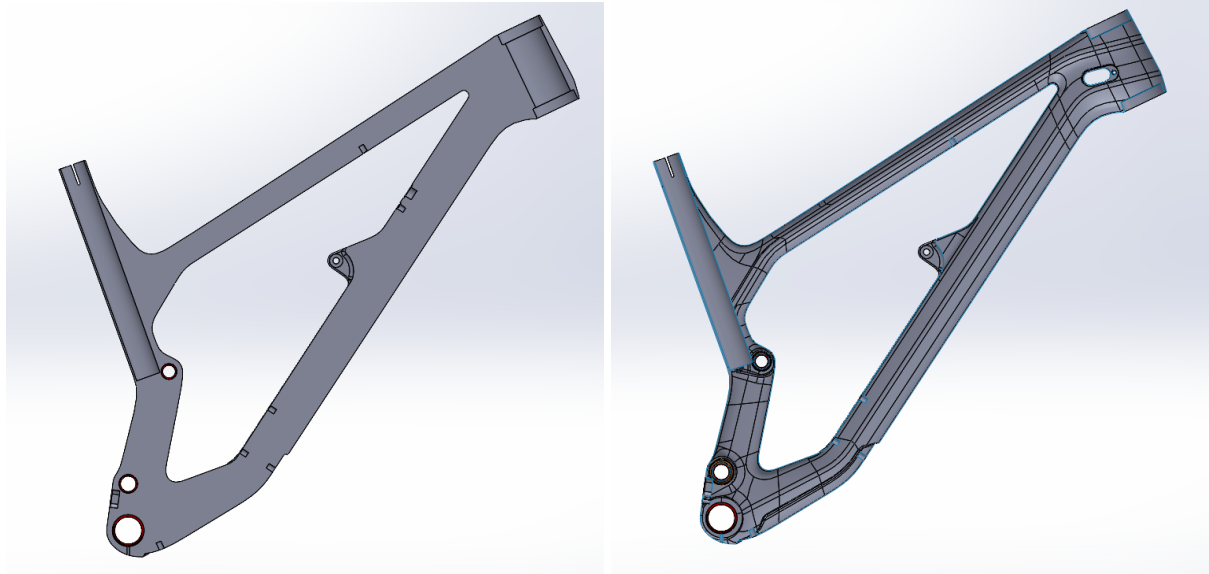


Figure 44 Cross-section of the solid model of a carbon front triangle to the left and surface body to the right.

For the aluminum frame that is manufactured and modeled as tubes welded together with solid parts one cross-section face of all the solid tubular elements was removed to make them surface bodies similar as with the carbon frame. The surfaces were then trimmed in the intersections to create the hollow frame as can be seen in Figure 45.

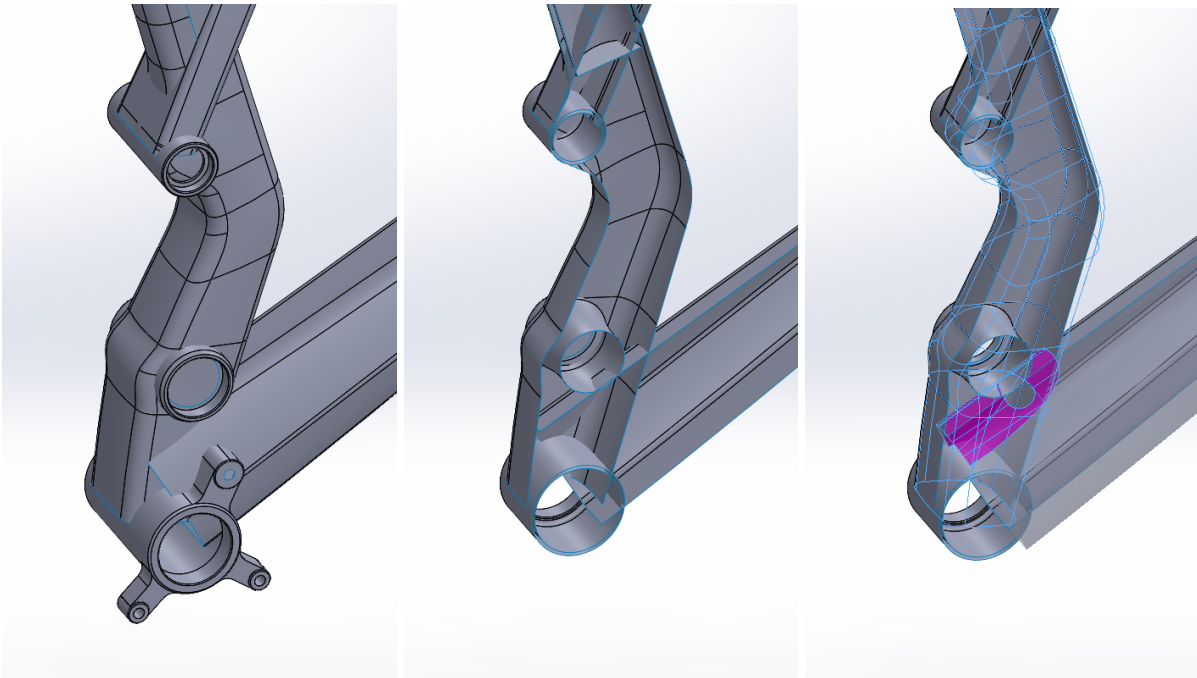


Figure 45 Solid aluminum frame made hollow and lastly trimmed.

The solid parts, such as the bearing seats and shock mounts was also transformed to surface bodies to be used for trimming. They were then removed and replaced by the actual solids as can be seen in Figure 46.

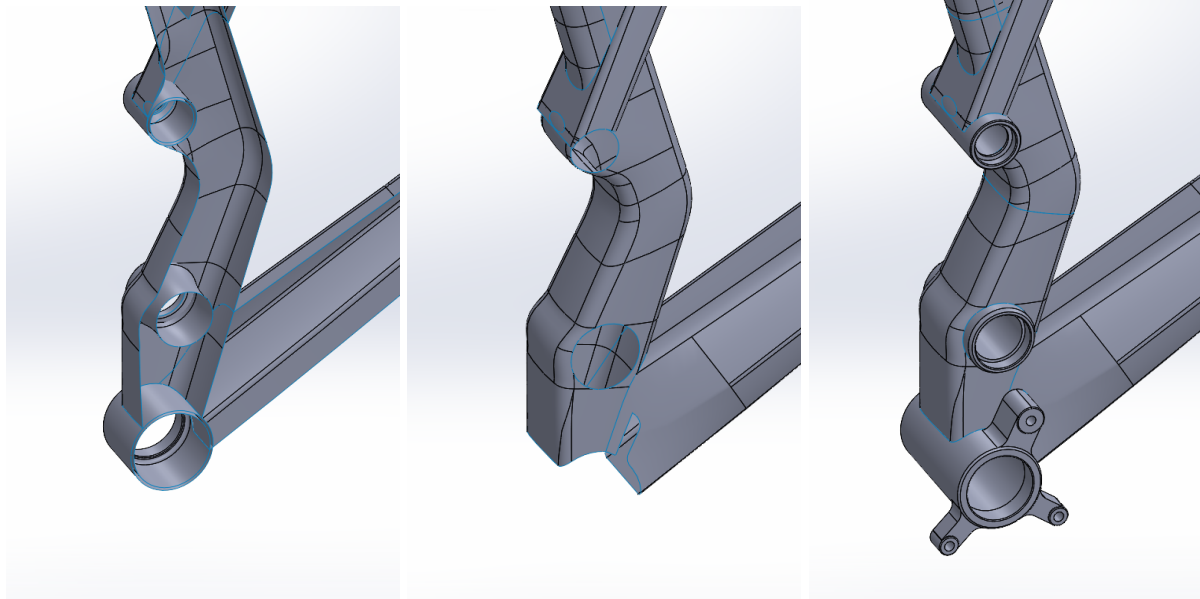


Figure 46 Surface bodies used for trimming and then replaced by the actual solids

In the rear triangle the solid tubular parts was made hollow in the same way as with the rest of the frame. The end pieces of an aluminum frame where the bearing seats are made of solid aluminum and in the 3D model the tubular elements did not match the end pieces so both had to be split to a flat cut so that they could be connected by a new surface. The right front end of the chain stays can be seen in Figure 47.

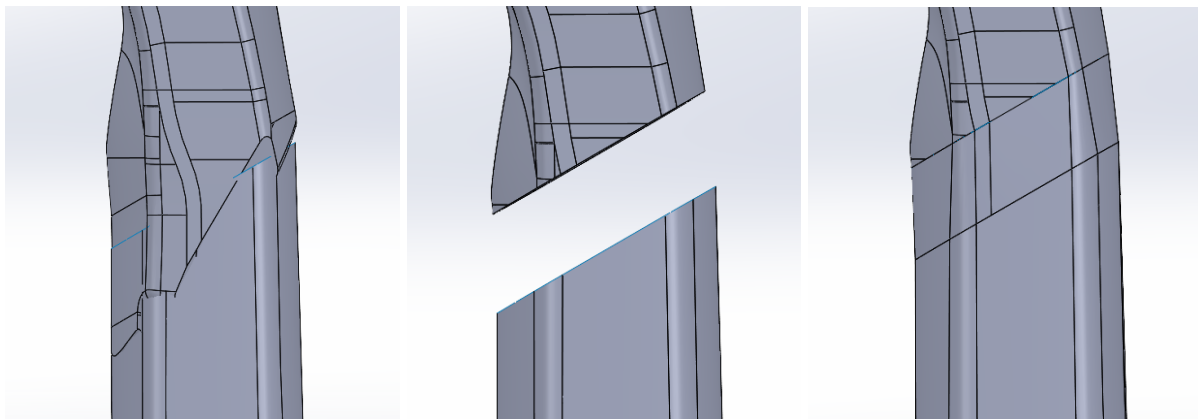


Figure 47 Connecting surface body with solid though splitting and creating new surface.

Unnecessary complex shapes such as small radiuses that would not affect the stiffness calculations but that would consume a lot of computational power were removed or simplified as can be seen in Figure 48.

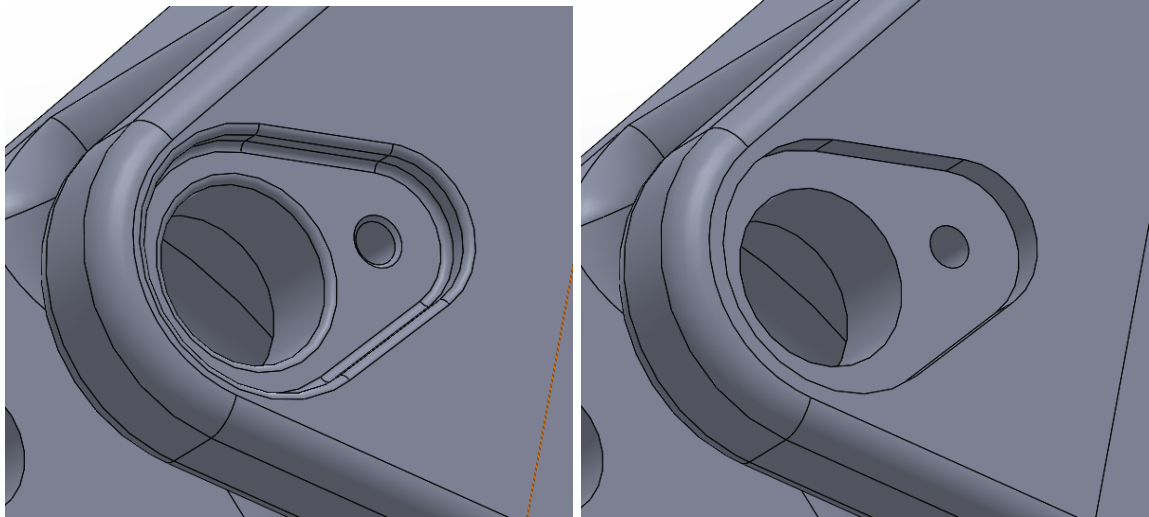


Figure 48 Removing unnecessary complex shapes to save computational power

The different parts of the frames were then split up into segment to be able to apply the right wall thickness for the simulations the splitting of one of the frames according to the wall thickness drawing can be seen in Figure 49.

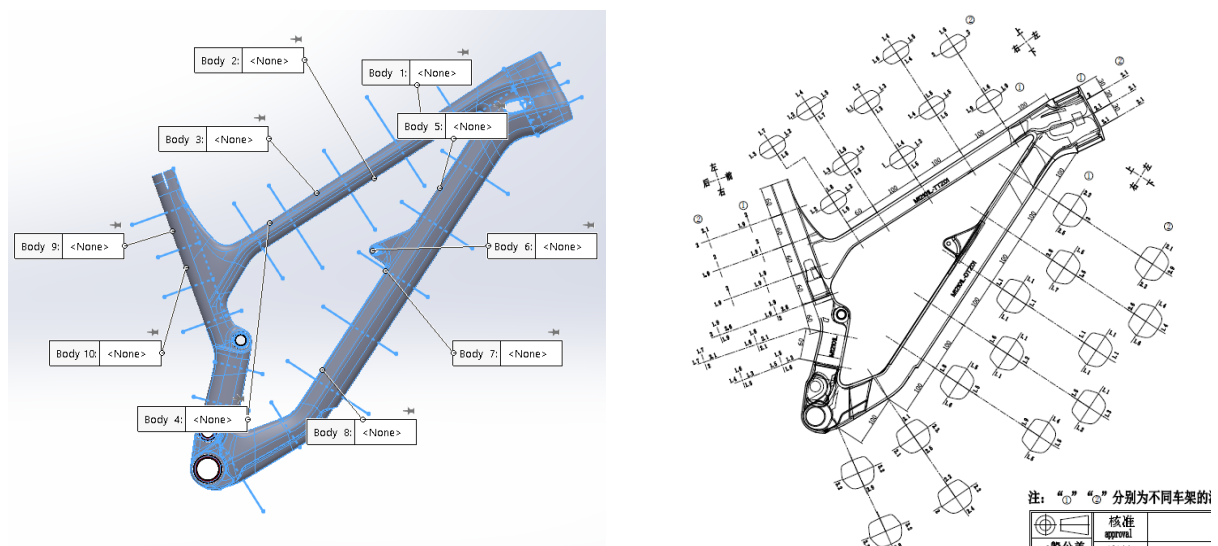


Figure 49 The frames were split into segments for different wall thicknesses.

The hollow, simplified parts were then mated together with all the real bolts as can be seen in Figure 50. All old references from the previous assembly were removed to save space and speed. The reason for creating mates in between the different parts was to be able to change the amount of compression of the rear shock. Two similar eyelet nuts as the ones in the shock dummy model were added to the shock mounts and the eye-to-eye distance were set to 50% compression for the first simulation.

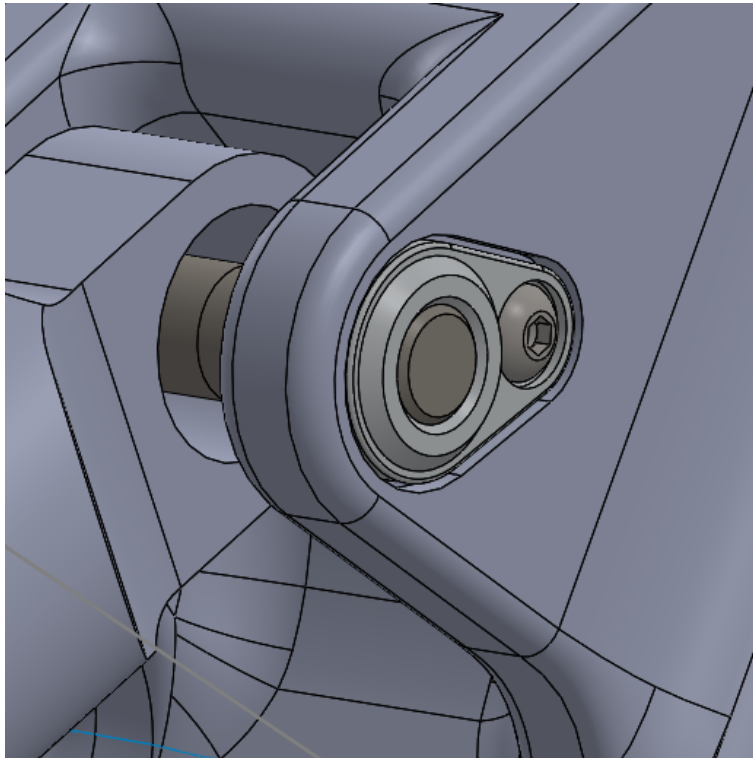


Figure 50 All real bolts and fasteners were used for the simulations to get accurate results.

Materials and wall thickness were applied to all parts. Bearing connectors were added to all the connections in between the frame parts and in the shock eyelets as can be seen in Figure 51.

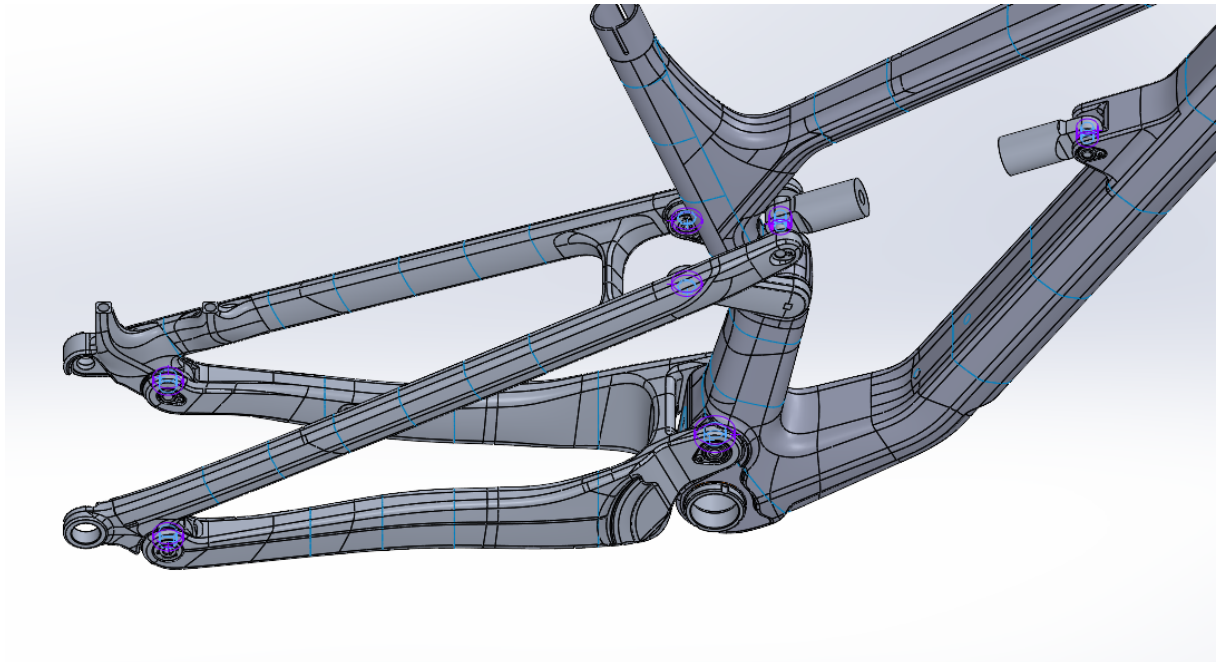


Figure 51 Bearing connectors applied to all connections in between the frame parts.

The two shock dummy eyelet nuts were connected by a rigid connector with a fixed length that could be set to either allow rotation or not similar as the old and new shock dummy.

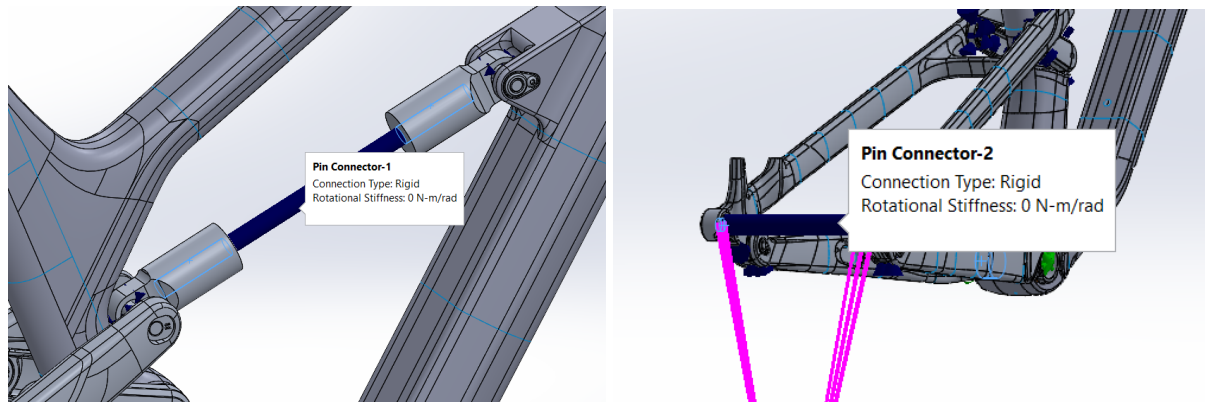


Figure 52 Pin connector as shock dummy and rear wheel axle.

Interactions between different parts were defined as well as for the splits for wall thickness and between hollow and solid elements. A fixture was added to the bottom bracket that locked translation but allowed rotation in the crank rotation direction. A coordinate system was added to the rear wheel and ground contact point as a reference for the force, that for the first test was 300 newtons horizontally. Another coordinate system in the front wheel axle position was used as reference for the fixture of the fork that constituted a force with free translation in the travel direction of the bike and rotation back and forth as well as to the sides. The forces added to the frame can be seen in Figure 53.

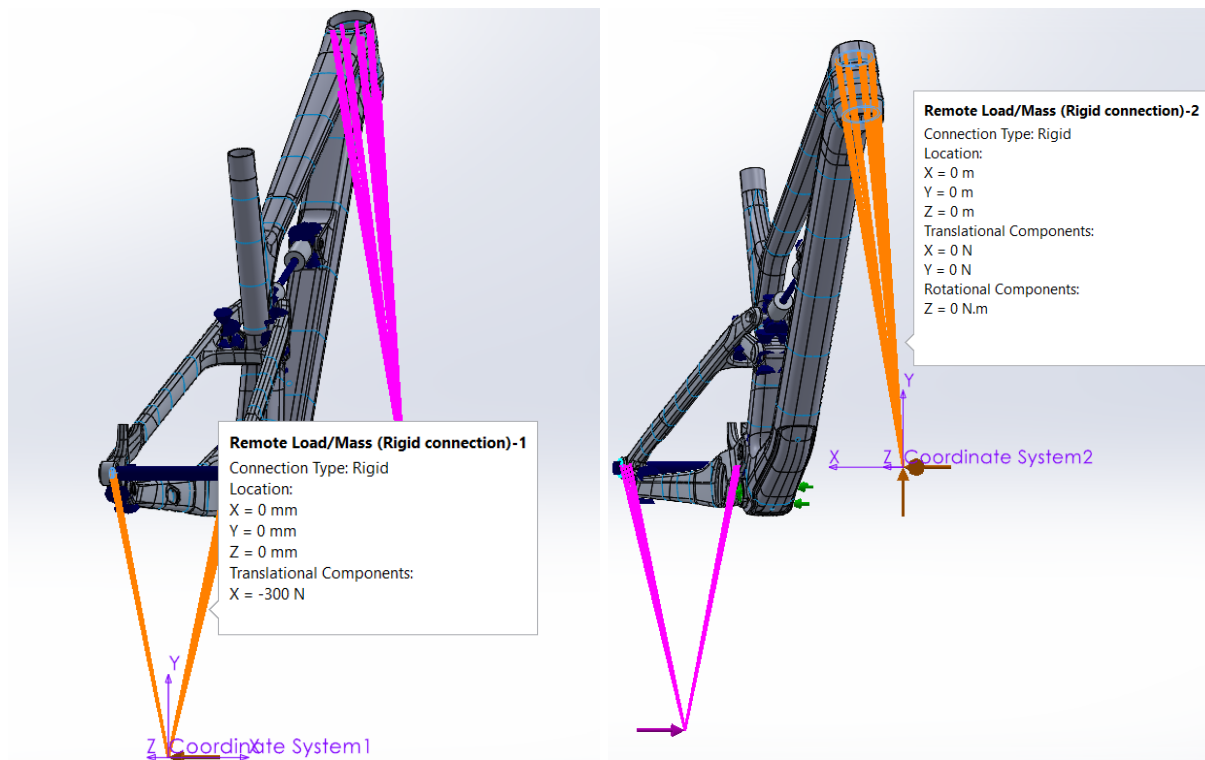


Figure 53 Forces added to the simulations of the frames.

As the final step a mesh was created. 10 millimeter was set as maximum and 2 millimeter as minimum for the first try. If that did not work the mesh size was decreased, either globally or locally on different parts depending on where the failure occurred. If the error remained the shape in the area was examined and simplified to remove potential causes of errors and after

some adjustments all three frames were meshed successfully. One of the meshed frames can be seen in Figure 54.

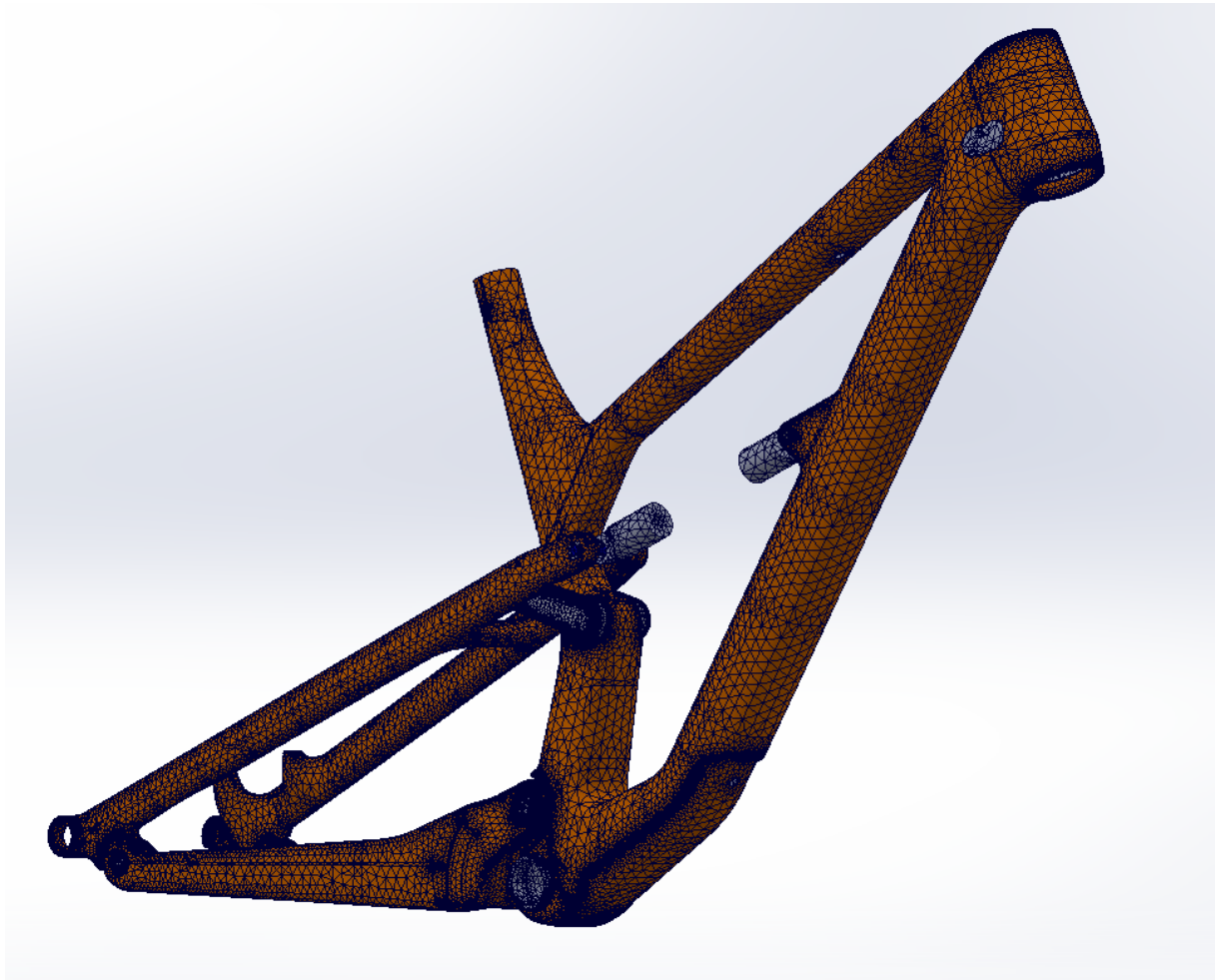


Figure 54 A successfully meshed frame.

When a mesh has been created the next step would be to run the simulation. Unfortunately, none of the three simulations could be solved. Different errors occurred in the last step of the solving process that could not be solved despite several attempts with different adjustments as well as help from experts in the company. A lot of time was spent on trying find the cause of the errors but lastly a decision of abandoning it was made. The three simulations had different errors and as they would all need to work for a reliable comparison it seemed unreasonable to succeed within reasonable time.

4.3 Experimental testing

According to the results of the pre-study and the deeper examination of the riding scenarios when stiffness was most noticed was the following intended to be evaluated further through experimental testing:

- Lateral forces acting on the rear triangle
 - Starting with an angled force direction
- The difference in measured stiffness with different shock dummies.
 - Adjusted to 50% compression.

It was decided to carry out the with use of the scrub load fatigue test bench as fixation for the frame. It is described in the following section.

4.3.1 Test setup

The scrub load fatigue test bench can be seen in Figure 55. To clarify the description of it the directions are referred to as a coordinate system with the following axis:

- X: horizontal, riding direction
- Y: vertical
- Z: horizontal, lateral direction



Figure 55 Canyon's test bench for lateral load on the rear triangle.

The frame was mounted on the testbench in an upright position in the front wheel axle and bottom bracket. A rigid fork dummy with adjustable length was mounted like a conventional fork: clamped with bearings in the headtube and, hence allowing rotation around Y. The front wheel axle was mounted on a bearing assembly on linear bearings allowing rotation around Z and translation along Y as seen in Figure 56. The bottom bracket was clamped with bearings only allowing rotation around Z, Figure 57.

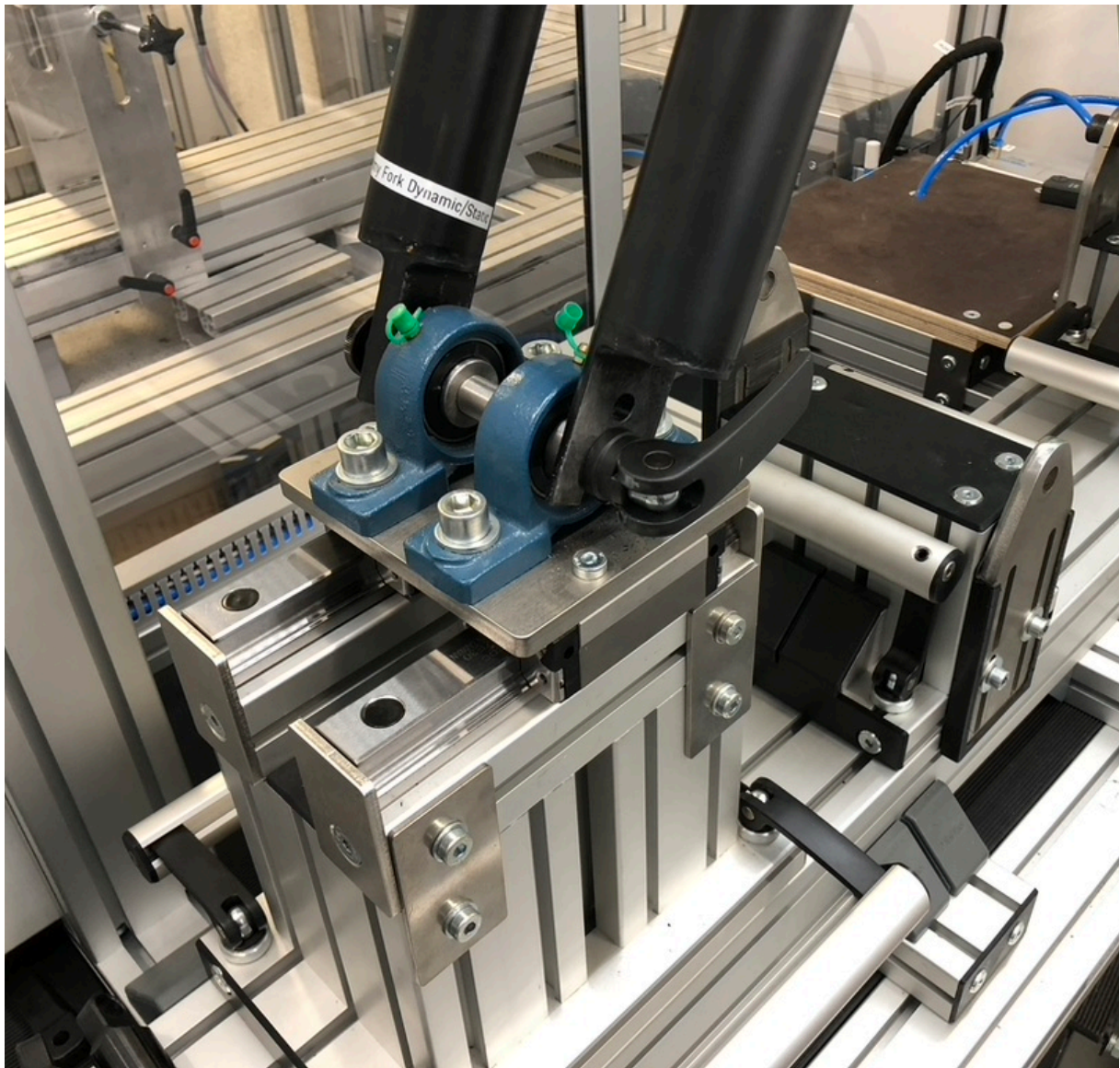


Figure 56 Fork dummy fixture in the scrub load fatigue test bench.



Figure 57 Bottom bracket fixture in the scrub load fatigue test bench.

The rear wheel axle was mounted on a wheel dummy assembly consisting of a metal profile imitating a cross-section of the lower radius of the wheel, see Figure 58. The wheel dummy was mounted on a linear bearing allowing translation in Z direction. The linear bearing could rise in Y direction allowing torsion of the rear triangle of the frame around the X axis. The position of the frame was aligned in X and Y direction with the help of two spirit levels on the flat top surface of the wheel dummy as can be seen in the figure below. The red, plastic arrow that was supposed to be aligned with the front side of the slider made sure the frame was centered in Z direction.

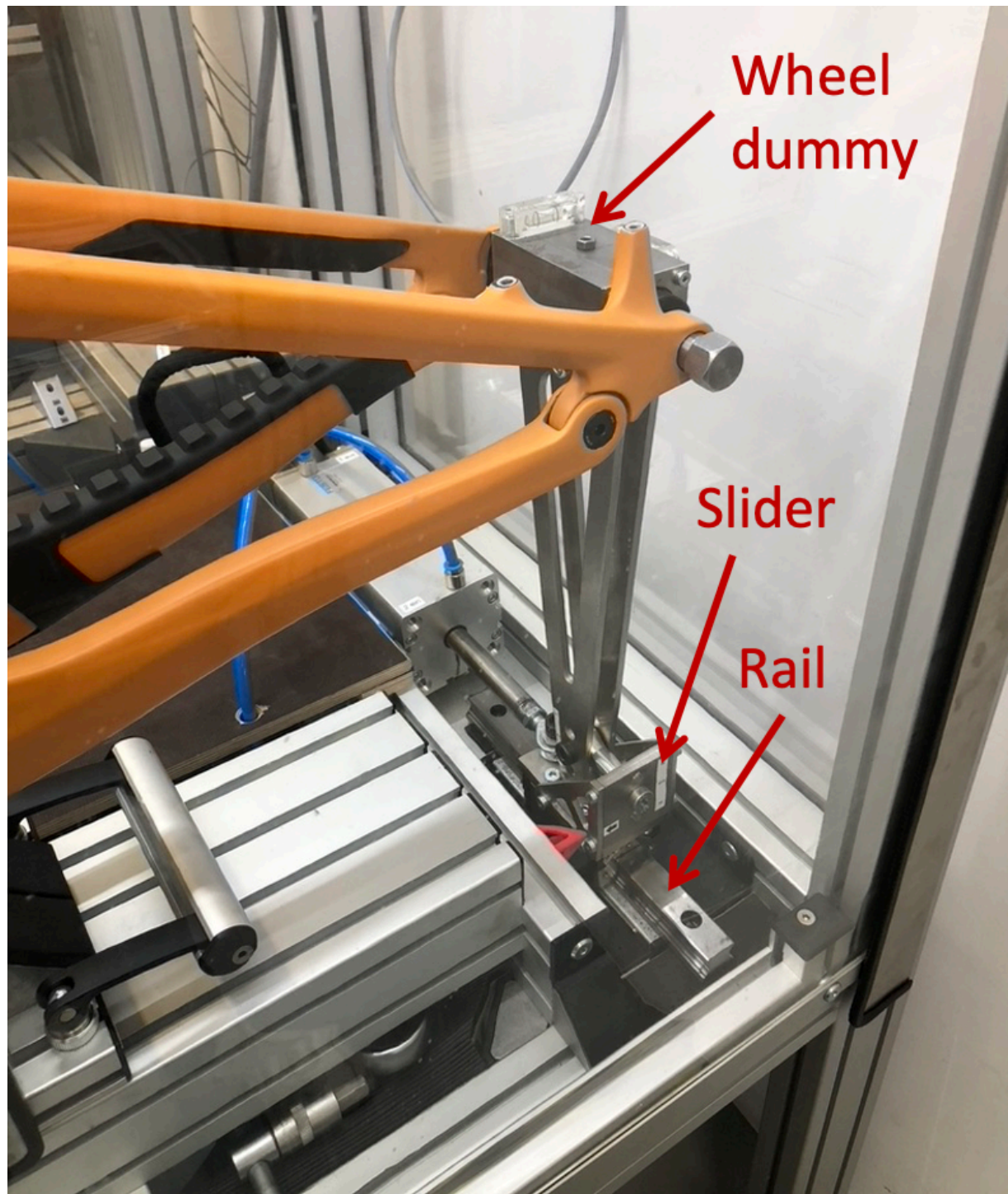


Figure 58 Rear wheel dummy and rail assembly and force actuator in the scrub load fatigue test bench.

The wheel dummy was mounted with a ball joint arrangement on the slider allowing smaller degrees of angulation in all directions. The mounting position of the wheel dummy on the slider could be adjusted for different wheel sizes, as seen in Figure 59, to get the right leverage of the force.

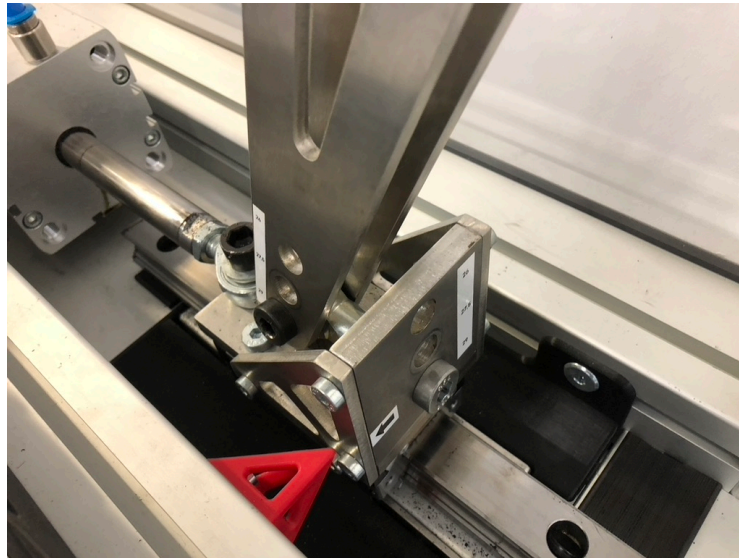


Figure 59 The slider on the linear bearing with adjustment for different wheel sizes.

The force was applied to the linear bearing slider horizontally in the Z direction by a pneumatic actuator that can be seen in the figure above. It could both pull and push; hence the test could be performed on both sides of the frame. The test bench was at the time of the project only used for dynamic fatigue testing, meaning repeatedly pushing or pulling on the wheel axle during many hours to examine potential weak spots. To assure accuracy in line with the existing stiffness measurement methods the pneumatic load introduction was not used in the experimental test.

A special shock dummy was used for the scrub load fatigue tests. It was similar as the normal rigid apart from having a ball joint in one of the eyelets where the bolt mounting it to the frame goes through. It can be seen in Figure 60. As mentioned earlier the test bench was under evaluation and the design of the shock dummy was questioned. The initial reason for using it might have been to reduce the impact on the shock mounts on the frame or to give the rear triangle more freedom to move. Whatever the background idea was the design did not comply with reality as it had too many degrees of freedom.



Figure 60 Ball jointed shock dummy.

4.3.2 Angled force test

The first load case to test was the angled force. The angled load introduction was created with a wire and pulley system that was built up in the scrub load test bench. A wire was fastened to the slider with wire clamps and a carbine hook and was then guided laterally, upwards in an angle of 13° from the vertical plane to a pulley wheel mounted on aluminum profiles above the frame. The 13° angle was considered suitable for a first test and as a significant difference from a horizontal force that would be tested later. A second pulley wheel was needed to get create clearance for the weights that were hung in a carbine hook fastened with wire clamps on the other end of the wire. A jack was used for lifting the weights. The frames were mounted and aligned in the same way as for the scrub load fatigue test. The initial test setup can be seen in Figure 61 and Figure 62.



Figure 61 The initial set up of the angled force test.

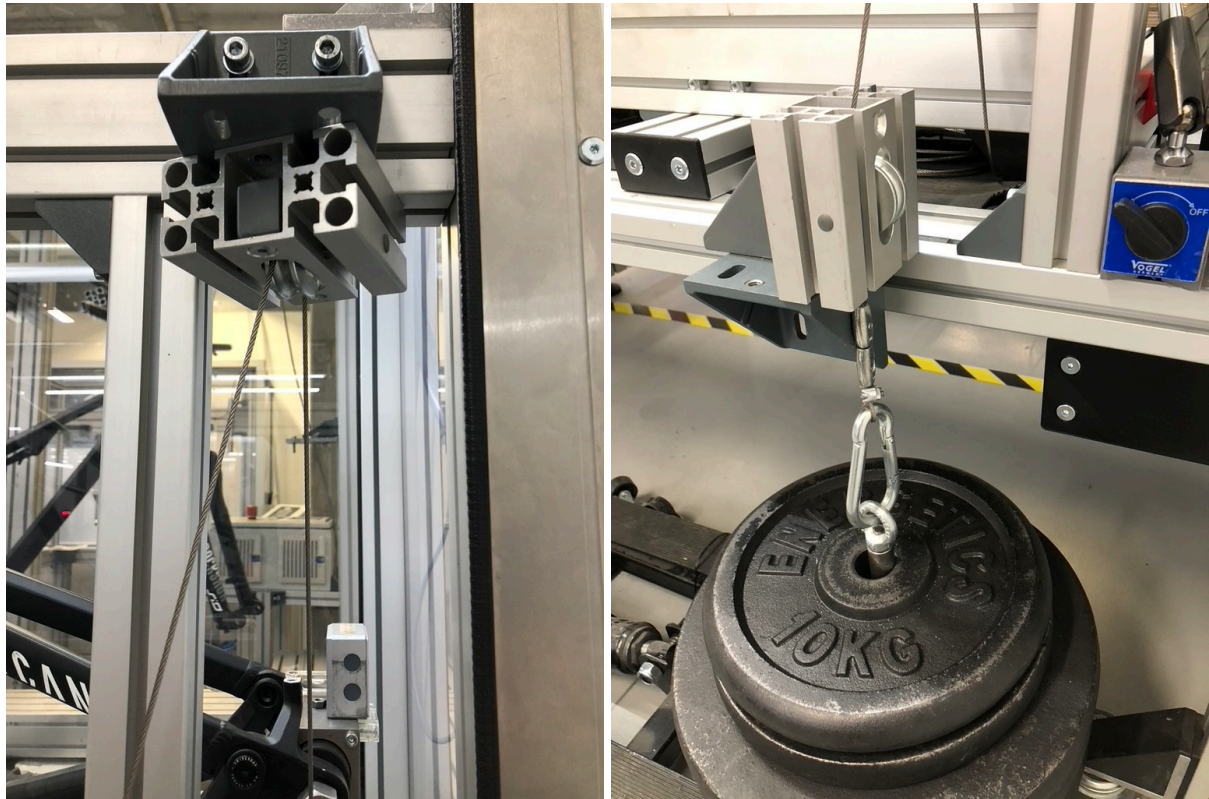


Figure 62 Guiding of the wire in the initial test setup of the angled force.

For the first test rounds all existing shock dummy options was included in the tests, meaning the new rotating, a standard rigid, and the ball jointed. According to the exploratory character of the tests the rigid and ball-jointed was included despite being unrealistic to evaluate any differences in the result. The three different shock dummies can be seen in Figure 63 below with the rigid on top follow by the ball-jointed and finally the new rotating. The shock dummies were set to 50% travel meaning that the frame was fixed in the position where the fork and shock would be half-way compressed.



Figure 63 The three shock dummies used in the first angular force test rounds.

Regarding choice of measurements points, as many as possible would be desirable to detect any promising patterns but what was more crucial was to ensure reliability and repeatability on different frames. The same digital gauges that were used for Canyon's existing stiffness tests were used for measuring the displacement. The jointed holders that made it possible to position them in any direction. As those types of gauges measured displacement with a spindle it was important that the surface to measure on was flat. As there are few standardized interfaces on bike frames apart from the ones that would most likely be used to fix the frame in the test bench and most surfaces are curved the measuring spots needed to be external parts.

The most important factor when choosing load was to achieve stable values. Mountain bike frames are designed to withstand impacts up to around 800 kg, hence the strength of the frame was not a limiting factor. A potential tradeoff was the stability of the results versus the stability of the test rig. Another limiting factor was the range of the measuring devices. They had a range of 25.4 mm which meant that the deflection of biggest measured displacement had to be smaller than that. What amount of load would be reasonable could not be predicted but had to be tested.

As the angled force would have a vertical component it would try to lift the wheel dummy upwards. Lifting the rail and wheel dummy and rail assembly would require a force bigger than its counteracting gravitational force. To be able to determine the magnitude of the resultant vertical force the assembly was weighted with a hand scale that showed 11.5 kilograms.

The weights were held together by a rod with a plate in the bottom and hook on the top in which the carbine hook and wire was mounted. It had a weight of 0.78 kilogram which would add to the applied load. The total forces acting on the imaginary, wheel and ground contact point could then be calculated as can be seen in Figure 64 where m_1 is the mass of the applied load, m_2 the mass of the weight holder and m_3 is the mass of the wheel dummy and rail assembly.

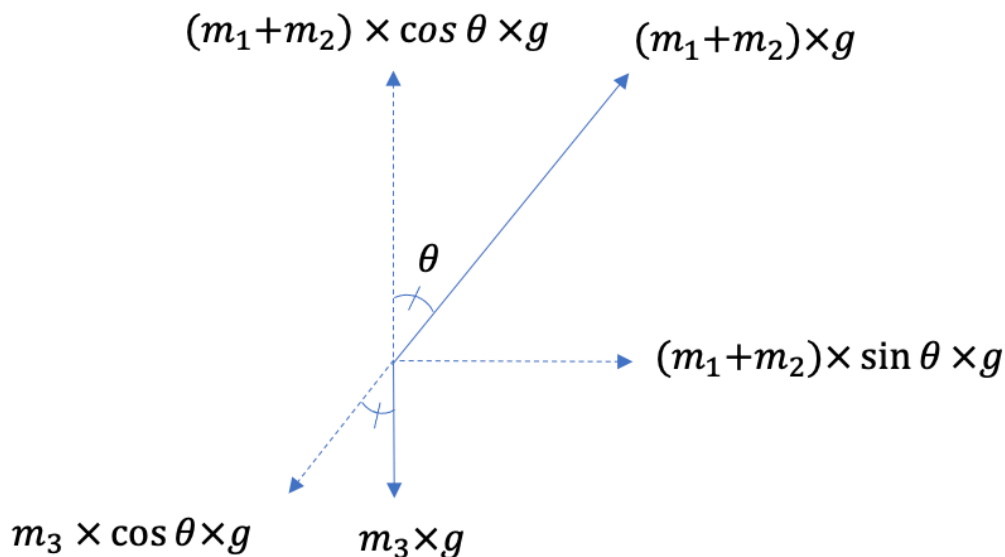


Figure 64 Forces acting on the wheel and ground contact patch

The resultant force components acting on the frame would be the following:

$$\begin{aligned}\nearrow &: (m_1 + m_2 - m_3 \times \cos \theta) \times 9.81 \text{ N} \\ \uparrow &: ((m_1 + m_2) \times \cos \theta - m_3) \times 9.81 \text{ N} \\ \rightarrow &: (m_1 + m_2) \times \sin \theta \times 9.81 \text{ N}\end{aligned}$$

The design of the rest of the test procedure was carried out in an exploratory manner with adoptions according to findings from previous test iterations.

4.3.2.1 First iteration

The experimental test was started with a first test iteration with parameters chosen randomly as a starting point. A load of 45 kg was used. It was let hanging until no more big changes occurred and the deflection was measured vertically and horizontally on the flat top surface of the wheel dummy and wheel axle respectively as can be seen in Figure 65. The test was repeated 3x3 times meaning three iterations of three cycles. The test was stopped after the first full set since the displacement was too small to be considered reasonable with the assumed accuracy of the setup and the gauges.

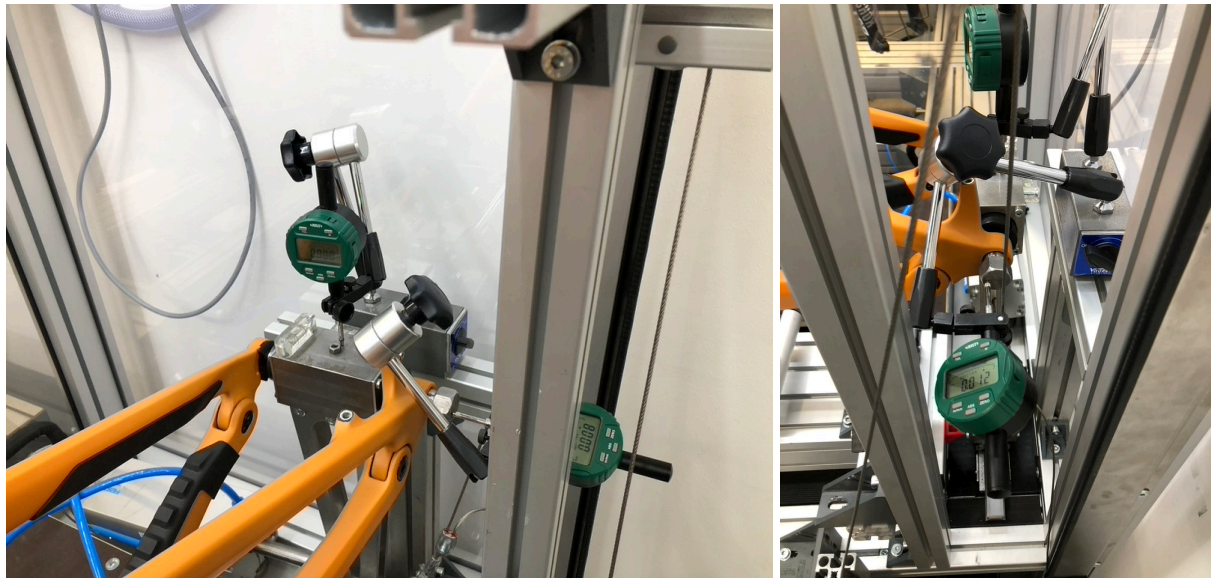


Figure 65 Locations for the digital gauges in the first test iteration, viewed from the front in the left picture and in the right picture: from the side.

4.3.2.2 Second iteration

In the second test iteration the measuring points were moved down to the slider where the force was applied and hence where the biggest movements occurred, one vertically and one for horizontally as seen in Figure 66. The gauges were also changed to thinner models that could fit in the limited space. An angle measuring device was added to the top of the wheel dummy to measure the torsional stiffness. A new test was carried out with the 45-kilogram load that now was let hanging for a fixed time of 2 minutes before reading the values as it was hard to be consistent in determining when big changes had stopped occurring.

It soon became apparent that the measured values were not stable. The range (the biggest measured value divided in the smallest) was almost 16% for the horizontal measurements for one of the frames and the test was stopped as could not be considered reliable. In a discussion with an engineer at the company a range of 10% was decided as the upper acceptable limit.



Figure 66 New locations for the measuring devices in the second test iteration.

4.3.2.3 Third iteration

It was assumed that a heavier load would give more stable values, but it was at the same time uncertain how stable the setup was. To examine that, a test with increased load was carried out as the third iteration. The load was increased in 10-kilogram increments while the equipment and the magnitude of displacement was observed. The wire started sliding in the clamps after a couple of increases and an additional wire clamp was added to both ends of the wire. The increases were stopped at 100 kilograms, without any issues, as that was considered a reasonable limit. The measurement range was lowered and a new test round with 100kg load and otherwise the same conditions was carried out. The range of the measured values was lowered to less than 4% which made the test considered reliable.

A test of the stability of the rig was then carried out. The calipers were left at the positions where they were supposed to sit during the tests, but the measuring points were changed to other parts of the test bench to check for movements. The biggest displacement measured was small enough to be considered neglectable. Ideally the test bench would have been infinite stiff to make sure that all displacement measured occurred in the frame, but as the tests was intended for comparison of frames rather than determining exact stiffness values the setup was considered stable enough to be reliable.



Figure 67 Test of the stability of the test setup.

4.3.2.4 Forth iteration

The increments of the angle measuring device used was 0.05° . The measured angle of the torsional displacement was smaller than 1° which made the accuracy of the measuring device considered insufficient. Instead, another gauge was added for a horizontal measurement on the center of the wheel axle as is shown in Figure 68. The difference in horizontal displacement on the ground spot and axle (Δ) was then used to calculate the angle as $\alpha = \sin^{-1} \frac{\Delta}{r}$ where r was the wheel radius.

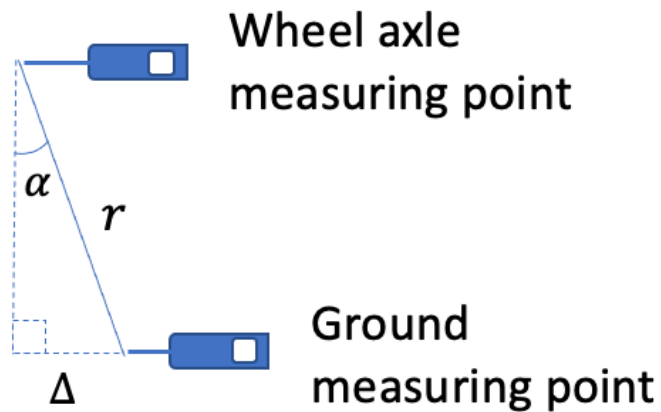


Figure 68 Angle displacement measurement.

The measuring time of 2 minutes made the test very time consuming and since the magnitude of the changes was decreased quite fast the test time was changed to 30 seconds. An extra trial run of 2 iterations of 3 cycles that was not used in the calculations was added to the test to equalize the setup before each new test round. The final angled force test was executed as follows below and the setup can be seen in Figure 70.

- 100-kilogram load on a 13° angle.
- 30 seconds test time.
- The following three measurement points:
 - Horizontal on the ground
 - Horizontal on wheel axle
 - Vertical on top of the slider.
- A non-affecting trial run of 2x3 cycles for stabilizing the setup before starting to measure.
- All three shock dummies tested on all three frames, i.e., nine test rounds in total.



Figure 69 Final test setup of the angled force.



Figure 70 Measuring locations in the final test setup of the angled force.

4.3.2.5 Results from the angled force test

Table 5 shows the test results from the first rounds of the angled force with the three frames and three shock dummies. The values shown in the table are averages from one test round, meaning three iterations of three cycles, i.e., nine tests in total of each configuration (frame and shock dummy). The force components used for the calculations of the stiffness were the following:

- Horizontal: $\approx 222.4 \text{ N}$

$$(m_1 + m_2) \times \sin \theta \times g = (100 + 0.78) \times \sin 13 \times 9.81$$

- Vertical: $\approx 742.6 \text{ N}$

$$((m_1 + m_2) \times \cos \theta - m_3) \times g = ((100 + 0.78) \times \cos 13 - 11.5) \times 9.81$$

The values shown in the table are the following:

- *Lateral displacement* is the horizontal displacement on the wheel axle, i.e., where the frame deflects, calculated with the horizontal force component.
- *Vertical displacement* is the vertical displacement in mm measured on the slider, calculated with the vertical force component.
- *Torsional displacement* is calculated from the difference in horizontal displacement on the top and bottom of the wheel radius as shown in Figure 68.
- *Subjective stiffness* is the perceived stiffness grading from the survey study.

- *Lateral stiffness* is the stiffness of the frame in horizontal direction calculated as the horizontal force component divided in the average lateral displacement on the wheel axle.
- *Vertical stiffness* is the stiffness of the frame in vertical direction calculated as the vertical force component divided in the average vertical displacement.
- *Torsional stiffness* is the torsional stiffness of the frame calculated as the torque (horizontal force component multiplied with the wheel radius) divided with the torsional displacement.
- The *Uncertainty* is calculated as the 95% confidence interval for the average presented as percentage of the average value.

The units used for the calculations were the same as for Canyon's existing stiffness measuring methods. The colors scale goes from green = stiffest, to yellow = softest and it is separated for each of the three columns for each shock dummy.

Table 5 Test results and uncertainty of the measured values for the angled load case.

	Shock dummy	Frame model	Lateral displacement [mm]	Vertical displacement [mm]	Torsional displacement [°]	Subjective stiffness [grading 1-9]	Lateral stiffness [N/mm]	Vertical stiffness [N/mm]	Torsional stiffness [Nm/°]
Rigid	B	5.36	3.29	0.50	7.0	41	259	165	
	Uncertainty					0.4%	0.3%	0.6%	
	D	5.45	3.00	0.55	6.7	41	283	148	
	Uncertainty					0.4%	0.2%	1.2%	
	K	4.27	4.94	0.38	4.0	52	172	205	
	Uncertainty					0.2%	0.3%	0.6%	
Average uncertainty						0.5%			
Rotating	B	5.60	2.64	0.51	7.0	40	322	160	
	Uncertainty					0.4%	0.7%	0.5%	
	D	5.70	2.88	0.55	6.7	39	296	148	
	Uncertainty					0.4%	0.8%	0.6%	
	K	4.32	3.92	0.55	4.0	51	217	142	
	Uncertainty					0.3%	0.1%	0.6%	
Average uncertainty						0.5%			
Ball joint	B	7.74	3.78	0.95	7.0	29	225	86	
	Uncertainty					0.3%	0.3%	0.4%	
	D	7.50	4.79	1.11	6.7	30	177	74	
	Uncertainty					1.0%	0.2%	1.9%	
	K	4.67	11.08	0.79	4.0	48	77	98	
	Uncertainty					0.7%	0.3%	1.2%	
Average uncertainty						0.7%			

If just comparing the “color-matching” of the results and the subjective scale the results are varying a lot and the overall pattern does not seem very promising. The lateral stiffness differs most to the subjective stiffness with the perceived softest (frame K) measuring stiffest with all shock dummies. The vertical deflection has better correspondence with the softest frame significantly softer with all shock dummies. The rigid shock dummy test results with the three frames complied fully with the subjective scale. The torsional varied a lot and did in general not seem promising.

The uncertainty, meaning the difference in the measured values, was quite small in general. The torsional stiffness had the highest uncertainty throughout which was expected since it depended on two measured values: the lateral displacement on the ground as well as on the wheel axle. The ball jointed shock dummy had the highest overall uncertainty which also was corresponded to the expectations with too many degrees of freedom.

To examine the reliability of the results the repeatability was evaluated with another test round with the same frames and identical procedure. The result in terms of stiffness can be seen in Table 6. The “Difference” is calculated as the difference of the two test rounds divided with the average. The “Average difference” is the average of all the differences for each shock dummy.

Table 6 Comparison of two test round.

		Shock dummy	Frame model	Test round	Lateral stiffness [N/mm]	Vertical stiffness [N/mm]	Torsional stiffness [Nm/°]
Rigid	B	1	41	259	165		
		2	43	255	178		
	Differenace		3%	1%	8%		
	D	1	41	283	148		
		2	46	271	165		
	Differenace		12%	4%	11%		
	K	1	52	172	205		
		2	55	256	215		
	Differenace		5%	39%	5%		
	Average difference		7%	15%	8%		
Tot avg. difference		10%					
Rotating	B	1	40	322	160		
		2	40	303	170		
	Differenace		0%	6%	6%		
	D	1	39	296	148		
		2	43	234	158		
	Differenace		11%	23%	6%		
	K	1	51	217	142		
		2	53	219	211		
	Differenace		2%	1%	39%		
	Average difference		4%	10%	17%		
Tot avg. difference		11%					
Ball joint	B	1	29	225	86		
		2	29	259	95		
	Differenace		2%	14%	10%		
	D	1	30	177	74		
		2	34	290	102		
	Differenace		13%	48%	32%		
	K	1	48	77	98		
		2	48	88	105		
	Differenace		2%	13%	7%		
	Average difference		6%	25%	16%		
Tot avg. difference		16%					

The difference in result from the two test rounds were quite big. Especially for a few of the compared pairs of tests such as the 48% difference in between the vertical stiffness of frame D. The lateral stiffness had the overall best repeatability and the vertical the worst. In addition to the bad repeatability was the slightly promising indications that was observed in the first round not repeated and the load case did not seem promising to investigate deeper.

4.3.3 Horizontal force

Even though no promising patterns was observed in the test of angled force the focus remained on the rear triangle. Alternatives for a new test setup was considered. One idea was to test a bigger angle. A smaller angle would be almost vertical which would act on the suspension when riding and most likely not be a load case in which the rider would be aware of the frame stiffness. Instead of just increasing the angle a fully horizontal force was chosen to test something as different as possible and because the test bench used already have that feature.

A new test setup was built up in the scrub load testbench. The wire was mounted on the same spot but with the slider turned around 180° to create space for the wire clamps. A pulley wheel was mounted on the edge of the test bench in line with the rail and on level with the mounting point on the slider to create a fully horizontal as well as lateral force to the frame. A second pulley was needed for clearance of the weights and this time it had to guide the wire upwards because of the small openings in the pulley wheel assemblies to avoid the wire rubbing the aluminum profiles. A bracket was added to the side of the carbine hook to prevent it from rotating and an extra 20-kilogram weigh was added to the jack to make it sink more steadily after unloaded from the hanging weights. The setup can be seen in Figure 72 - Figure 73.

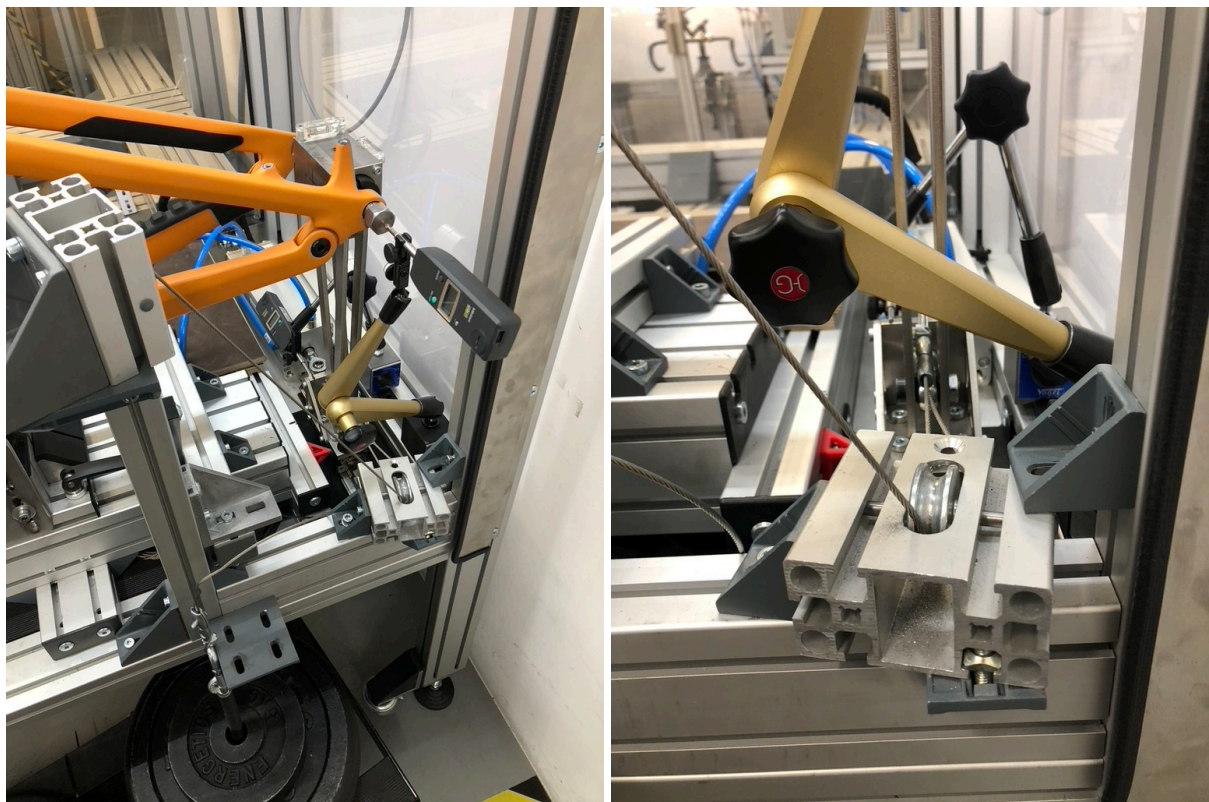


Figure 71 Wire guiding in the horizontal force test setup.



Figure 72 Test setup for the horizontal force.

For the first trial test of the horizontal load case test the measurement points were remained unchanged from the angled force test, i.e., horizontal on the slider and on the wheel axle and vertical on the slider as can be seen in Figure 73.

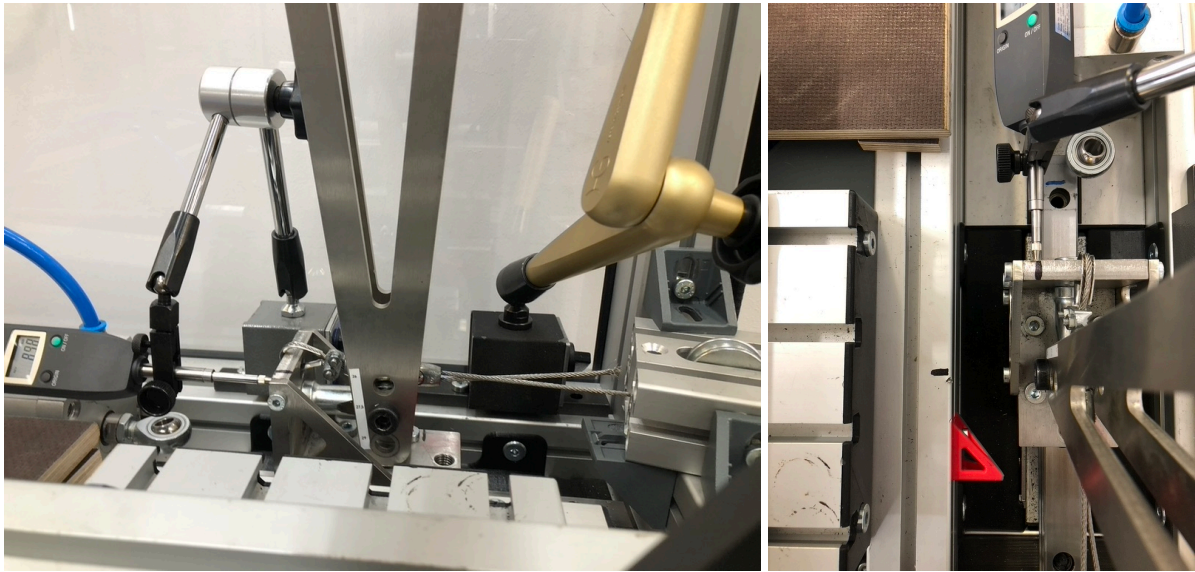


Figure 73 Measuring locations in the horizontal force setup.

A load of 45 kilogram was used which corresponded to double the horizontal component of the angled force. A tripling of the force from the previous test, 67.5 kilogram, was also tested. The measured vertical displacement in this test was very unstable (up to 30% difference in range) and very small, less than 1 millimeter, and the vertical measurement was discarded from the test. The range of the other load was slightly smaller with heavier load however the heavier load resulted in over 20-millimeter displacement on the ground which was too much as the gauges range was 25.5 millimeter. Hence, the 45-kilogram load became the choice which gave a force of approximately 450 newtons $((45+0.78) * 9.81)$.

4.3.3.1 Result horizontal force

The tests were performed in the same way as with the angled force, 3x3 repetitions per shock dummy, 30 seconds measuring time and 2 equalization iterations for every new configuration and starting with the same three frames.

The torsional stiffness calculated from the test corresponded well with the subjective ranking for both the rigid and rotating shock dummy. The ball jointed, on the other hand, did not correspond and the values varied a lot. In combination with the initial skepticism to the reasonability of that design and to be able to prioritize promising traces it was discarded from the test.

To continue examining the promising pattern of the first three frames two more were added. Their measured torsional stiffness corresponded quite well to the subjective ranking. Regarding lateral stiffness, the subjectively softest was measured as stiffest with both shock dummies and lateral stiffness did not seem to correspond to how the frames were perceived when riding. The results can be seen in Table 7. The designations in the table are the same as for the angled force.

Table 7 Test results from frames in size large.

	Shock dummy	Frame model	Lateral displacement [mm]	Torsional displacement [°]	Subjective stiffness [1-9]	Lateral stiffness [N/mm]	Torsional stiffness [Nm/°]
Rigid	A	7.17	0.67	7.1	63	485	
	Uncertainty				1.1%	1.9%	
	B	8.02	0.74	7.0	56	439	
	Uncertainty				0.6%	1.2%	
	C	7.24	0.76	6.8	62	428	
	Uncertainty				0.8%	1.1%	
	D	8.07	0.72	6.7	56	448	
	Uncertainty				0.5%	0.7%	
	K	6.61	0.83	4.0	68	370	
	Uncertainty				0.6%	1.6%	
Average uncertainty per type of stiffness					0.7%	1.3%	
Average per type of shock dummy					1.0%		
Rotating	A	7.60	0.71	7.1	59	453	
	Uncertainty				0.4%	0.7%	
	B	8.46	0.77	7.0	53	422	
	Uncertainty				0.5%	0.6%	
	C	7.60	0.81	6.8	59	401	
	Uncertainty				0.8%	1.6%	
	D	8.23	0.77	6.7	55	422	
	Uncertainty				0.9%	1.5%	
	K	6.64	0.79	4.0	68	387	
	Uncertainty				0.6%	1.5%	
Average uncertainty per type of stiffness					0.6%	1.2%	
Average uncertainty per type of shock dummy					0.9%		

The uncertainty was in general slightly higher than in the angled force test. One reason for that was that the torsional stiffness that naturally has a higher uncertainty as it was based on two measured values constituted a bigger part of the total in this test where only lateral and torsional stiffness was measured. The results and the uncertainty were quite even in between the two shock dummies.

To further evaluate the promising pattern three more frames were added, or rather one new and two already tested in size medium instead of large as that was the only size available for the new frame. The results can be seen in Table 8.

Table 8 Test results from frames in size medium.

	Shock dummy	Frame model	Lateral displacement [mm]	Torsional displacement [°]	Subjective stiffness [1-9]	Lateral stiffness [N/mm]	Torsional stiffness [Nm/°]
Rigid	A	7.53	0.77	7.1	60	418	
	Uncerativity				0.9%	1.7%	
	D	7.76	0.70	6.7	58	464	
	Uncerativity				0.6%	1.1%	
	N	9.91	0.98	2.9	45	313	
	Uncertainty				0.7%	1.1%	
	Average uncertainty per type of stiffness				0.7%	1.3%	
Average uncertainty per type of shock dummy					1.0%		
Rotating	A	8.06	0.82	7.1	56	394	
	Uncertainty				0.6%	1.1%	
	D	8.12	0.74	6.7	55	440	
	Uncertainty				0.6%	1.2%	
	N	10.43	1.09	2.9	43	282	
	Uncertainty				0.7%	1.3%	
	Average uncertainty per type of stiffness				0.6%	1.2%	
Average uncertainty					0.9%		

The torsional stiffness corresponded worse to the subjective than with the large frames however for the medium frames the lateral stiffness had full correspondence. The difference between frame A and D was rather small both in lateral and torsional stiffness as well as subjective stiffness and the overall result could be considered to have quite high correspondence.

To assess the reliability a repeatability test was performed. Instead of testing all frames again two frames were tested three times and fully dismantled from the test bench in between. The difference was smaller than the angled test with an average difference of 6% for the rigid shock dummy and 5% for the rotating as can be seen in Table 9.

Table 9 Test of the difference in values of three repetitions of two of the frames.

Shock dummy				
Frame model				
Test round				
Average lateral stiffenss [N/mm]				
Average torsional stiffness [Nm/°]				
Rigid	A	1	63	485
		2	60	465
		3	60	462
	Difference		4%	5%
	D	1	55	440
		2	59	465
		3	60	472
	Difference		7%	7%
	Average difference		6%	
	Rotating	A	1	59
2			57	439
3			60	458
Difference		4%	4%	
D		1	58	464
		2	57	441
		3	57	427
Difference		2%	8%	
Average difference		5%		

5 Discussion

This chapter is divided into a discussion about the method as well as the result and is finished with the most important conclusions of the project and recommendations for further work on the topic.

5.1 Method discussion

The method of the project was chosen based on the uncertainties identified as crucial to be able to solve the problem. The uncertainties were formulated as the three research questions, that were based on each other and therefore would be examined in order. The first question was about how the rider is affected by frame stiffness. Because feelings are controlled by many different factors there cannot be a right answer to that question, but the idea was to find a generalized pattern. The chosen source of data was a survey study. The choice was governed by the conditions of the project. Another option would have been to do a physical riding study to examine the problem more in depth and in a more controlled way. Options for that was considered but it was assumed that it would most likely have meant that the whole project would have focused on that, which in the end might have been more valuable for the company since that type of research does not exist, but it was not considered suitable for the scope of the project. The test would have needed to be some sort of a blind test which already makes it a bit complicated and, bike frames with known differences in stiffness would have been needed. As there is no standardized system for measuring frame stiffness there are no frames with known differences in stiffness so that would have had to be established first.

As bike frame stiffness is controlled by material and shape one of those parameters would have had to be modified. Different material and same shape are difficult to achieve since manufacturing methods are material specific. The better choice would have been to modify the shape such as done in the riding test carried out by the author with the cut-off chain stay bridge. It would have been limited to only those kinds of bridges since the main parts of a bike frame are crucially load bearing. The small size of the bridges would however have made them easily coverable and suitable for a blind test. That kind of test could most likely have been done as part of the project, but prioritization had to be made and a survey was assumed to maybe be a bit less reliable but more efficient.

Another trade-off in the choice of data collection method was to decide what customer group to target. It is unlikely for a beginner mountain bike rider to be aware of the frame stiffness. The reason for that is firstly that it requires forces big enough to deflect the frame. Today's mountain bikes are generally stiff and designed to withstand high forces and it requires high speed or impacts to reach that, which are less common for beginners. A type of rider for whom frame stiffness really matters are the professional athletes that can push the equipment to its limits. Their needs are often highly affecting bike development since they are racing with the bikes, and they are designed based on what makes them faster. They might also have the privilege of having several bikes or getting new bikes frequently and can be able to create an awareness of different aspects such as the stiffness thanks to get to experience differences. Professional athletes are a small customer group and most of the riders of Canyon bikes are normal people with intermediate riding skills that might be able to notice deflection in some situations. Since athletes are involved in the development process though for example testing prototypes and their opinions in that way most likely already reaches the developers the choice was to focus on the mass of people riding and buying Canyon's bikes: normal people.

The expected outcome of the project was a better understanding of how frame stiffness could be measured in a way that correlates with how full suspension mountain bikes feel when riding them. The outcome is highly dependent on knowledge about how stiffness feels when riding a bike. That was examined in the project and to support the evaluation of different methods, both old and new, a reference of subjective stiffness was formed. The subjective reference got in that way an important role in both determining the magnitude of the problem, through the evaluation of existing methods, and in the outcome of the project as the tested measurements methods was evaluated based on that. The reliability of the finale results is thereby based on the reliability of the subjective grading, which because being subjectivity adds an uncertainty to the outcome of the project.

The reason for choosing Canyon employees for the subjective grading was because people involved in development were seen as likely to possess the ability to feel and separate differences in bikes as that is part of their work and because they usually have ridden and actively tested many different bikes. Another reason was that they were the only people likely to have ridden enough different Canyon models to be able to do the grading. A larger number of people participating in the grading would have been desirable but was difficult to achieve. There might be a risk that the employees were biased by their opinions and prejudices as many of them had been involved in the development of the bikes that they graded. That risk would have been eliminated with a blind test, but it would have been too time consuming to do it with sufficiently different frames and people.

The choice of using simulations for quick testing an evaluation of different ideas seemed reasonable and would most likely have been a useful tool that would had saved time from physical testing if it would have worked. The possibility of not getting it to work was not considered. That is excused with a lack of previous experience of doing simulations. The errors that stopped the simulations is assumed to have been caused by some misunderstanding of the procedure description that was computerized translated from German. A bad decision was to work with preparing simulations for three frames at the same time as much time was spent on it before the problem was noticed. However, if the simulations would have worked the parallel approach would have made it more efficient so in the end it is all seen as a question of bad luck.

Having to rely fully on experimental testing was not the best as the time it required limited the number of tests possible to carry out. It took a lot of time to prepare the different load cases that also had to be restarted a couple of times as the scrub load test bench was needed for its intended purpose. The mounting of the different frames took a lot of time and it need to be adjusted according to size, suspension and wheel dimensions and the measuring devices remounted with every frame. Lastly a mistake was that the supply of frames was not examined when creating the subjective grading questionnaire which included some frames that were not accessible.

5.2 Result discussion

The outcome of the project was a better understanding of how frame stiffness of full suspension mountain bikes could be measured with better correspondence to the perceived stiffness. If using the subjective stiffness from the survey study as reference the tested horizontal load case showed the most promising result. Regarding type of stiffness measurement, the torsional stiffness for the five frames in size large and for the horizontal for the three in size medium had the best correspondence to the reference. The rigid and rotational shock dummy showed similar results. The loss of the simulations limited the number of ideas to thoroughly evaluate, and the promising traces could not be confirmed further.

The fact that the measurements method was supposed to correlate with the feeling of using the product added uncertainty in accordance with the nature of feelings. The success of the result was assessed based on the subjective reference of Canyon employees grading the perceived stiffness of the tested frames. The difference in the grading of the frame stiffness of the same frame was up to 7 on a scale from 1-9 in the first round of the questionnaire and changes both in the grading and in the respondent's confidence occurred in the second round. The results were filtered to remove obvious uncertainties but there was still a deviation in the result. The reliability to the reference on which the result was evaluated can thereby be questioned. A reliable reference would be necessary to evaluate the results. What is a reliable reference is uncertain. As feelings are personal there will always need to be some generalization and what level that should be done on, whose opinion to involve and how many must be determined. It might be necessary to decide who the most important user is, who the bike should be designed for and in that way whose perception should be the reference regarding the stiffness. The most reasonable might seem like the type of customer contributing to the biggest profit. The survey aimed for that type of customer, the general mountain bike rider, indicated an uncertainty and lack of perceived importance of frame stiffness. Due to that it might be more reasonable to focus on riders on a higher level or even athletes as they usually have an opinion and what they think is best might also be what is best for the general customer. In that case the athletes' perception of the stiffness of different frames should be used as reference in the development of a new measurement method.

The belief that the existing stiffness measurement methods were not well-functioning seemed to be shared by the Canyon employees according to the result from the questionnaire. However, what that belief was based on is more uncertain especially due to the big variations in the subjective grading of the frames. According to the generalized average perception the error could be confirmed, but the reliability to that reference is, as already mentioned, uncertain.

In retrospect, with the knowledge gained from the project, a better approach seems to be to focus more on the riding perception and determine whose perception to rely on. The difficulty of designing a test bench does not seem to be how to fix the frame or how to load the weights, but rather what load case to test and if that is known it should be simple to imitate. That might sound contradicting when looking at the differences between the test rounds in the experimental testing. The reason for the differences were not examined but as the uncertainty, meaning the difference in between the test runs within one test round, was much smaller compared when the frame was removed and remounted it must be caused by differences in how they were mounted. The fixation of the bottom bracket in the scrub load fatigue test bench might have been what caused the differences as it consisted of several parts tightened manually and it was also controlling the lateral position of the frame in the test bench.

The difference in measured stiffness with the existing stiffness test benches was not evaluated and it is in that way not known if the uncertainty should be considered big or not. The principle of the stiffness test methods with manually loading and measuring entails an uncertainty. If reliable and repeatable results are required another testing principle might be beneficial to consider. Lastly, the idea about separating front and rear triangle stiffness makes sense as the information would be easier to interpret and use in the development process, but whether it corresponds to the way stiffness is perceived when riding could not be confirmed in the project as it was only focused on the rear triangle. It was considered to separate the front and the rear in the grading, but it was assumed to have been too complicated for some respondents and a quantity was prioritized over quality.

5.3 Conclusions and recommendations

To, in short, conclude the results from the project the answers to the research questions are summarized followed by some recommendations for further work on the topic.

5.3.1 Conclusions

1. How is the rider affected by the frame stiffness when riding a full suspension mountain bike?

The frame stiffness of a full suspension mountain bike has a varying degree of impact on different riders. The majority thinks the stiffness is mostly affecting the control of the bike. The riding situations when the frame stiffness is most noticeable to the rider is when cornering and when riding in rough terrain.

2. What forces are making the rider notice the deflection of a full suspension mountain bike frame?

The forces that the bike is affected by in the situations when the stiffness is most noticeable for the rider are assumed to be lateral forces with a somewhat steep angle of incidence relative the vertical plane.

3. What type of measurements can indicate how the stiffness of a full suspension mountain bike is perceived when riding it?

Despite the angled force being considered the more common load case when riding, a test with a fully horizontal lateral force showed the best correspondence to the perceived stiffness when riding the bike. The most promising types of stiffness measurements in the load case was torsional stiffness around the rear wheel axle for some of the frames and directional, lateral stiffness for some.

5.3.2 Recommendations for further work

The main recommendation for further work on the topic is first and foremost, more tests to follow up and validate the promising patterns. In addition to that is a more detailed examination of the riding perception of frames stiffness considered necessary as a better understanding is needed to develop a reliable measurements method. The optimal would be to do some sort of blind tests in different type of terrain with different types of riders and bikes. In addition to investigate their perception it would be desirable to use some sort of sensors on the bike to examine where and when deflection occurs to be able to compare feelings with facts. If no generalized pattern can be observed a decision of who's perception to take in account is necessary.

A requirement from Canyon was that a new measurement method for frame stiffness should follow the same material and workflow as the existing. That would facilitate both the development and implementation of a new method, but as the existing do not work it might be necessary to consider a bigger change. Another requirement is that the method should provide reliable and repeatable results. It is not known how reliable and repeatable the results are with the existing methods, considering the measurements, but the extensive involvement of the

operator might be a risk. A method where the risk of human factor impact is minimized is desirable. That could be finite element simulations. As no conclusions could be made about that in the project it is recommended to examine further. If it would be possible to simulate situations when the rider is affected by the frame stiffness in a realistic way it would be the best choice as that could be used early in the development process, before a prototype is manufactured which would save both time and cost.

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