Bachelor's project

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

10001, 10009

BEAT REAR SUSPENSION

Bachelor's project in Product and System Design
Supervisor: Lars Petter Bryne (NTNU), Magne Tessem (Stokke), Erik Lyberg (Stokke).
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CANDIDATES:				
10001, 10009				
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STUDY: Product and system design			**SIDES/ATTACHEMENTS** 67/0	**BIBL. NR:**

SUPERVISORS:
Lars Petter Bryne (NTNU), Magne Tessem (Stokke), Erik Lyberg (Stokke).

TITLE:
Beat Rear Suspension

SUMMARY (ENGLISH)

The task for this project was to create a back-wheel suspension system for the Beat stroller.

The project started by coming up with different solutions for a suspension mechanism and then sketching them. The best concept was picked, developed into a 3D-model, and then 3D-printed. The whole process from idea to final prototype included a lot of calculations, FE analyses, DFM and testing. There was also a lot of research done on patents for suspension systems, materials, spring properties, test procedures and standards. Most of the steps in this project were evaluated by the lead engineer.

The result of this project was a functional prototype of a suspension system made of PA12 for the back wheels of the Beat stroller. The suspension does not compromise the brake system and does not hinder the folding of the stroller. With this new suspension, the vibration peaks of the stroller were reduced by approximately 40 %.

SUMMARY (NORWEGIAN)

Oppgaven handler om a lage fjæring/demping på barnevognen BEAT

Projektet startet med å komme på forskjellige ideer og løsninger på mekanismen til fjæringen, Den beste løsningen ble valgt, tegnet til en 3D modell, så laget prototype av. Hele prosessen fra ide til en ferdig prototype inneholder mye beregninger, FE analyser, DFM og testing.
Det ble også gjort en del leting av patenter for diverse fjærings systemer, materialer, fjær egenskaper, test prosedyrer samt standarder. De fleste segmentene er evaluert av stokkes ingeniører.

Resultatet av dette projektet er en fungerende prototype av fjærsystemet, som er printet i materialet PA12. Fjæringen blokerer ikke barnevognens sammenslåing. Vibrasjons toppene til barnevognen under testing er redusert med ca 40%.

TERMINOLOGY

Identity	Symbol	Comment
Sigma	σ	stress
Tau	τ	shear
Theta	ϴ	angle
Beta	β	angle
Alpha	α	angle
Deg	°	Degrees
DFM		Design for manufacturing
BOM		Bill of material
CW		Clockwise
CCW		Counterclockwise
V01		Version 1
V02		Version 2
V03		Version 3
SCP		The Spring calculator professional
VB		Vibascout – acceleration meter
Newton	N	Force
Amin	Amin	Acceleration minimum
Amax	Amax	Acceleration maximum
FEA		Finite Element Analysis
NX		CAD siemens NX
IST		The spring calculator

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1. INTRODUCTION

This is a bachelor thesis. Stokke AS has requested a study of designing and implementing suspension to the Beat stroller. The project is done by two students and supervised by the Beat project's lead engineer.

1.1 BACKGROUND

Stokke's engineers have already done some research on a suspension solution, but they were not sure about its potential. The requirement for the students was to come up with a new design of suspension system for the back wheels and implement it to the Beat stroller. The task for the students was to research the potential of the system, and decrease the impact on both the baby and the chassis on bumpy roads.

1.2 APPROACH TO THE PROBLEM

The approach to this problem was first to get to know the stroller. Disassembling and assembling it a few times helps us to learn all the functions of the stroller and notice all potential obstacles. This helps us get familiar with the respective regulations and standards of the product that might be affected by future changes that would be made in the stroller. Throughout the project there was a lot of calculations, research, 3D printing and testing done to optimize the results.

1.3 ASSIGNMENT

The Beat stroller was ready to go out on the market without rear suspension. The absence of rear suspension causes unnecessary discomfort for both the child and the parent and also causes a lot of impact to the stroller, which reduces the longevity of the product. This project is about creating a concept where a rear suspension is integrated into the design, so that it would reduce a significant amount of the direct impact force.

In this assignment the candidates will do the following:

- Get familiar with the regulations for the product
- Create and develop ideas by using concept evaluation and design study, based on criteria such as: comfort, user friendliness, safety and function.
- Produce prototypes of selected concepts
- Choose a concept for further developments, in collaboration with Stokke's engineers.
- Carry out a full evaluation of chosen concept, including strength analysis (FE analysis)
- Physical testing according to Stokke's standards.
- Final report

The expected outcome is as follows:

A stroller that is more comfortable for the baby on bumpy roads and with reduced stress forces on its components.

It should include concepts of design study, prototypes, strength analysis combined with physical testing and a design that is esthetic and functional.

1.4 APPROACH

This table shows all the steps for a complete process. It starts from an idea or a request and goes all the way to the final product.
This project is specific, and it does not require all the steps. The goal of the project is not to make a manufactured produced suspension system, but rather to create a working prototype.

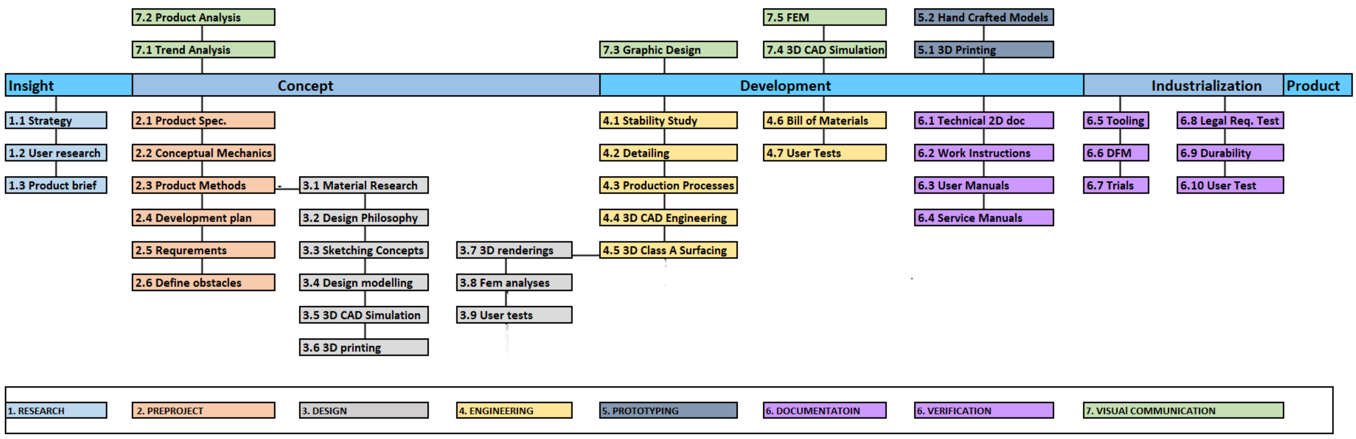


Illustration 1 Approach steps

Here is a list of steps that was done during this project.

Pre-project

The focus in the pre-project phase is to collect facts and data that can help to make better decisions during the project period. Highlighting all critical factors and obstacles ensures that the chosen path is efficient from idea to product, or in this case prototype.

- **2.2 Conceptual mechanisms**
  Creating concepts for the mechanical functionality.
- **2.3 Product methods**
  Material research, design concepts and rapid prototyping.
- **2.4 Development plan**
  A development plan helps to keep track on milestones. It also gives an indication on the status in the project.
- **2.5 Requirement**
  All of Stokke's products follow strict requirements. Most of the products are made for children, and they must be safe. All necessary requirements were studied and considered in this step.
- **2.6 Define obstacles**
  Listing all possible obstacles helps to point out time losses. With this information it is easier to make a better plan.

DESIGN

- **3.1 Material research**
  Research of different materials for the project according to Stokke's standards and manufacture possibilities.
- **3.2 Design philosophy**
  Stokke has given a lot of freedom to this project to experiment with possible design solutions. Nevertheless, Stokke has its own design philosophy, and this was considered.
- **3.3 Sketching concepts**
  All ideas for possible solutions was visualized by sketching.
- **3.4 Design modeling**
  Make more detailed sketches and drawings.
- **3.5 3D CAD**
  3D CAD and specifically Siemens NX allow to create 3D models for visualization and for further 3D-printing.
- **3.8 FEM Analyses**
  FEA helps to optimize the design and makes sure that the design can handle all necessary impacts, before making any prototypes.

ENGINEERING

- **4.1 Stability**
  Stokke has strict requirements for the stroller's stability. This project had to fulfill all necessary requirements.

5. Prototyping

- **5.1 3D-printing**
  With a working 3D model, it is possible to make a 3D printed prototype for the suspension mechanism.

VERIFICATIONS

- **6.6 DFM (design for manufacturing)**
  The components must have a design that is optimized for manufacturing and assembling the product.

- **6.7 Tests**
  The stroller with suspension must pass several necessary tests.

Processes for this project are selected in red.

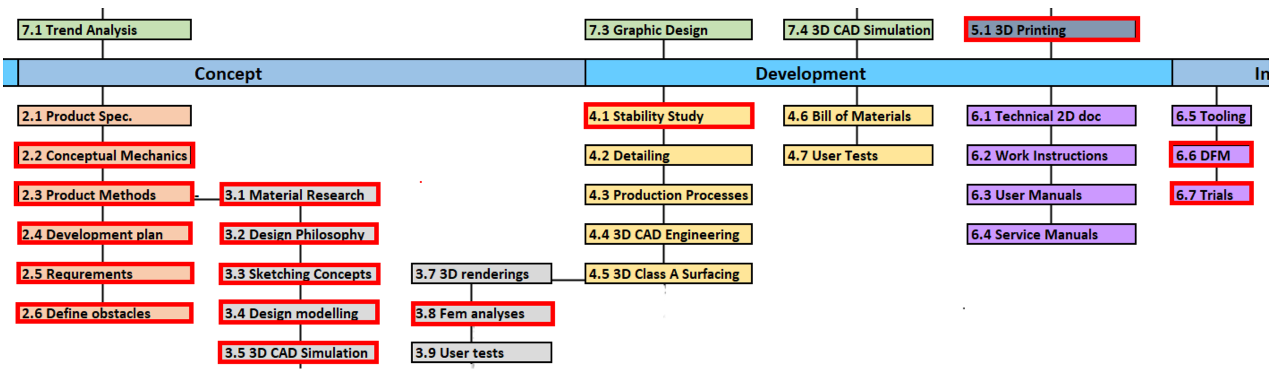


Illustration 2 Approach steps in our project

2.MAIN

2.1 CONCEPT SKETCHING

During brainstorming sessions, it was established that the focus would be on the functionality of the product, and not so much on the design. The result of three days of work was several sketches with four main concepts with different types of suspensions.

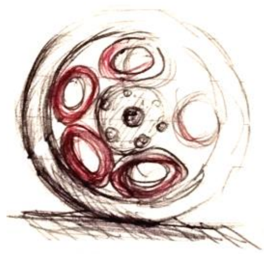
To make concept evaluation easier, all the concepts were sketched on paper.
Before making the final decision on which concept was the best to develop, all concepts were evaluated by the lead engineer.

2.1.1 WHEEL CHANGES

Airless tire

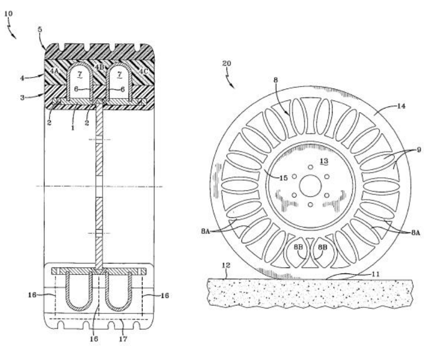
One of the concepts that were investigated was the airless tire concept. Picture 1 shows tires produced by Michelin. This company integrated dampening into the wheel. Most of these concepts are protected by patents, this patent has ref (US Patent No. US 7,143,797 B2, 2006). It's hard to redesign this into something unique. Choosing this concept would probably mean that the brakes must be moved further down to the center of the wheel.

Picture 1 Michelin airless tire



Sketch 1. Airless tire

Patent

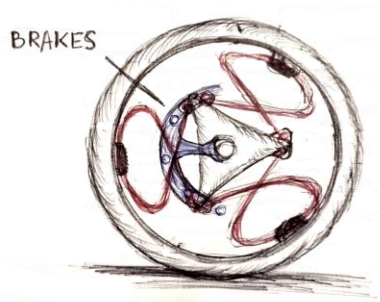


Picture 2 US patent

Loop wheel

This is a patent pending design by Sam Pierce from loop wheels. This concept would require redesigning the actual wheel and its braking system and adding a disk for the brake, like shown in **Error! Reference source not found.**.

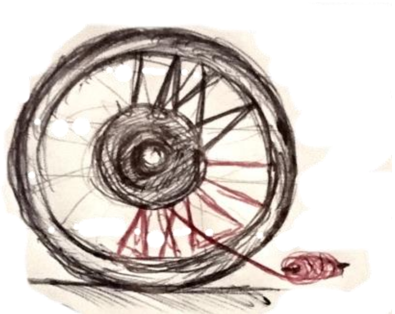
Picture 3 Loop Wheel



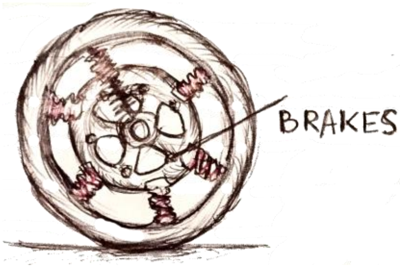
Sketch 2. Loop wheel

Rubber band and spring spokes

The concept with rubber band is based on the same principles as the loop wheel. The difference is that the spokes inside the wheels are made of rubber bands. The suspension would happen between the wheel rim and the center. How this would work in practice and how the rubber bands would act after some years of usage in variating weather and temperature is not certain.



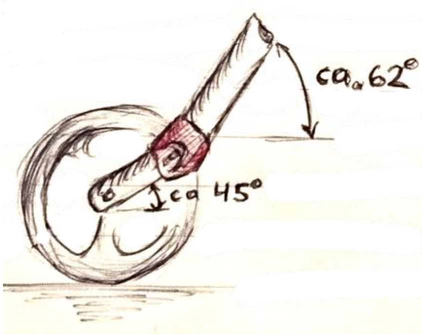
Sketch 3. Rubber suspension



Sketch 4. Springs as spokes

2.1.2 ROTATION AT BRAKE PIN

This concept is based on a hinge system. The brake pin pierces through the rotation point and then goes into the wheel. The suspension has an internal torsion spring.



Sketch 5. Internal torsion spring

Sketch 6. External torsion spring

The inconvenience with this concept is that the torsion spring requires complex internal design and DFM. The fact that the spring must be preloaded makes the assembly process more complicated.

2.1.3 LIENEAR SUSPENSION

The linear suspension has a linear spring that is placed inside a chassis or inside an attachment to the chassis. This concept is simple but might not be so convenient for this project.

Sketch 7. Linear spring

2.1.4 HINGE FUNCTION

The hinge function has a lot of room for tweaking and trying different design solutions. It's also the most common suspension system on strollers in general. The biggest challenge in this concept would be placing the brake system in a way that does not interfere with the suspension.

Sketch 8. Internal spring, external hinge

Sketch 9. Internal spring, smal lever arm

Sketch 10. Welded ears

Sketch 11. Internal mechanisme

Sketch 13. Hinge and brake at same location

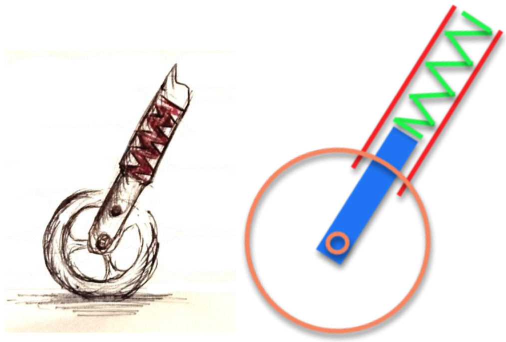
Sketch 12. Hinge over wheel

There are various ways to design hinge mechanisms with different lever arms from the rotation point to the spring attachment. From the simplest with ears welded on the chassis as in Sketch 10, to the most intricate design like the one with it inserted inside the chassis, as shown in Sketch 11.

2.2 CONCEPT EVALUATION

2.2.1 CONCEPT ONE, LINEAR

A linear suspension could be an easy solution for this project, because of its simplicity and possibility to integrate it in the support bar. The wheel can then travel linearly along the suspension/bar.
The suspension could also be placed above the cross bar with the brake mechanism. This means that the brake system would be untouched.



Sketch 14. Linear suspension

Reason for elimination:

This would probably be a good solution for the front wheel suspension, but the back wheels are exposed to forces that come from angles almost perpendicular to the direction of contraction. Impact forces from bumps would most likely ruin the suspension mechanism over time.

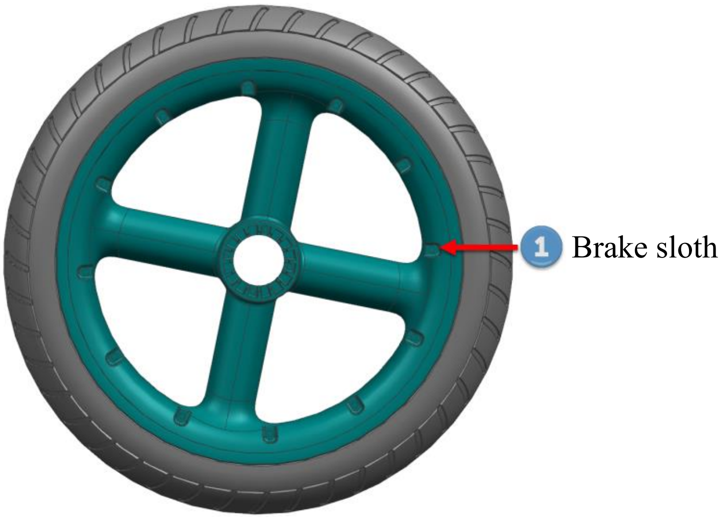
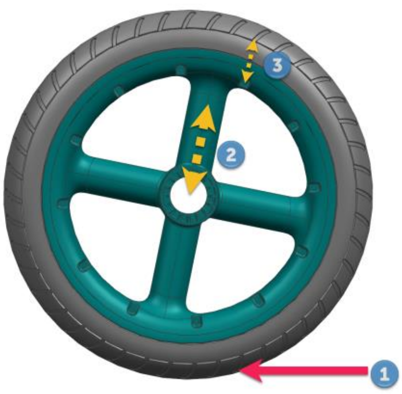


Illustration 3. Brakes sloths



1. Applied force
2. Motion of the wheel
3. Movement of the brake sloth

Illustration 4. Force/motion

2.2.2 CONCEPT TWO, AIRLESS

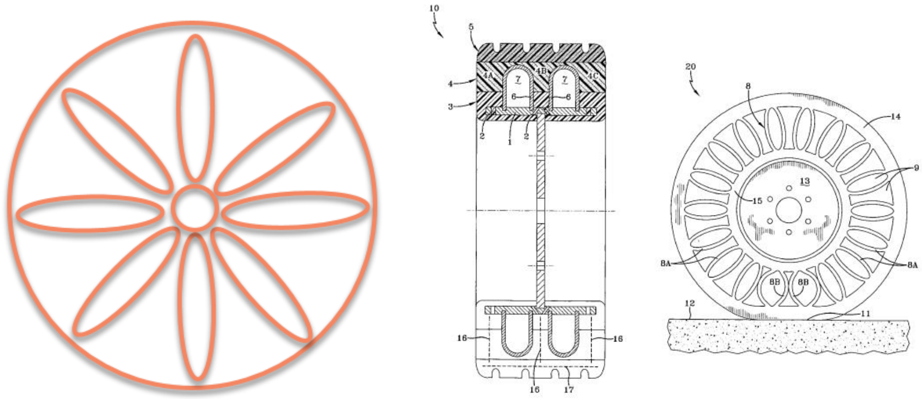


Illustration 5. Internal wheel sispension

Concepts with suspending wheels could be a very good solution for this project, it could also be applied to other Stokke strollers without suspension.

Reason for elimination:

Using this concept would require working around the patent and redesigning the brake system of the stroller.

2.2.3 CONCEPT THREE, SPRING INSIDE ROTATION POINT

This is a concept that is based on a hinge connection, and with a torsion spring placed in the rotation joint. The brake pin would be piercing the spring coil and into the brake sloth.

Picture 4. Torsion spring

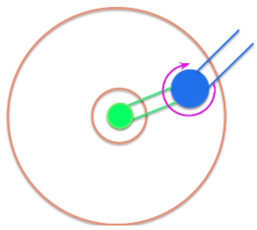


Illustration 6. Torsion spring rotation

Reasons for elimination:

-To achieve the necessary level of suspension, this kind of spring must be very large.
-The spring must always have some tension, even when the stroller is resting. This makes the assembly process more complicated.

2.2.4 CONCEPT FOUR, HINGE WITH COMPRESSION SPRING

This concept has a hinge connection with the rotation point close to the brake pin, it allows us to leave the brake system functioning without any modifications. The compression spring is placed tangent to the rotation trajectory of the hinge.

Illustration 7. Hinge with spring and lever arm

Sketch 15. Hinge system

Reasons why this concept was chosen:

- It has a good mechanical solution for suspension.
- The mechanism of this concept is quite simple to manufacture and to assemble.
- The brake system requires no change.
- It is easy to experiment with different spring types, stiffnesses and sizes.
- Variation of design solutions: the spring can be hidden under sliding walls or the spring can stay open to assure customers that this stroller has back wheel suspension.
- It does not compromise the folding of the stroller

2.2.5 EVALUATION

After sketching up different concepts and figuring out how the different functionalities would work, it was decided on a concept evaluation meeting with Stokke engineers that the best option is concept number four with a hinge mechanism and with a compression spring as a suspension. This concept was chosen because of its simplicity, and the fact that the suspension mechanisms do not require any change to the already existing brake system.

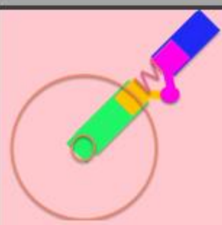
	Consept 1 *Linear*	Concept 2 *Airless tire*	Concept 3 *Inside spring*	Concept 4 *Hinge*
ROUND ONE ***Rotation system***				
ROUND TWO **Hinge** ***system evaluation***				
	Compression	**Dual-rate**	**Gas**	
SUSPENTION ***Type***				

Table 1. Eliminations

Round two

The second hinge concept has better mechanical benefits because there is a lever arm between the rotation joint and the spring that can be adjusted easily relative to the other hinge designs. Simultaneously this system does not compromise the brake system of the stroller.

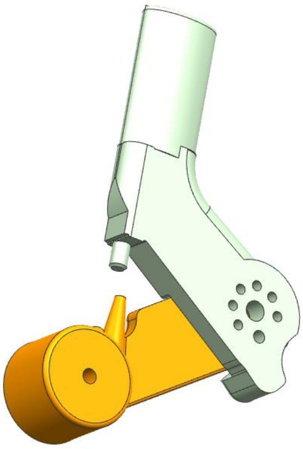
Suspension type

Using a gas suspension or a damper were considered, but they are more expensive then coil springs, and would increase the cost of the production. It is also hard to find small enough sizes with the necessary properties. Compression springs are therefore preferable for this project.

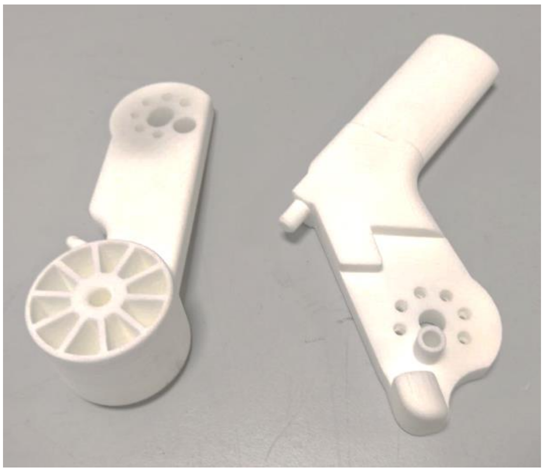
2.3 PROTOTYPING AND 3D-MODELING

2.3.1 PROTOTYPE V01

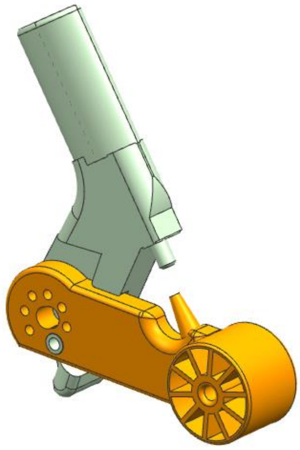
The first prototype was rapidly designed with focus on its suspending functionality.
A 3D-printed prototype worked very well as a suspension, but the plastic parts of the mechanism were not very stiff.
This is the first prototype that was produced in PA12 material. Before making this prototype, it was ensured that the brake pin would function normally,



Picture 5. 3D model left



Picture 6. 3D print in PA12



Picture 7. 3D model right

Picture 8. Complete V01 prototype

Picture 10. Spring in normal state

Picture 9. Spring fully compressed

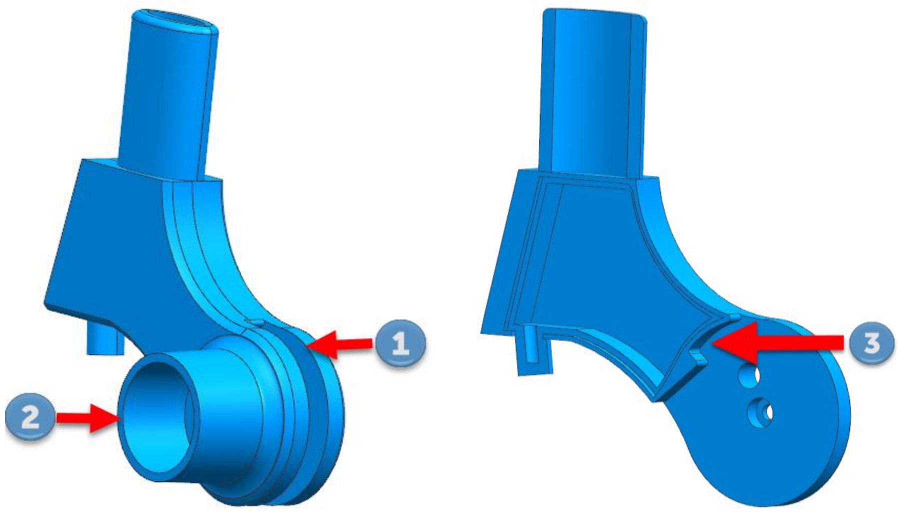
The functionality of this prototype works well, even though the spring does not have the right properties. There were some issues with the stability, but this was expected with this type of rotation design. The brake system was functioning normal without any complications. Simultaneously, it seemed like the folding was as good as before, as shown in Picture 11 below.

Picture 11. Folding with and without suspension

After stability tests and functionality tests of the prototype V01, it was clear that the stability needed to be improved.

2.3.2 PROTOTYPE V02

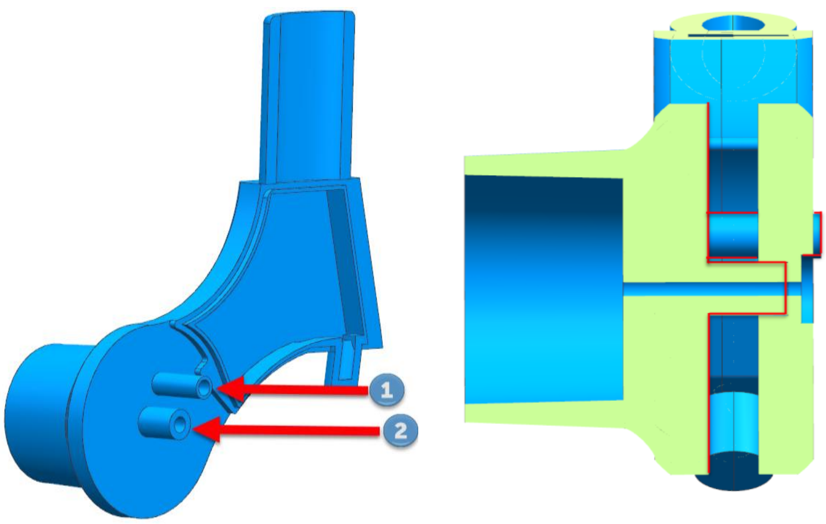
After stability and functionality testing prototype V01, it was decided that the stability needed to be improved. Stability V02 was improved by making the wheel-base part insert into a fork part and merging the insert of the crossbar with the base part as shown in Illustration 8. The functionality of the suspension is unchanged.



1. Fork
2. Merged design
3. Sliding area

Illustration 8. Fork and endstop

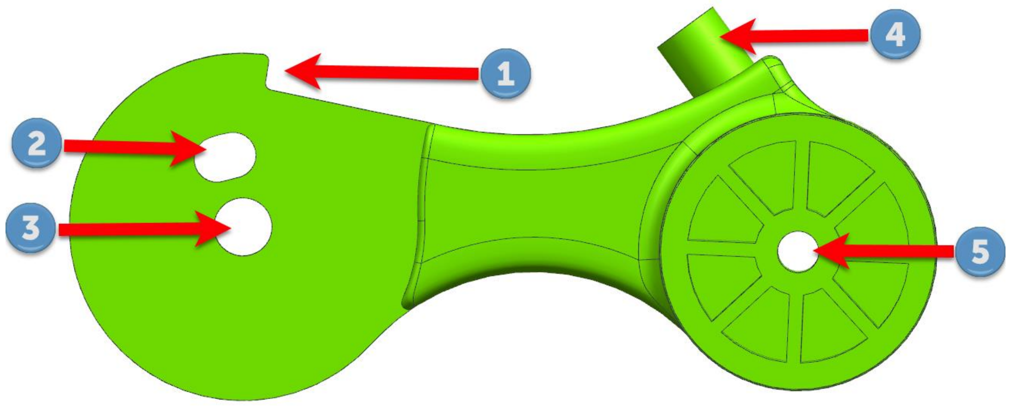
The fork part was split into two parts. Doing this allows us to design for manufacturing. Illustration 9 below shows two pins that extrude from the right side of the part. Pin number one is designed to guide the brake pin through the parts and into the brake-slots in the wheel. Pin number two is basically just for increasing the diameter of the rotation pin for stability. This extruded pin goes halfway into the second part as illustrated with a red line on Illustration 9.



1. Brake pin guide
2. Rotation

Illustration 9. Brake/rotation pin

There was an end-stop added to the wheelbase, this is made so that it fits inside the fork. It was also necessary to make an eccentric hole to allow free motion between the stationary brake-pin guide and the wheelbase as shown in Illustration 10.shown in illustrated .



1. End stop
2. Eccentric hole
3. Rotation point
4. Spring pin
5. Wheel center

Illustration 10. Wheelbase

The end-stop restricts the rotation when the wheelbase has rotated 16° relative to the stationary fork. The end-stop is designed to take the force from the pre compressed spring and restrict the base from rotation CW as shown in Illustration 12.

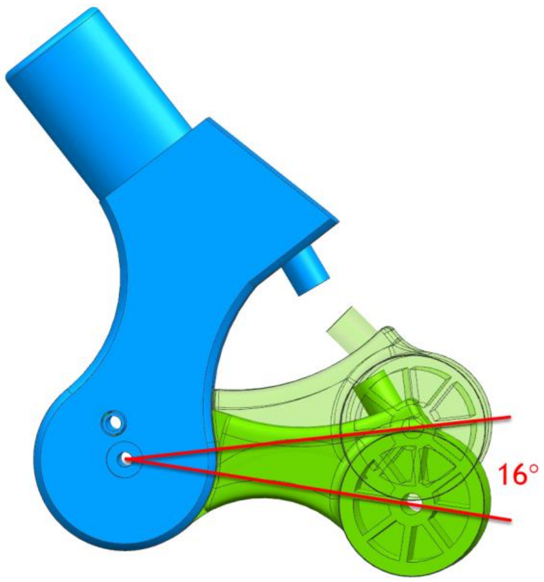


Illustration 12. Rotational degree of freedom

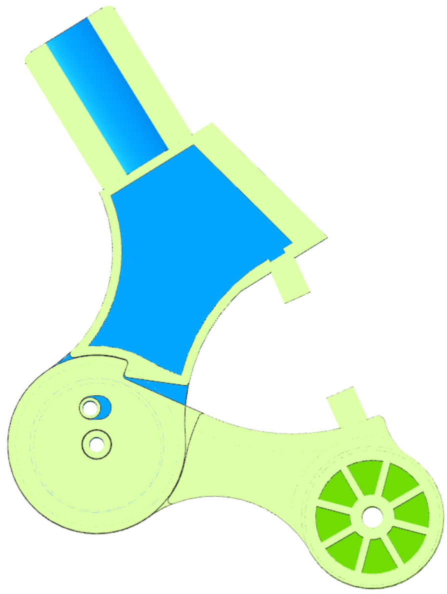


Illustration 12. Crosssection

Some of the concerns that were highlighted with a revision was that the strength of the end stop might need improvement.
Another thing that was highlighted in the internal engineering review was the part's total strength when the shell body did not have any ribs or screw towers to hold the parts together. It was decided that two top parts should be glued together.

Parts were printed in a material called P12 or PA2200 which is a nylon based thermo polymer. The SLS machine prints prototypes using a laser that melts polymer in a bed of microscopic thermo plastic pallets.
The P12 has good material properties for both strength surfaces and function. The precision of the print is also within a tolerance of ± 0.3% with a lower limit of ± 0.3 mm data gathered from (3D hub, 2020) and with a layer height of 100 µm.

TYPICAL PHYSICAL PROPERTIES PA12			
MECHANICAL PROPERTIES	TEST METHOD	ENGLISH	METRIC
Color/Appearance	Visual	White	White
Density	DIN 53466	0.034 lb/in^3	0.95 g/cm^3
Elongation at Break	ASTM D638	4 - 15%	4 - 15%
Flexural Strength	ASTM D790	6,850 psi	47 MPa
Flexural Modulus	ASTM D790	189 ksi	1,300 MPa
Heat Deflection Temp @66 psi	ASTM D648	350°F	177°C
Heat Deflection Temp @264 psi	ASTM D648	187°F	86°C
Izod Impact Strength (notched)	ASTM D256	0.8 ft-lb/in	43 J/m
Tensile Modulus	ASTM D638	247 ksi	1,700 MPa
Tensile Strength	ASTM D638	6,815 psi	46 MPa
Surface Finish	Up-facing surfaces	350 microinches	9 µm RA
Volume Resistivity (22°C, 50%RH, 500V)	ASTM D257-93	—	3.1 x 1014 ohm x cm

Table 2. Material properties

Table 2 shows that thermo polymer has tensile modulus of 1300MPa
which is good for prototyping. It does not have the same properties as an injection molded PA6 part which has tensile modulus of 5300 with GF 30%, but for functionality and other small tests it is good enough.
For testing the prototypes for stability, frequency, impact, etc., it is important to have as similar material properties as possible. Tests with PA12 give worse results, but by running these tests with this material it forces the design of the parts to be more solid and conservative.

Picture 14. V02 Left

Picture 13. V03 Front

Picture 12. V02 right

2.3.3 PROTOTYPE V03

In the V03 prototype there are three major improvements: better stiffness, more esthetics and room to fasten the "sibling board" as shown in Picture 15.

Picture 15. Sibling Board

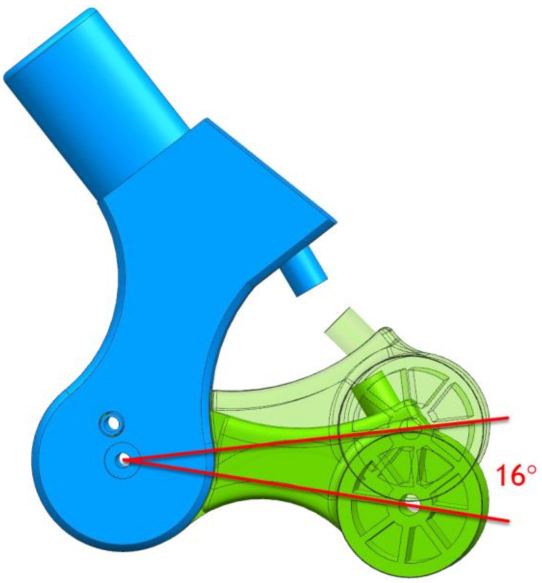


Illustration 13. V02

Illustration 14. V03

The stiffness was improved by extruding the chassis sloth from 45mm to 73mm as shown in Illustration 14. V03Illustration 14

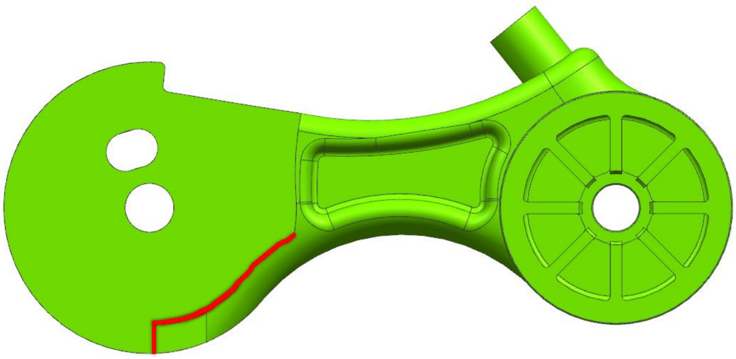


Illustration 15. T-bar from the side

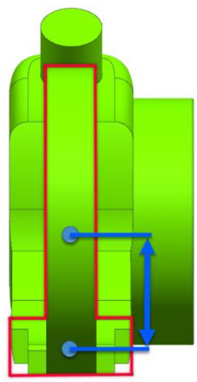


Illustration 16. T-bar "cross section"

The wheelbase stiffness was also improved by making it in a T-bar shape as illustrated with red lines in Illustration 16. The distance from the mass center is lowered.

Another feature that was added in the V03, was a sloth to prevent dangerous openings on the rotation joint. A stair like transition was made to reduce the opening to less than 5mm. According to standards, dangerous opening are openings within 5-12mm.

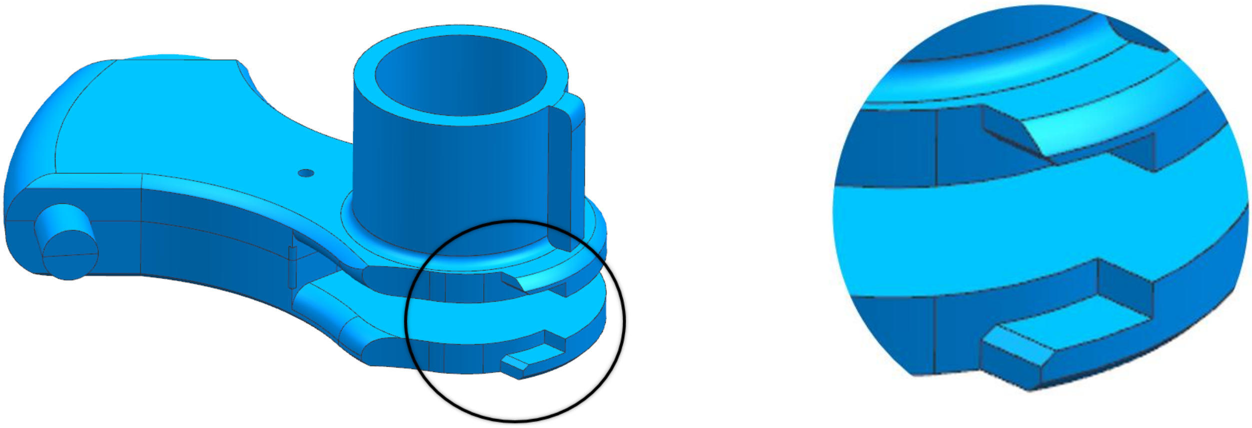


Illustration 17. Fork wirh steps

The steps are made that way to make molding easier, and so that the fork assembly will not be affected. The stair transition will not act like an end stop. The end stop will be inside the fork part, so the rotation join has one specific end stop.

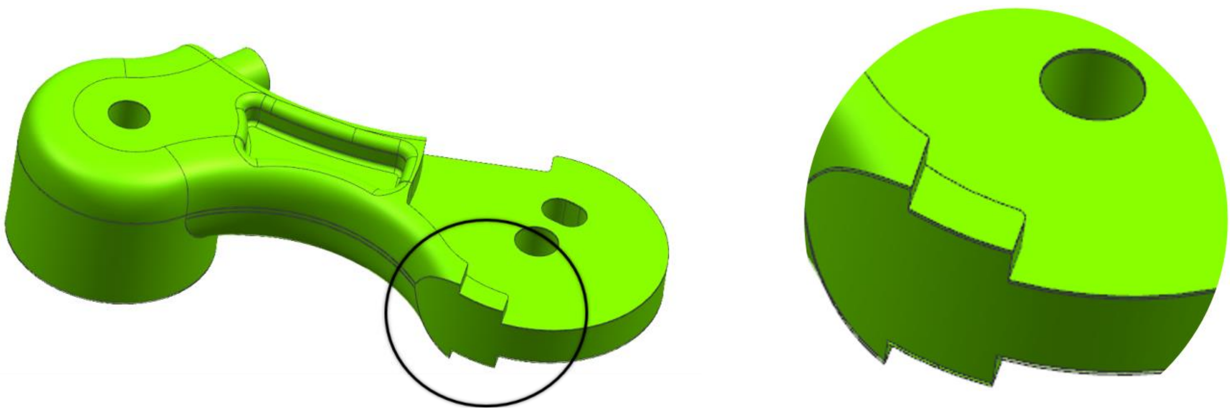


Illustration 18. Wheelbase with steps

These stairs prevent to stride with the standard of dangerous openings as well as they add strength to the mechanism, this is explained in chapter

Undercut

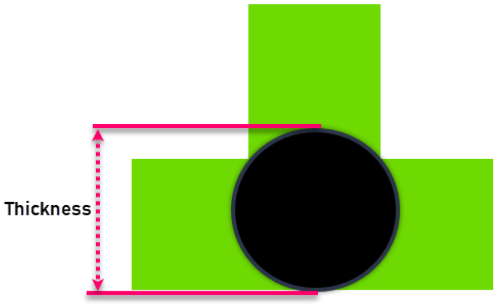
Undercut is a situation when the mold is entrapped with surrounding plastic. There are several methods to avoid this inconvenience, some of them are redesigning the part or adding sliders to the mold design. Sliders are expensive and they add more complexity to the mold, and the more complex the part is, the more machining is needed on the cavities. Undercuts are difficult to machine.

Sinkmarks and warping

Sink marks appear if the plastic solidifies faster on the outside than the inside. The result will be an uneven surface.
The same can be said about warping. Not having a uniform wall thickness might result in the solidifying process that is creating inner forces, and it can result in warping as illustrated in Illustration 22.

The V03 model does not have uniform wall thicknesses, and it is outside the thickness range that 3D hub recommends. To prevent sink marks and warping, the model must be stripped for material to get the wall thickness as uniform as possible.

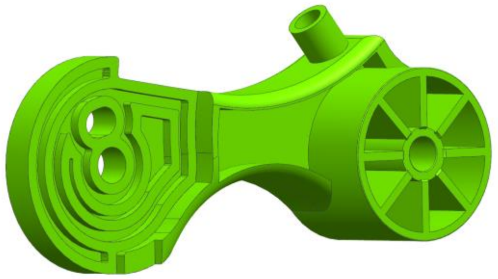
The illustration above shows the wall thickness in a color plot. The color scale goes from dark blue (0mm) to red (9mm). It is calculated by using a technique called “the rolling ball”. This means the thickness is defined by placing many imaginary balls in the geometry, and then calculated by the overall thickness, as illustrated in Illustration 24 below.

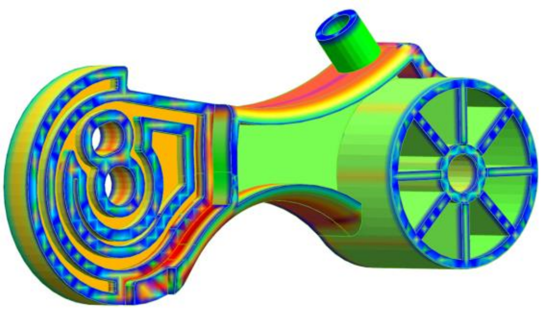


As the project continues, some changes must be done to the design to get a uniform thickness. Deciding where it is and isn't ok to get minor sink marks and warping, helps us to modify the design in terms of keeping the stiffness of the part.

1. This place should not warp or have any sink marks.
2. One of the tests has shown that there was some deformation in this location. Removing material from here might affect its stiffness, but for the sake of the illustration, some material will be removed.
3. Removing material from the core of this cylinder will make molding more complex.
4. This segment does not have to be very stiff, which means that a lot of material can be removed. Necessary stiffness will be achieved by adding ribs in the model.
5. It is better to leave this T-bar shape untouched to keep its stiffness.

These changes would make the part much more uniform, and the risk of sink marks and warping is greatly reduced.





Draft angles

3D hub recommends having a minimum of 2° draft angles on all vertical walls. This would prevent drag marks that come from the friction between the mold and the plastic.

The minimum allowed draft angle is 2°. If the walls do not have these draft angles, the part might stick to the mold when trying to extract the part from the cavities. This might create drag marks on the respective surfaces. It is recommended to have a minimum wall thickness of 0.8mm after making draft angles in the model. The minimum thickness of vertical walls must remain.

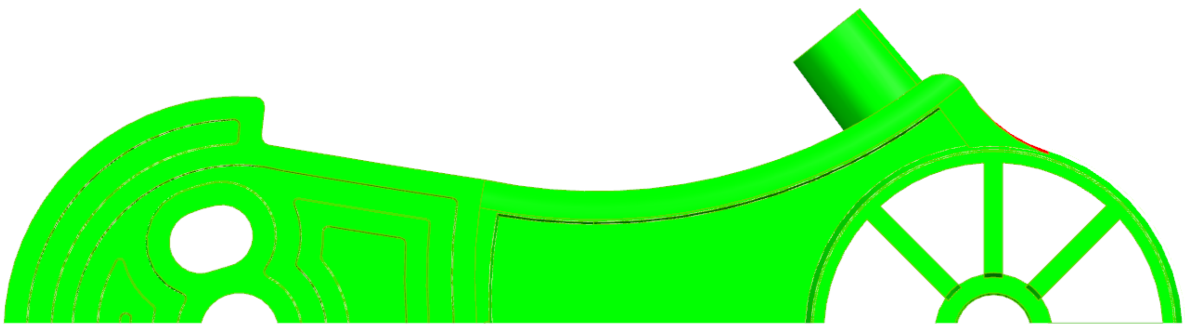


Illustration 29. Wheelbase half

On the wheelbase, the draft angles are 3° on the walls with a green color as shown in the cross section below. The lack of draft angles in the wheel cylinder with a red color is made so that the part is forced to stay in one of the cavities, while using ejector pins to eject the part, there are no requirement for surfaces in this area

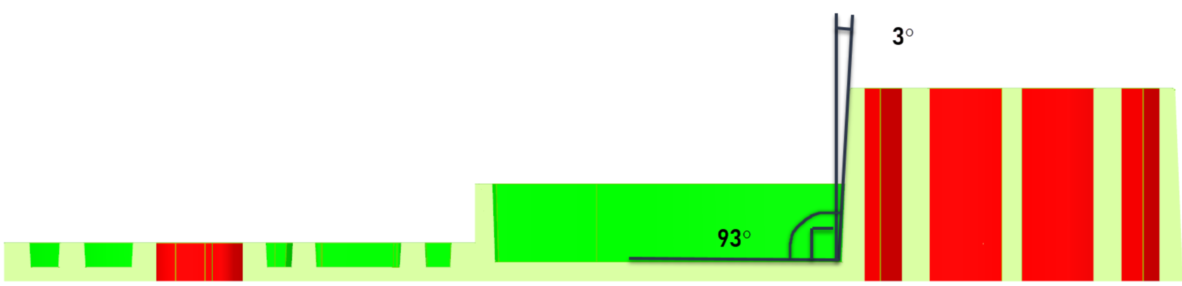


Illustration 30. Cross Section of wheelbase, with draft angles

Siemens NX has a draft angle analyzer tool, which is very helpful for DFM as seen in the color plot in Illustration 31. Green walls have an angle of 92-93°, red walls are perpendicular to the horizontal surface or have less than 92°. The illustrations below compare the color plots from the model without draft angles (left), and with draft angles on the right side. Vertical walls that are colored red do not have draft angles.

2.3.5 STIFFNESS CALCULATION. Some edges were rounded, and the base rotation area is thicker.

2.3.4 DESIGN FOR MANUFACTURING

The design process for manufacturing has a lot of guidelines that must be followed. For this project it would be suitable to manufacture the base in a plastic/aluminum mold. This project has followed the guidelines made by 3D Hub, (3D hub, 2020).

3D hub's table helps to choose an appropriate material before going forwards with DFM.

Material	Recommended wall thickness [mm]	Recommended wall thickness [inches]
Polypropylene (PP)	0.8 - 3.8 mm	0.03" - 0.15"
ABS	1.2 - 3.5 mm	0.045" - 0.14"
Polyethylene (PE)	0.8 - 3.0 mm	0.03" - 0.12"
Polystyrene (PS)	1.0 - 4.0 mm	0.04" - 0.155"
Polyurethane (PUR)	2.0 - 20.0 mm	0.08" - 0.785"
Nylon (PA 6)	0.8 - 3.0 mm	0.03" - 0.12"
Polycarbonate (PC)	1.0 - 4.0 mm	0.04" - 0.16"
PC/ABS	1.2 - 3.5 mm	0.045" - 0.14"
POM (Delrin)	0.8 - 3.0 mm	0.03" - 0.12"
PEEK	1.0 - 3.0 mm	0.04" - 0.12"
Silicone	1.0 - 10.0 mm	0.04" - 0.40"

Table 3. Wall thickness

The wheelbase can be made of Nylon (PA 6) with a recommended wall thickness of 0.8-3mm as shown in Table 3. The reason for the specific recommended wall thickness is to prevent sink marks and warping in the part.

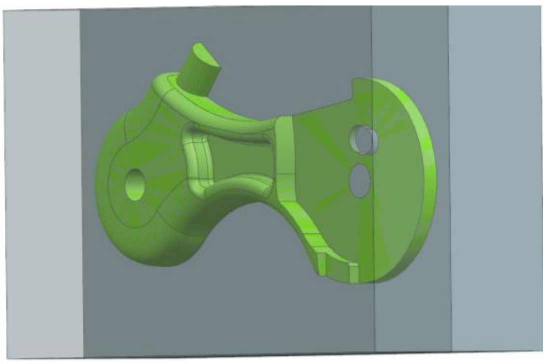


Illustration 19. Mold with part

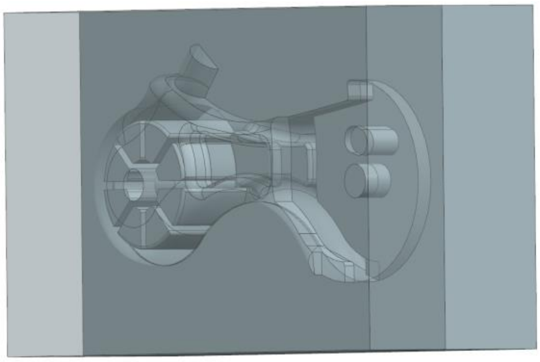


Illustration 20. The parts negative

When producing models for molding, it is important that the Cavities can be divided without any undercut.

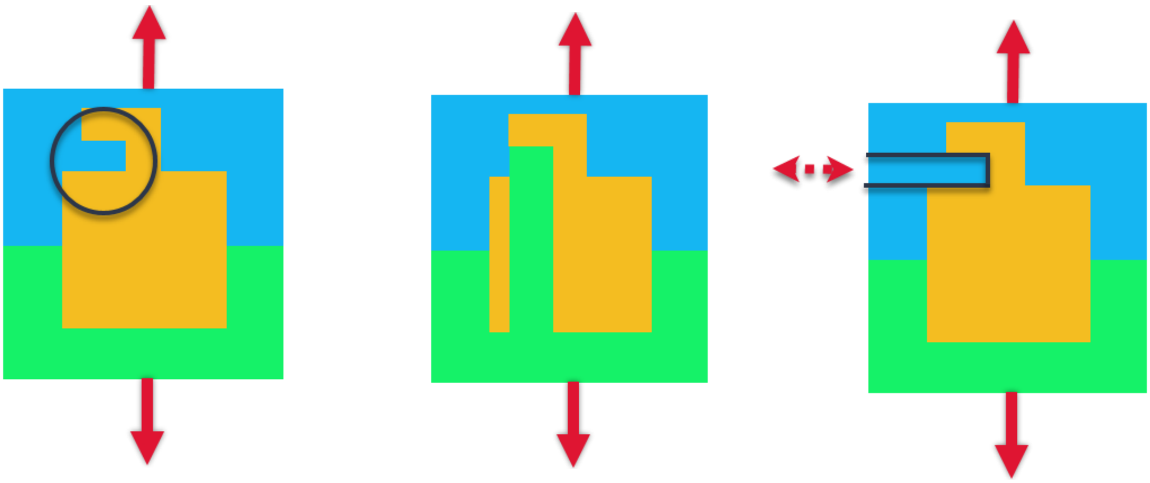


Illustration 21. Solutions to undercut

Undercut

Undercut is a situation when the mold is entrapped with surrounding plastic. There are several methods to avoid this inconvenience, some of them are redesigning the part or adding sliders to the mold design. Sliders are expensive and they add more complexity to the mold, and the more complex the part is, the more machining is needed on the cavities. Undercuts are difficult to machine.

Sinkmarks and warping

Sink marks appear if the plastic solidifies faster on the outside than the inside. The result will be an uneven surface.
The same can be said about warping. Not having a uniform wall thickness might result in the solidifying process that is creating inner forces, and it can result in warping as illustrated in Illustration 22.

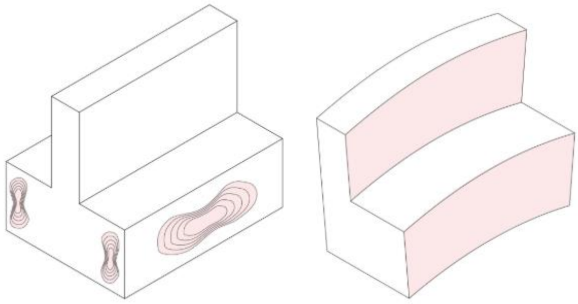


Illustration 22. Sinkmarks and warping

The V03 model does not have uniform wall thicknesses, and it is outside the thickness range that 3D hub recommends. To prevent sink marks and warping, the model must be stripped for material to get the wall thickness as uniform as possible.

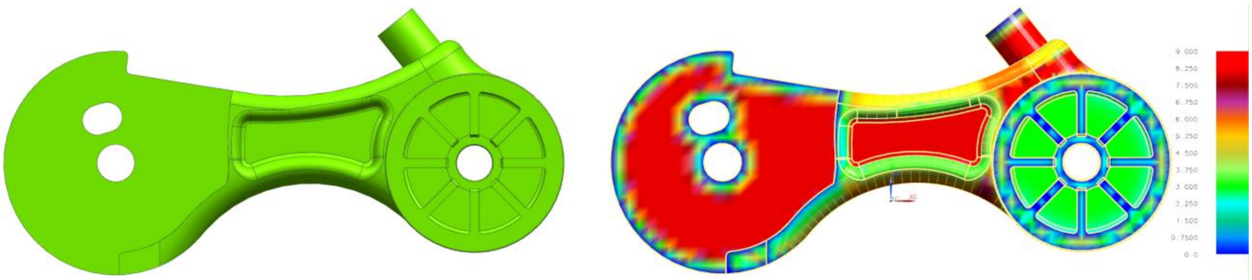


Illustration 23. Color plot of thickness

The illustration above shows the wall thickness in a color plot. The color scale goes from dark blue (0mm) to red (9mm). It is calculated by using a technique called “the rolling ball”. This means the thickness is defined by placing many imaginary balls in the geometry, and then calculated by the overall thickness, as illustrated in Illustration 24 below.

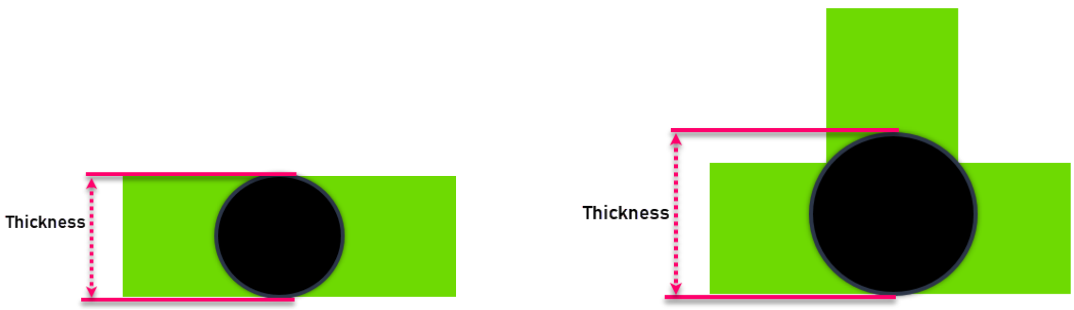


Illustration 24. The rolling ball

As the project continues, some changes must be done to the design to get a uniform thickness. Deciding where it is and isn't ok to get minor sink marks and warping, helps us to modify the design in terms of keeping the stiffness of the part.

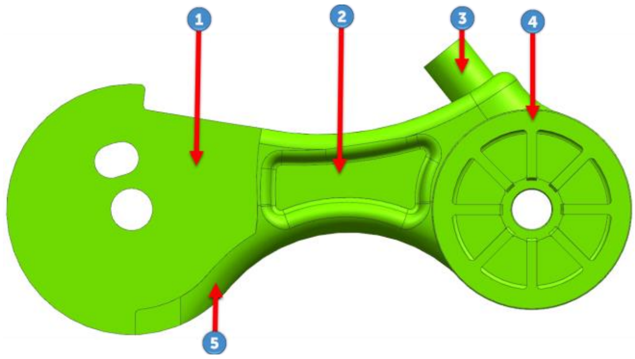


Illustration 25. Modifications

6. This place should not warp or have any sink marks.
7. One of the tests has shown that there was some deformation in this location. Removing material from here might affect its stiffness, but for the sake of the illustration, some material will be removed.
8. Removing material from the core of this cylinder will make molding more complex.
9. This segment does not have to be very stiff, which means that a lot of material can be removed. Necessary stiffness will be achieved by adding ribs in the model.
10. It is better to leave this T-bar shape untouched to keep its stiffness.

These changes would make the part much more uniform, and the risk of sink marks and warping is greatly reduced.

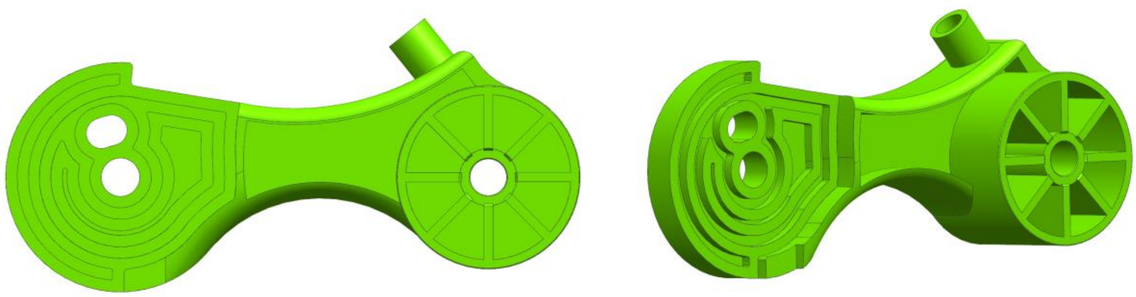
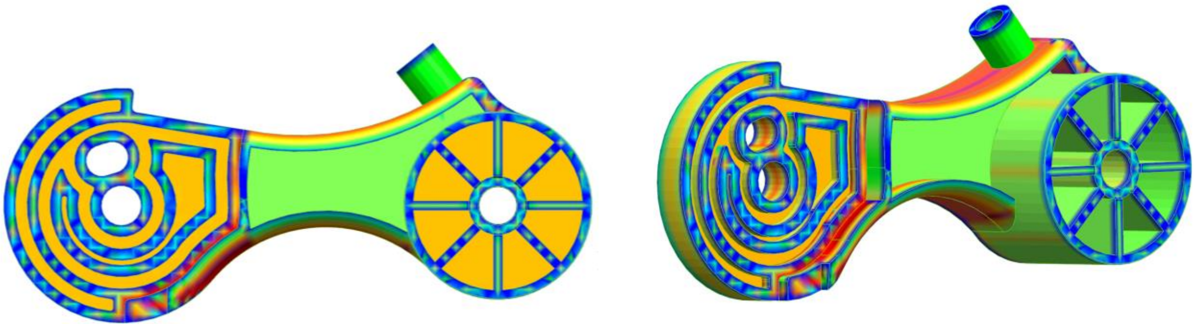


Illustration 26. V03 with wallthickness reduction



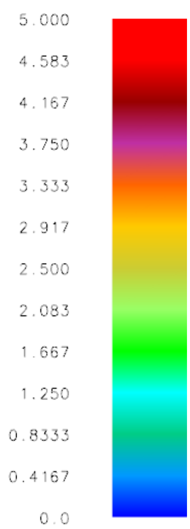
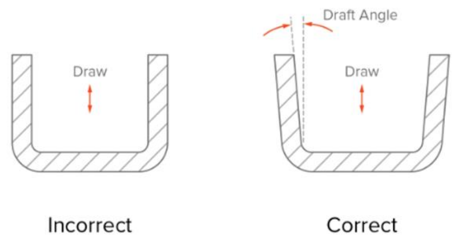


Illustration 27. Color plot of wall thickness with modifications

Draft angles

3D hub recommends having a minimum of 2° draft angles on all vertical walls. This would prevent drag marks that come from the friction between the mold and the plastic.



[1]

The minimum allowed draft angle is 2°. If the walls do not have these draft angles, the part might stick to the mold when trying to extract the part from the cavities. This might create drag marks on the respective surfaces. It is recommended to have a minimum wall thickness of 0.8mm after making draft angles in the model. The minimum thickness of vertical walls must remain.

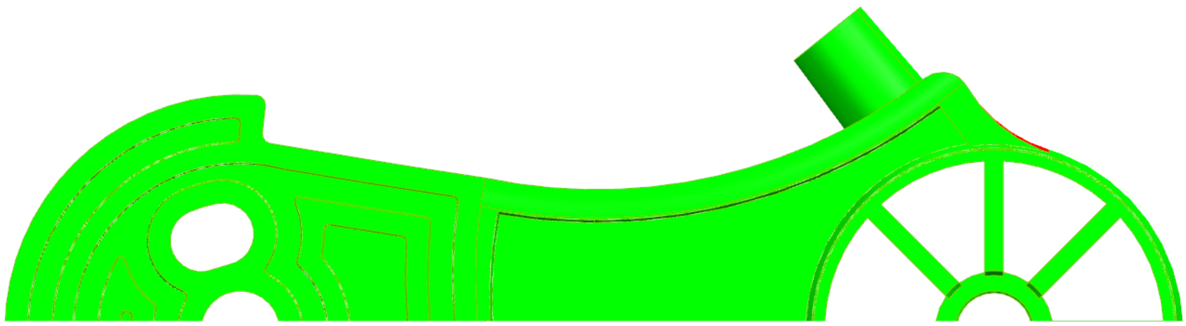


Illustration 29. Wheelbase half

On the wheelbase, the draft angles are 3° on the walls with a green color as shown in the cross section below. The lack of draft angles in the wheel cylinder with a red color is made so that the part is forced to stay in one of the cavities, while using ejector pins to eject the part, there are no requirement for surfaces in this area

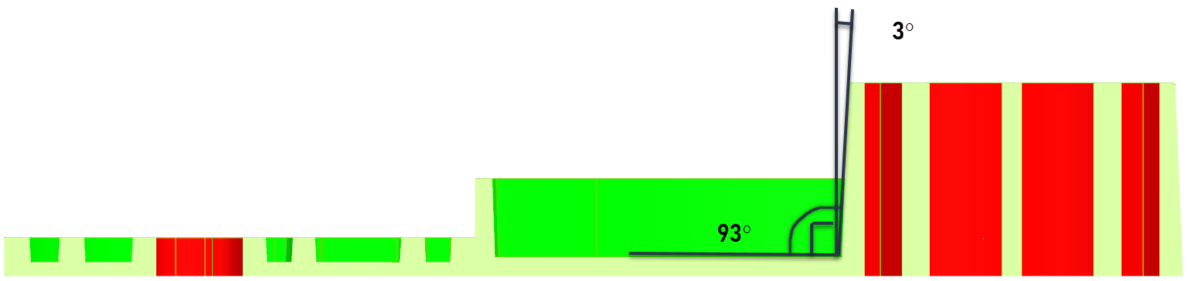


Illustration 30. Cross Section of wheelbase, with draft angles

Siemens NX has a draft angle analyzer tool, which is very helpful for DFM as seen in the color plot in Illustration 31. Green walls have an angle of 92-93°, red walls are perpendicular to the horizontal surface or have less than 92°. The illustrations below compare the color plots from the model without draft angles (left), and with draft angles on the right side. Vertical walls that are colored red do not have draft angles.

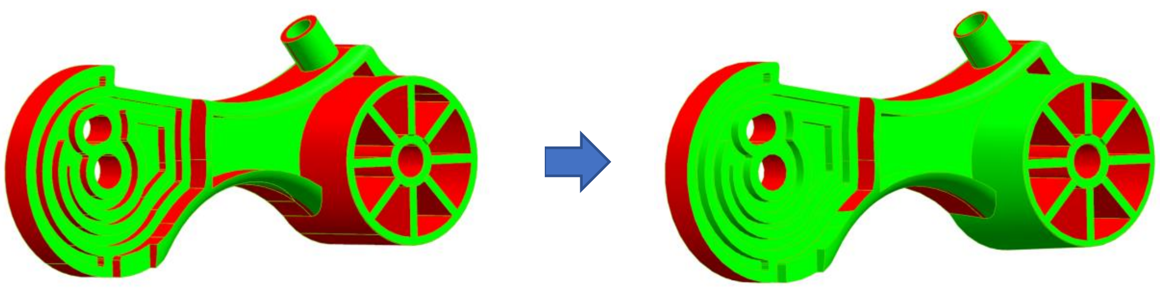


Illustration 31. Color plot with and without draft angles

2.3.5 STIFFNESS CALCULATION

While calculating stiffness, the old design was compared with the newest V03 design. V03 has a rotation area that is thicker and has a T-shaped bracket at the bottom. This gives the part more moment of inertia.

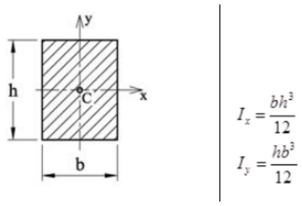
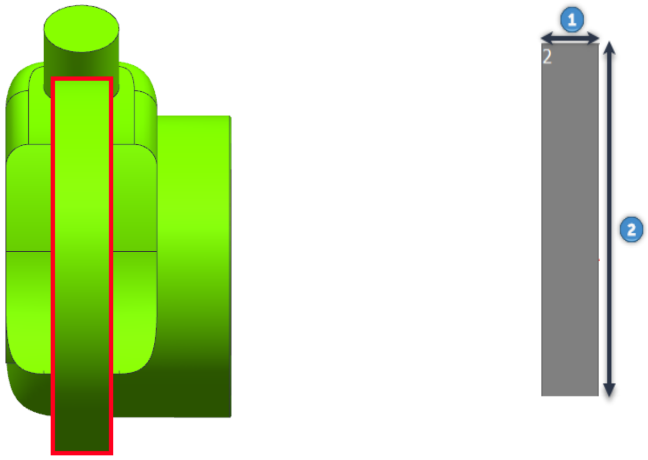


Figure 1. Moment of inertia

V02

This model has a weak design when it comes to stiffness. The moment of inertia in the x direction should be increased so that the material does not get deflected when the stroller is loaded with weight.

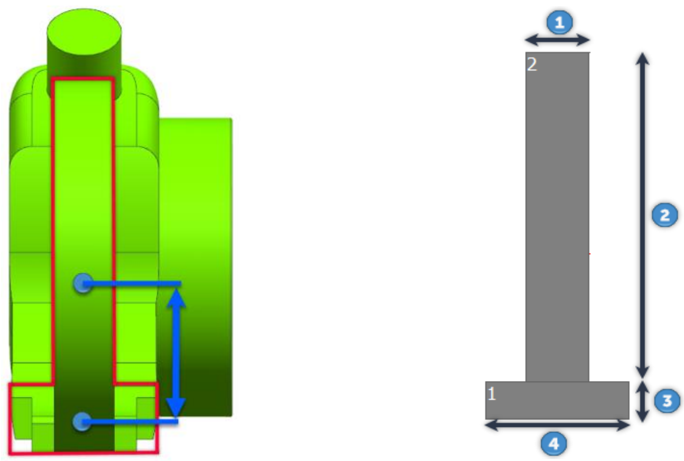


1. 6mm
2. 50mm

Illustration 32. V02 design of rotation area

V03

Comparing these designs, you can see that the thickness is increased from 6mm to 8mm, and that the rotation area is designed as a T-shape.



1. 8mm
2. 45mm
3. 5mm
4. 18mm

Illustration 33. V03 Design of rotation area (T-shape)

Moment of inertia, Ix

The tables below compare the compution between V02 and V03 in the x-axis. The yeld modular that was chosen should be the same as the yeld modular of PA6 GF30, because the final product should be made of PA6 GF30 .
GF30 means that 30% glassfiber would be inserted into the PA6 plastic when molded. This material has a modulus of elasticity of 5400 Mpa according to (ESIGNER, 2018).

V02

X Axis Properties			
Elastic Modulus	E	5.4000E+06	MPa
From bottom to centroid	y (bot)	25.0000	mm
From centroid to top	y (top)	25.0000	mm
Area of shape	A	300.0000	mm²
Moment of Inertia	Ix	62,500.0000	mm^4
Section Modulus	Sx	2,500.0000	mm³
Section Modulus (bottom)	S (bot)	2,500.0000	mm³
Section Modulus (top)	S (top)	2,500.0000	mm³
Radius of Gyration	rx	14.4338	mm
Plastic Modulus	Zx	3,750.0000	mm³
Shape Factor		1.5000	
From bottom to plastic n.a.	yp (bot)	25.0000	mm
From plastic n.a. to top	yp (top)	25.0000	mm
Polar Moment of Inertia	J	63,400.0000	mm^4
Product of Inertia	Ixy	0.0000	mm^4
Maximum Moment of Inertia	Imax	62,500.0000	mm^4
Minimum Moment of Inertia	Imin	900.0000	mm^4
Angle from x axis to Imax axis	ß	0.0000	degrees
		Clockwise	

Table 5. V02 X-axis properties

V03

X Axis Properties			
Elastic Modulus	E	5.4000E+06	MPa
From bottom to centroid	y (bot)	22.5000	mm
From centroid to top	y (top)	27.5000	mm
Area of shape	A	450.0000	mm²
Moment of Inertia	Ix	105,937.5000	mm^4
Section Modulus	Sx	3,852.2727	mm³
Section Modulus (bottom)	S (bot)	4,708.3333	mm³
Section Modulus (top)	S (top)	3,852.2727	mm³
Radius of Gyration	rx	15.3433	mm
Plastic Modulus	Zx	6,046.8750	mm³
Shape Factor		1.5697	
From bottom to plastic n.a.	yp (bot)	21.8750	mm
From plastic n.a. to top	yp (top)	28.1250	mm
Polar Moment of Inertia	J	110,287.5000	mm^4
Product of Inertia	Ixy	0.0000	mm^4
Maximum Moment of Inertia	Imax	105,937.5000	mm^4
Minimum Moment of Inertia	Imin	4,350.0000	mm^4
Angle from x axis to Imax axis	ß	0.0000	degrees
		Clockwise	

Table 4.V03 X-axis properties

The "MD Solids" software compares the two different versions. MD Solids has a section in its app which is called section properties, and it's great for these types of calculations. This section is primarily focused on the stiffness in the x-axis because that's where some deflection happens with a loaded stroller.
The analysis shows that the x-axis on V02 has Ix= 62 500mm^4 and V03 has Ix=105 927mm^4, Increasing the thickness and adding the T-shaped bar together made an improvement in stiffness by **41%** according to MD Solids.

Moment of inertia Iy

Table 6 and Table 7 below shows that the V03 has an increase in moment of inertia Iy by 79%. This is irrelevant since the y-axis is dynamic when the spring is not fully compressed.

Y Axis Properties			
Elastic Modulus	E	5,400.0000	GPa
From left to centroid	x (left)	3.0000	mm
From centroid to right	x (right)	3.0000	mm
Area of shape	A	300.0000	mm²
Moment of Inertia	Iy	900.0000	mm^4
Section Modulus	Sy	300.0000	mm³
Section Modulus (left)	S (left)	300.0000	mm³
Section Modulus (right)	S (right)	300.0000	mm³
Radius of Gyration	ry	1.7321	mm
Plastic Modulus	Zy	450.0000	mm³
Shape Factor		1.5000	
From left to plastic n.a.	xp (left)	3.0000	mm
From plastic n.a. to right	xp (right)	3.0000	mm
Polar Moment of Inertia	J	63,400.0000	mm^4
Product of Inertia	Ixy	0.0000	mm^4
Maximum Moment of Inertia	Imax	62,500.0000	mm^4
Minimum Moment of Inertia	Imin	900.0000	mm^4
Angle from y axis to Imax axis	ß	90.0000	degrees
		Counterclockwise	

Table 6. V02 Y-axis properties

Y Axis Properties			
Elastic Modulus	E	5,400.0000	GPa
From left to centroid	x (left)	9.0000	mm
From centroid to right	x (right)	9.0000	mm
Area of shape	A	450.0000	mm²
Moment of Inertia	Iy	4,350.0000	mm^4
Section Modulus	Sy	483.3333	mm³
Section Modulus (left)	S (left)	483.3333	mm³
Section Modulus (right)	S (right)	483.3333	mm³
Radius of Gyration	ry	3.1091	mm
Plastic Modulus	Zy	1,125.0000	mm³
Shape Factor		2.3276	
From left to plastic n.a.	xp (left)	9.0000	mm
From plastic n.a. to right	xp (right)	9.0000	mm
Polar Moment of Inertia	J	110,287.5000	mm^4
Product of Inertia	Ixy	0.0000	mm^4
Maximum Moment of Inertia	Imax	105,937.5000	mm^4
Minimum Moment of Inertia	Imin	4,350.0000	mm^4
Angle from y axis to Imax axis	ß	90.0000	degrees
		Counterclockwise	

Table 7. V03 Y-axis properties

2.3.6 FINITE ELEMENT ANALYSIS

Finite element analysis helps to understand stress distribution in the most critical parts of the suspension mechanism. The wheelbase part is more exposed to torsion and linear forces than the other parts of the suspension mechanism. The wheelbase was analyzed with FEA in Siemens NX. It would be possible to find maximal stresses and critical areas, but there is not enough information on loads and constrains to make the simulation accurate enough. For this reason, the FEA in this project has rather academical purposes but is still very useful for locating where major stresses can occur.

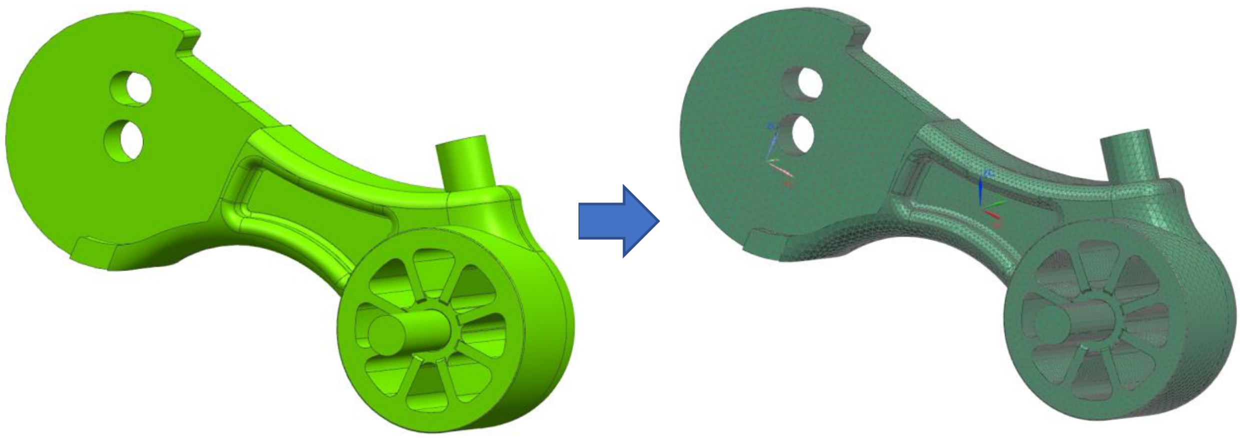


Illustration 34. Wheelbase Mesh

Because of the designs complexity, it is ok to use a mesh with element type CTETRA(10) and element size 2mm. The chosen material is polypropylene.

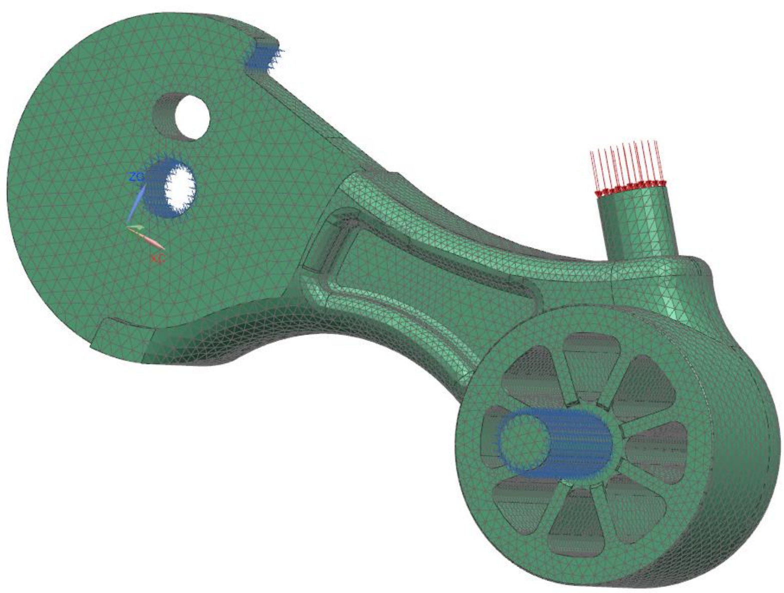


Illustration 35. V03 Mesh, constrains and force

Case 1.

The first simulation has constraints in the rotation point, stop notch and on the wheel pin. The load is supposed to simulate force from the spring that is acting on the wheelbase.

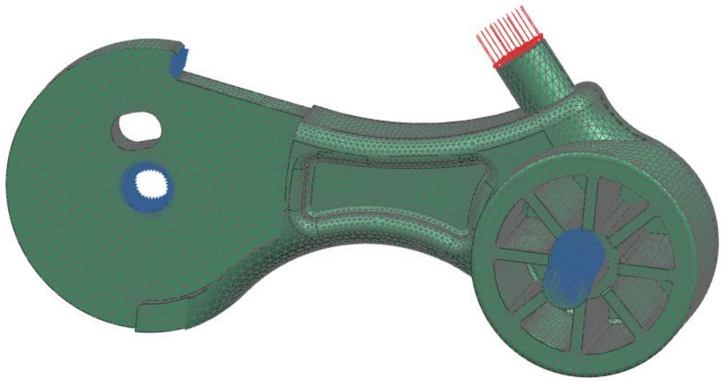


Illustration 36. V03 Mesh, constrains and force case1

There is a higher stress concentration that appears at the stop notch as shown in yellow in Illustration 37 below. The constrains at both the notch and the wheel, together with the spring force, makes the deformation as illustrated. The deformation shown in the illustration is similar to the deformation acting during the handle test.

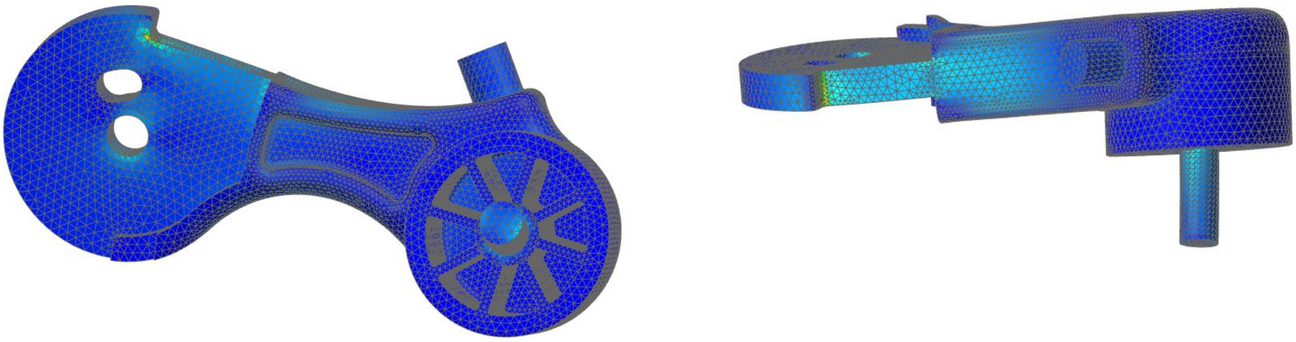


Illustration 37. FEA results on V03, case 1

Case 2.

In this case the focus was on the middle section of the part. The section of the part which is inserted into the fork is fixed. This means that there won't be deformation in this area.

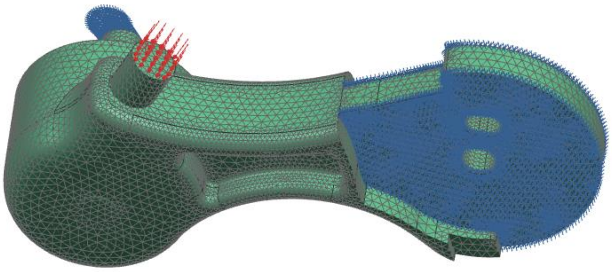


Illustration 38. Forces and constrains case 2

When analyzing the results, the maximal stress was in the corner where the rotation area meets the middle section and creates a notch. It is important to make an edge blend here to avoid this stress concentration.

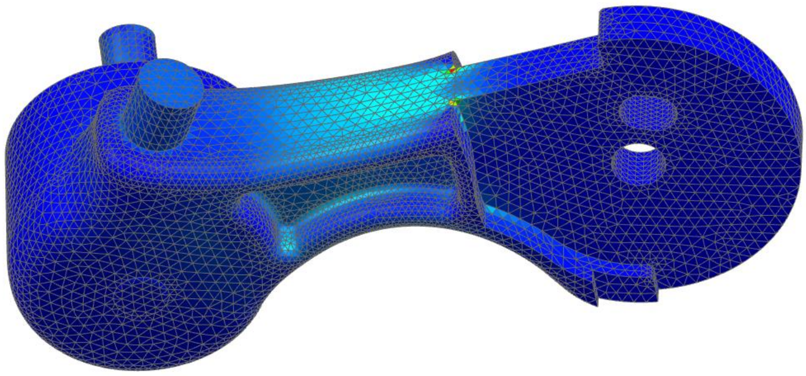


Illustration 39. FEA stress concentration

When excluding the notch, the stress was equally distributed in the top and the bottom of the middle section.

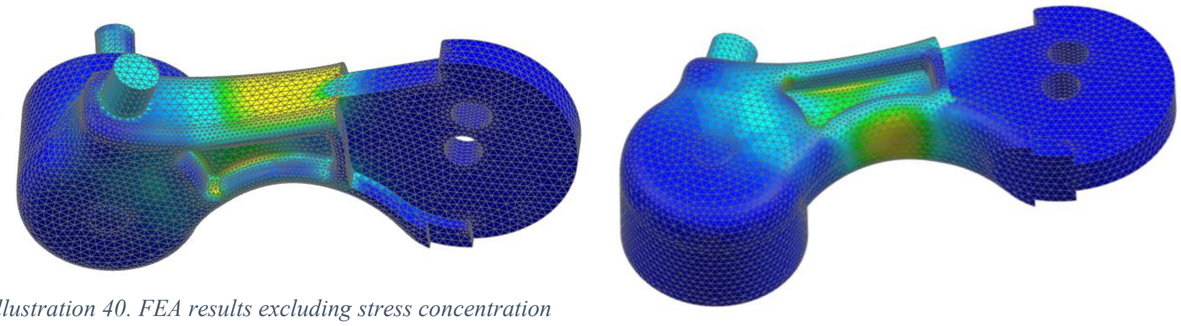


Illustration 40. FEA results excluding stress concentration

2.3.7 TOPOLOGY OPTIMIZATION

Topology optimization is a tool based on Finite Element Methods that can optimize designs within the existing model, according to the chosen constraints and loads. It is based on removing material where there aren't any stresses or shear forces acting.

Like in the FEA section, it would be interesting to research the wheelbase part of the suspension mechanism for possible design improvement. The middle section of the part has an H-beam shape. The middle section was redesigned to rectangular solid beam. Solid Works ran its topology study on this beam volume. A wheel pin was added to the model, it was made to simulate the forces and the lever arm that come from the wheel.

MESH AND BOUNDARY CONDITIONS

This mesh has tetrahedron elements. Tetrahedron elements mesh usually gives less accurate results than mesh with hexahedron elements, but in this case, tetrahedron elements mesh is good enough and requires less computing power.

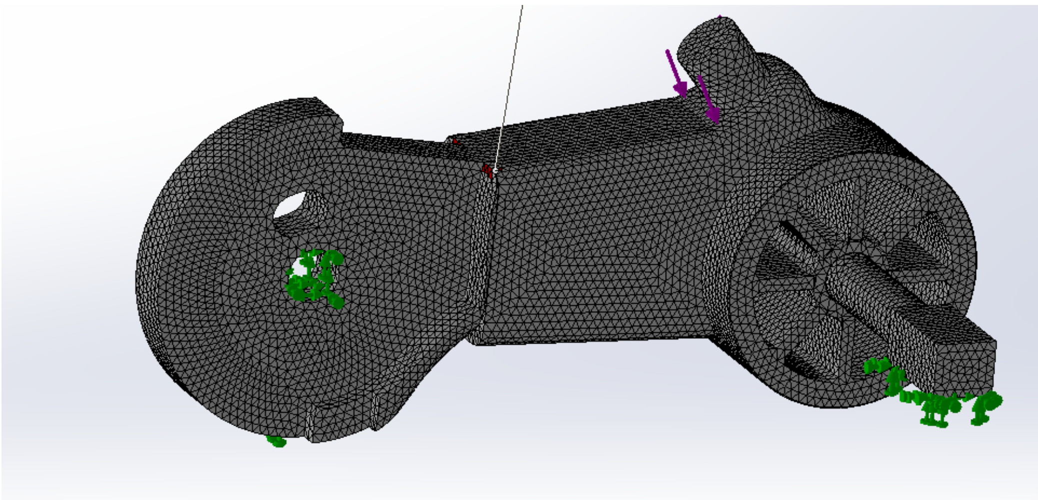


Illustration 41. Solid Works Mesh with constrains and forces

This model is exposed to several sets of forces. Some of them work simultaneously and some of them at different times. To get a better understanding of how stresses are distributed in the model, four cases with different load and constraint sets were analyzed.

CASE 1.

Fixed constraints were applied to the rotation point and on the wheel axle. The purple arrows simulate pressure from the spring and on to the part as shown in Illustration 43.

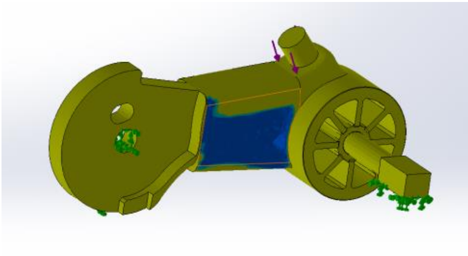


Illustration 43. Colorview of removable material

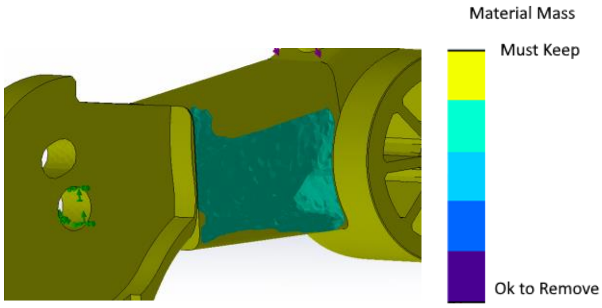


Illustration 42. Result case 1

The result shows that a U-profile beam would be optimal for this case.

CASE 2.

Fixed constraints were applied to the rotation point, and a load was vertically applied to the wheel pin to simulate weight of the stroller.

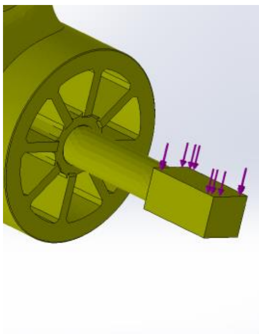


Illustration 45. Aplied force case 2

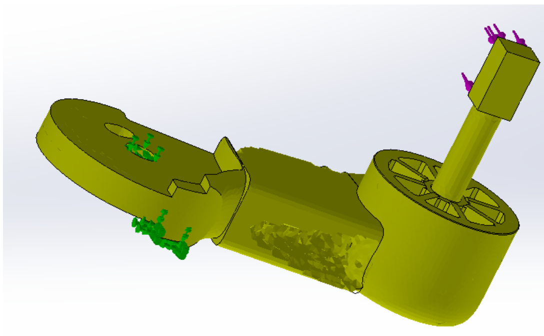


Illustration 44. Result case 2

The result from this analysis shows that an H-beam shape is optimal for this case.

CASE 3.

Fixed constraints were applied to the rotation point. Vertical and horizontal loads were applied to the wheel pin to simulate a turn with the stroller.

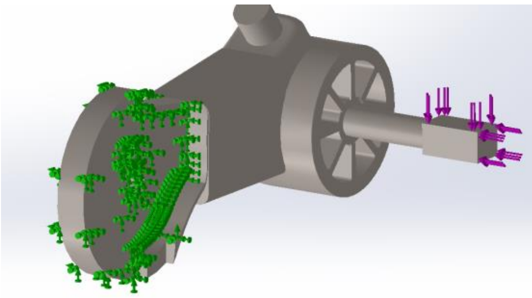


Illustration 47. Constrains and force case 3

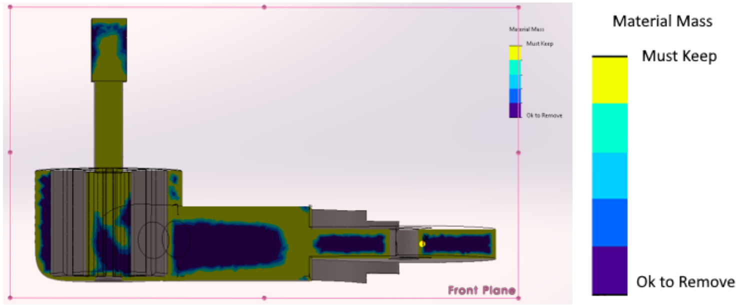


Illustration 46. Result case 3

The result shows that the optimal shape for the combined set of forces has a hollow structural section, with thicker walls towards the center of the stroller.

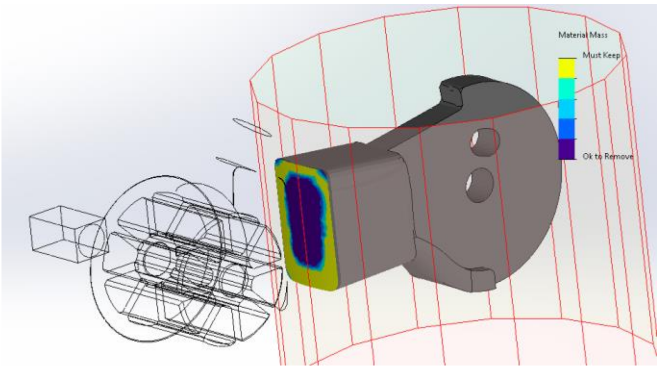


Illustration 48. Crosssection result case 3

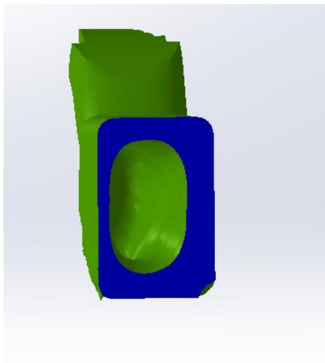


Illustration 49 Crossection

CASE 4.

Fixed constraints were applied to the rotation point. And in this case only the horizontal force was applied to the wheel pin.

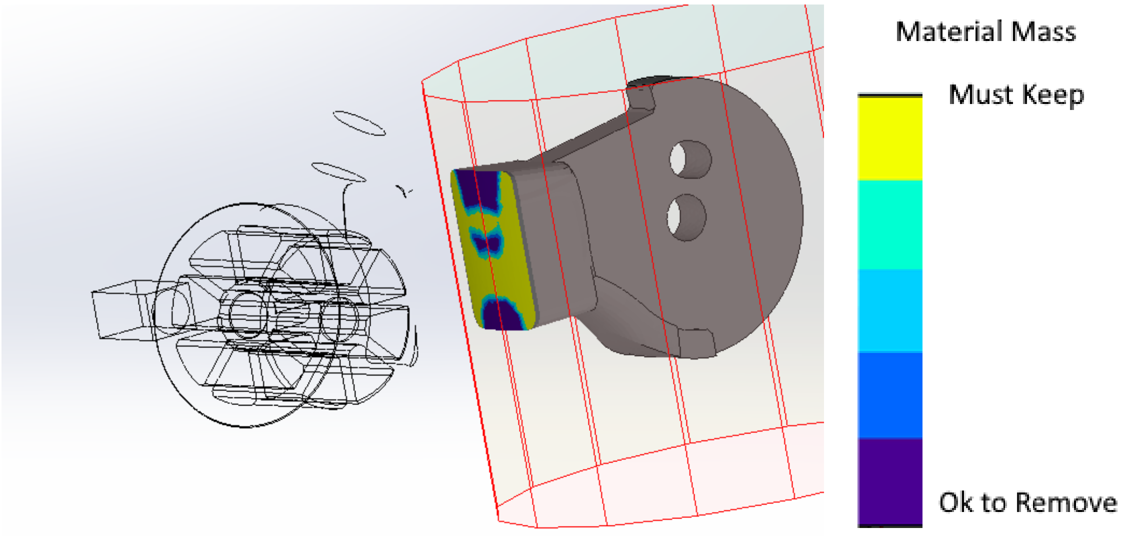


Illustration 50. Cross section case 4

The result shows that the optimal shape for this case is an H-profile oriented horizontally

CONCLUSION

It is difficult to measure and simulate all necessary forces and boundary conditions for this part because of a lack of precise enough information about loads and constraints to make a proper simulation. This topology optimization was done mostly for an academic study. Nevertheless, it gives a better understanding of distribution of stresses and suggests alternative design solutions.

2.4 SPRING DETERMINATION

There are two types of progressive springs. Constantly increasing rate springs and dual-rate spring.

Constantly increasing rate springs have proportionally increasing distance between coil segments from one end to another. These springs help to keep vehicles steady during acceleration, however usually it is not used as a suspension spring.

Dual-rate springs consist of two parts. One part has a bigger distance between coil segments (pitch) then the other part. The bigger is the pitch the stiffer is the spring. In other words, a dual-rate spring has the quality of two connected springs with different stiffness.

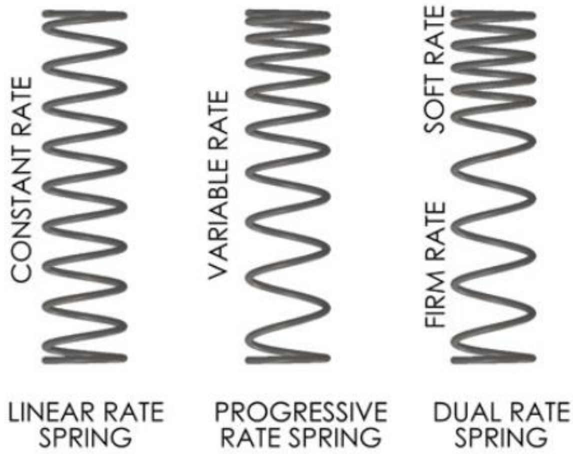


Figure 2. Different springtypes

Choice of springs

The urban stroller is more often exposed to small vibrations like cobblestone. In this case, it's good to have soft suspension. But the stroller will also be exposed to strong impulses from bumps on the road. For this reason, a dual-rate spring might be a good solution. The softer part of the spring takes small frequencies while the part with a firm rate will reduce the impact from larger bumps.
The issue with duel-rate springs is that they are not easy to find on the market. They must be ordered from specialized companies. The price for a small batch is very high.

(Sledsolutions, 2018)


Picture 16. Dual rate spring

2.4.1 STATIONARY SPRING CALCULATION

This is a calculation of the necessary reaction force of the springs. According to Stokke's standards, a fully loaded stroller means that the stroller has a total mass of 40 kg. Each of the wheels loaded with approximately 10kg. Let's assume that there is a force of 100N that acts vertically from the end of the chassy.

MD solids can be used to calculate these types of scenarios with good accuracy. As shown in the picture below, we can simulate the suspension with trusses.

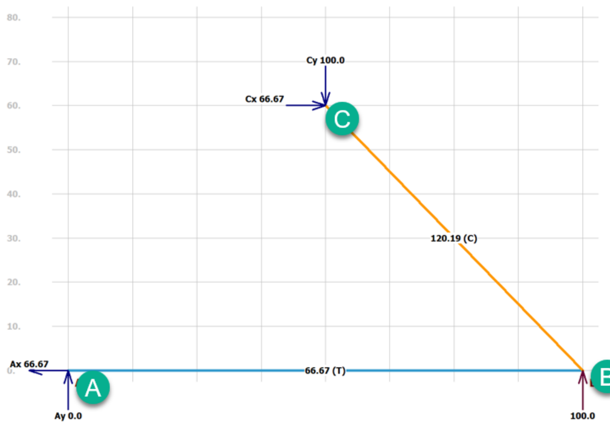


Illustration 51. MD-Solids tusses calculations

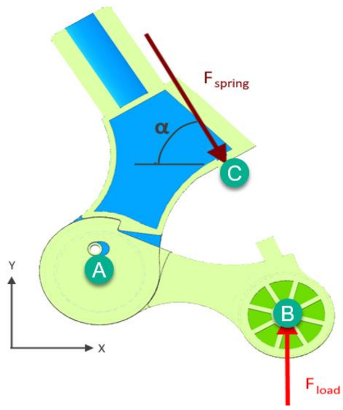


Illustration 52. Force placement

$$\boldsymbol{F2} = \frac{\boldsymbol{F1}}{\mathbf{cos(33.7)}}$$

$$\boldsymbol{F2} = \frac{\mathbf{100}\boldsymbol{N}}{\boldsymbol{cos}(\mathbf{33.7})}$$

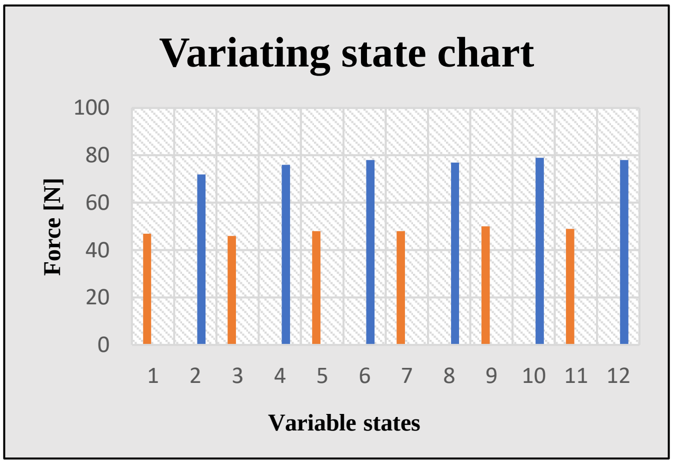
$$\boldsymbol{F2} = \mathbf{120}\boldsymbol{N}$$

The result of the calculation shows that each spring must be able to hold a load of 120N and not be contracted too much when the stroller is stationary.

2.4.2 DUAL RATE SPRING CALCULATION

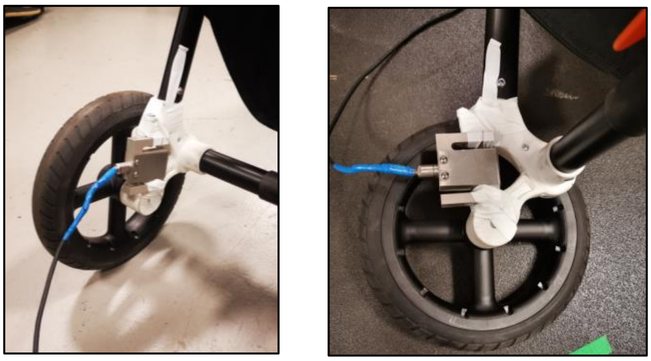
2.4.2.1 Soft Rate spring

The active force was measured with the help of a force meter. The force meter was attached to the suspension mechanism replacing one of the springs, as shown in Picture 17 below.
In the first stage of the test, the stroller stayed still.
The test was run several times. In Graph 1, the red spikes represent the result. The variation of the normal forces value was caused by the material of the 3D printed prototype and a slightly different placement of strollers in each of the tests.



Graph 1 Forces in variable states

For the second stage of the test, the stroller was placed on a vibration machine. The machine spins a cylinder with a bump, the cylinder spins the stroller wheel, and the bump gives hits to the stroller.
These hits give peak forces, which are illustrated as blue spikes in Graph 1. An average normal force, when the stroller is stationary, is around 48N. The peak's average is around 76,7N.
The average spring force is around 62N.



Picture 17. Placement of the forcemeter

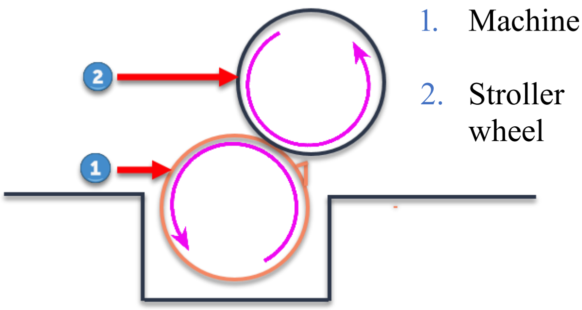


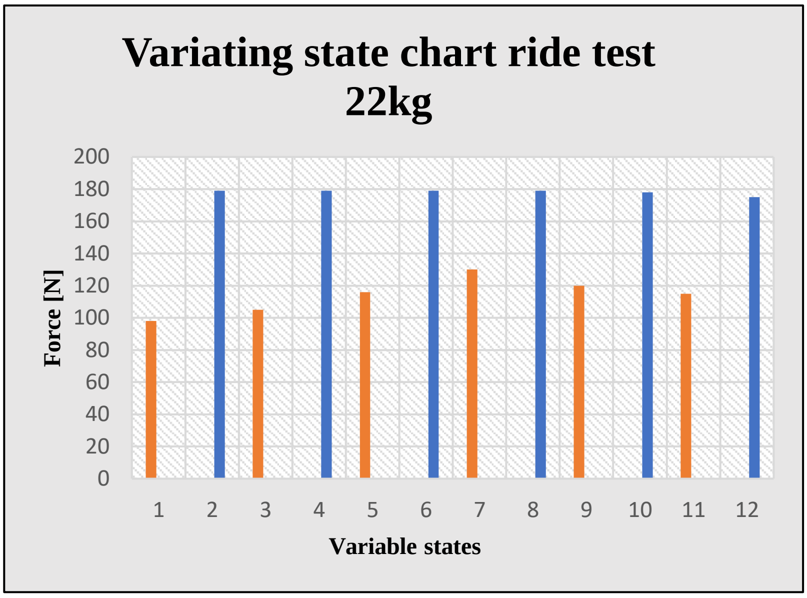
Illustration 53. Vibration machine consept

The test was run on a stroller with a 9kg load in the seat, which is equivalent to a one- to two-year-old kid, according to (healthline, 2020) as shown in Table 8, below.

Age	50th percentile weight for male babies	50th percentile weight for female babies
Birth	7.8 lbs. (3.5 kg)	7.5 lbs. (3.4 kg)
0.5 months	8.8 lbs. (4.0 kg)	8.4 lbs. (3.8 kg)
1.5 months	10.8 lbs. (4.9 kg)	9.9 lbs. (4.5 kg)
2.5 months	12.6 lbs. (5.7 kg)	11.5 lbs. (5.2 kg)
3.5 months	14.1 lbs. (6.4 kg)	13 lbs. (5.9 kg)
4.5 months	15.4 lbs. (7.0 kg)	14.1 lbs. (6.4 kg)
5.5 months	16.8 lbs. (7.6 kg)	15.4 lbs. (7.0 kg)
6.5 months	18 lbs. (8.2 kg)	16.5 lbs. (7.5 kg)
7.5 months	19 lbs. (8.6 kg)	17.4 lbs. (7.9 kg)
8.5 months	20.1 lbs. (9.1 kg)	18.3 lbs. (8.3 kg)
9.5 months	20.9 lbs. (9.5 kg)	19.2 lbs. (8.7 kg)
10.5 months	21.6 lbs. (9.8 kg)	19.8 lbs. (9.0 kg)
11.5 months	22.5 lbs. (10.2 kg)	20.7 lbs. (9.4 kg)
12.5 months	23.1 lbs. (10.5 kg)	21.4 lbs. (9.7 kg)

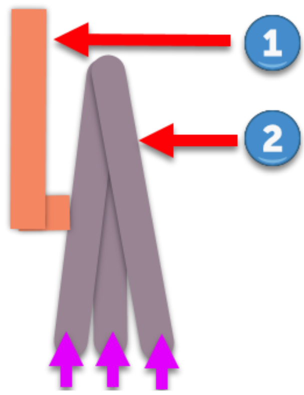
Table 8. Age-weight overview

Ride test helps to calculate the force that the firm part of the duel-rate spring will be expose to.
For this test, the stroller was loaded with 22kg in the seat. The force meter was attached in the same way as in the vibration test.
The test showed an average value in the extremal forces of 178N.
Normal force when the stroller in static position is 114N.
This means that the average force acting on the spring is equal to 146N.



Graph 2. Forces in variable states on ride test

The variation of the normal forces value was caused by the material of the 3D printed prototype and slightly different placement of the stroller in each of the tests, as shown in the illustration below.



1. Chasse
2. Wheel

Illustration 54. Placements after each tests

2.4.2.2 Firm Rate Spring

To calculate the firm rate side of the spring requires at first to find the most extreme conditions for the stroller in day-to-day usage. After some research, the conclusion was that tipping the stroller backwards on to the back wheels and going down roadsides or down staircases would give the highest level of stress on the stroller. The stroller was loaded with 22kg to simulate the weight of a baby, 10 kg in the shopping basket and the stroller has 9 kg of its own weight.

Normal forces and the impact forces were measured with the help of a force meter that was placed in the left back base replacing the spring, as shown in Picture 18, below.

Picture 18. Placement of the force-meter

Picture 19. drop test

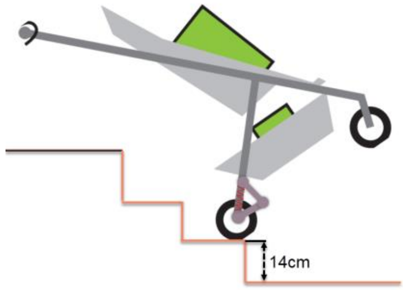


Illustration 55. Drop test details

To perform the impact test, the stroller was placed on the last step of the stairs at Stokke's office. The stair steps are 14 cm high.

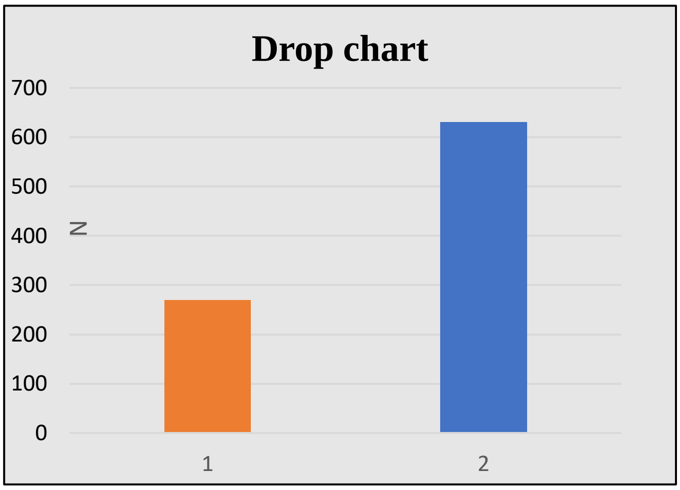
When the stroller tilted back onto the back wheels, the force meter showed that the normal force acting on the left base is 220N. This could be also calculated by taking the total weight of the stroller and dividing it by two.

$$22kg + 10kg + 9kg = 41kg$$

$$41kg * 9.81\frac{m}{s^2} = 402N$$

$$\frac{402N}{2} = 201N$$

The stroller was pushed forward and dropped 14 cm down on the back wheels as shown in Illustration 55. The force meter then showed the peak force of 630N.
The chart to the right shows that the normal force is placed at 230N and the peak force/impact force at 630N. This data helped to find the optimal properties for a dual rate spring.



Graph 3. Forces in the drop test. (1) normal force (2) drop force

2.4.2.3 Composition of Dual Rate Springs.

Dual-rate springs have two suspension rates: soft and firm. The soft rate part of the spring takes small vibrations in a normal day to day use, while the firm rate part takes extremal hits.

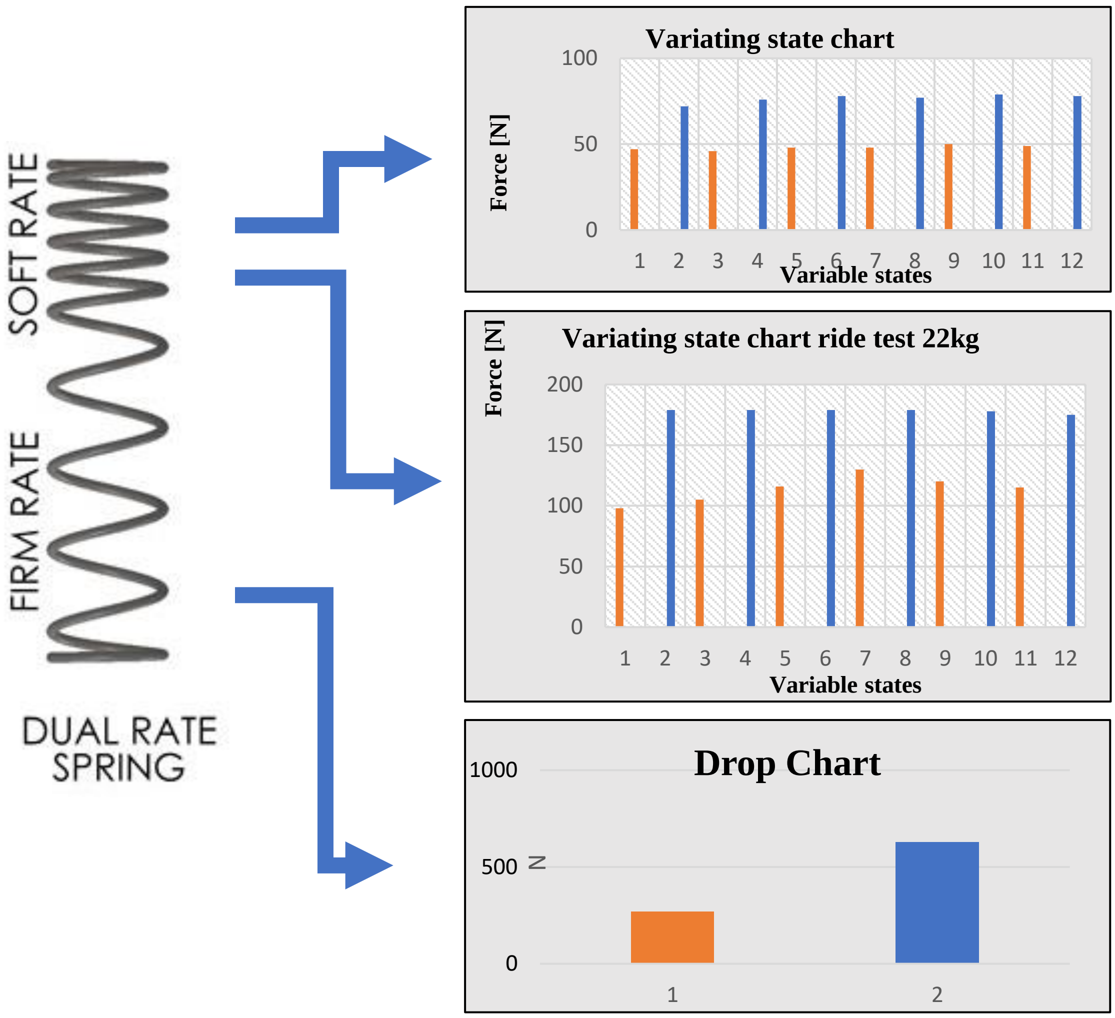


Illustration 56. Dual spring distriubution

The graphs above illustrate how the dual-rate spring in this project should distribute vibrations and hits. Data from the vibration test and the ride test give the average value of the normal forces and the extremal forces.
The soft rate side is meant to take vibration and normal forces in day-to-day normal strolling.

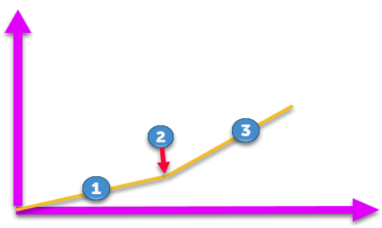


Illustration 57. Foreseen dual rate spring force graph

1. Firm rate & soft rate
2. Soft rate at limit
3. Firm rate

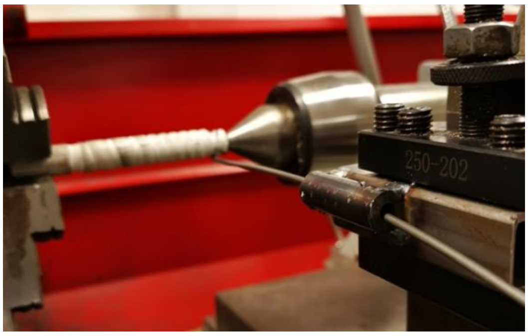
The firm rate part of the spring should take extremal forces, and it should activate when the pitch of the soft rate side is fully contracted. The firm part would protect the stroller and the baby from major impacts, as shown for example in the stair drop test.

2.4.3 DUAL SPRING MANUFACTURE

Several spring prototypes were manufactured at Stokke to simulate the duel rate springs. A guiding cylinder was designed with 2 different pitches: the stiff part was 10mm, the soft part was 5 mm. The thread was wound on the 3D printed guiding cylinder with a dual rate pitch.

Picture 20. 3D printed dual rate jig.

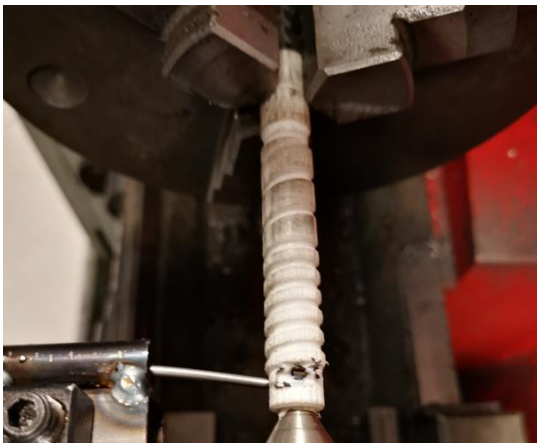
The 3D-printed guide was put into the lathe. A hole was made in the cylinder and the spring thread was inserted into the hole to hold the thread in place.



Picture 21. Lathe with jig and spring wire

Picture 22. Spring wire connection to jig

The lathe was manually rotated while the feeder was adjusted, so that the thread was pushed in the sloth of the 3D printed guide. The inconvenience of doing it this way was the tension on the feeder thread; the spring was not as tight as it should be.



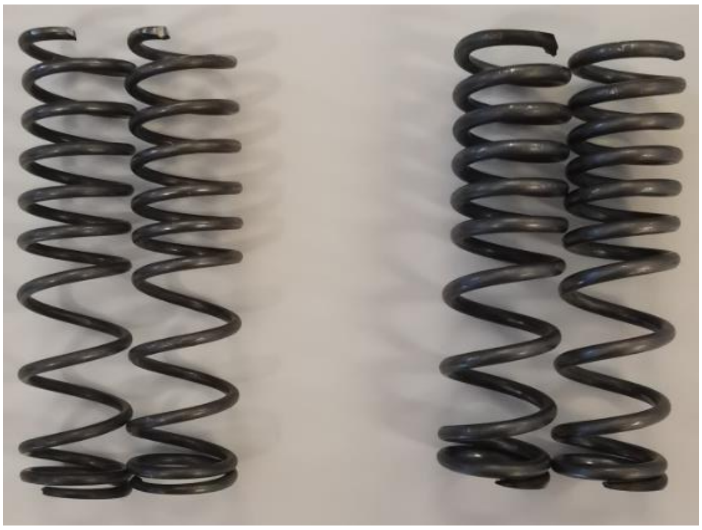
Picture 23. Spring wire fabrications start

Two sets of dual rate springs were made with two different thicknesses: 2.5mm and 2mm. Information about the wire material was not available, so the quality of the spring is questionable. The only information available was that it is a spring wire.

Picture 24. Finish with coiling the soft rate side.

Picture 25. Finish dual-rate spring on jig

In Picture 26 below you can see that there are some pitches that look bigger than others. This could be caused by the tension in the thread that was created by spinning the lathe chocks.



Picture 26. Result with 2mm wire (left), and 2.5mm wire(right)

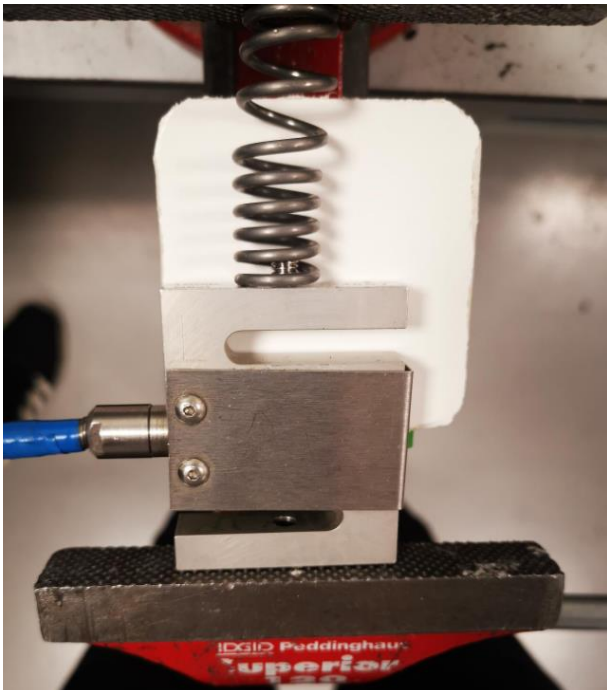
2.4.4 INSTITUTE OF SPRING TECHNOLOGY

COMPARISON

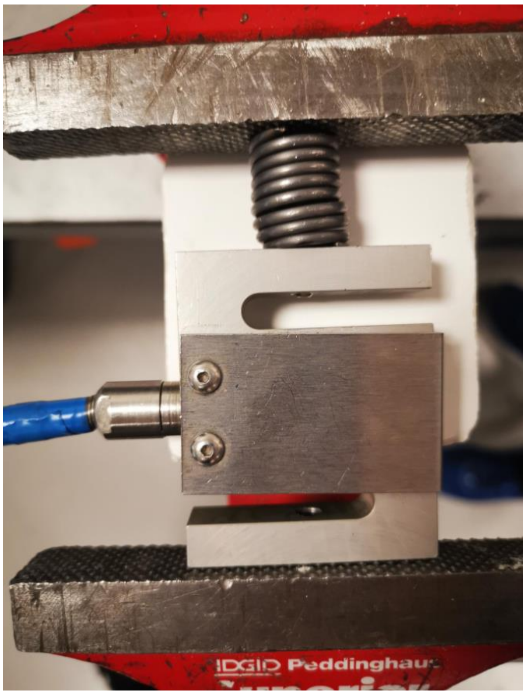
The Spring Calculator Professional (SCP) is a spring calculation software created by the Institute of Spring Technology.
This software can also simulate/calculate a dual-rate spring and a progressive spring.

The springs that were tested in the vibration test had a diameter of 2.5mm and were made supposedly of JIS G 3522, which could be defined as a "piano wire".

This "home-made" spring was inserted into a vice with a force meter connected to one of the ends as shown in Picture 27. The spring was compressed completely, and the force meter showed 360N.



Picture 27. Force test setup



Picture 28. Force test with spring fully contracted

The result of this test did not match the results from solid-state calculations. The reason for this could be that the material was not correctly estimated and that the "home-made" springs do not have the same properties as properly manufactured springs.

In the SPC Calculator you can choose: material (1), operating temperature (2), close ends (3), coin positions (4), wire diameter (5), coil diameter (6), distance between coils (7) and pitch between coils (8).

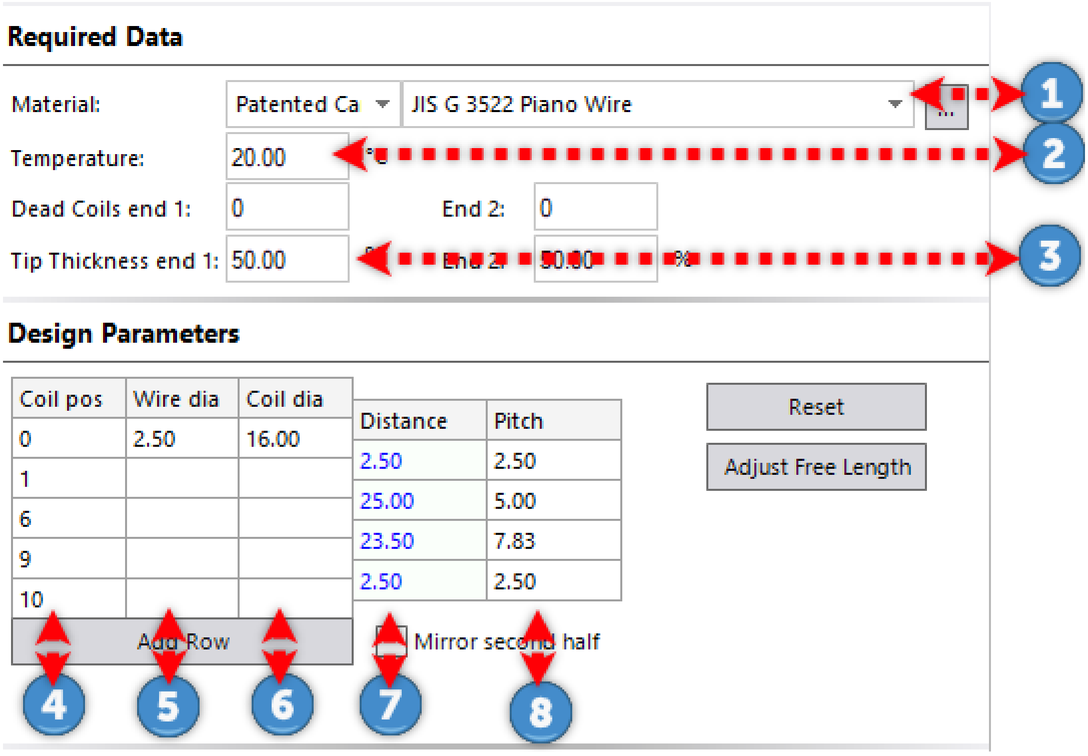


Illustration 58.Spring institute calculator setup

The program with these values would give a calculated solid load when a spring is fully compressed to 25mm. 10 coils * 2.5mm diameter = 25mm.

		Value	Units
Free length	L_0	53.50	mm
Solid length	L_c	25.00	mm
Solid load	F_c	830.83	N
Min index		5.40	
Max index		5.40	
Min stress factor		1.27	
Max stress factor		1.27	
Total coils	N_t	10.00	
Solid stress	τ_c	1828	MPa
Solid stress (uncorrected)	τ_c	1828	MPa
Solid stress (corrected)	τ_c	2319	MPa
Max outside diameter	$D_{e,}$	16.00	mm
Min inside diameter	D_{in}	11.00	mm
Wire length		427.88	mm

Table 9. Result from spring calculator

Table 9 above shows SCP calculated a solid load of 830N, which is 460N more than the test with the force meter, which showed 360N.

Ideal Spring

The ideal spring for this project would be a spring that can operate with two different load sets. The first load set would represent a normal ride. The soft rate side would be active during the day to day normal strolling, as shown in Illustration 59 below.

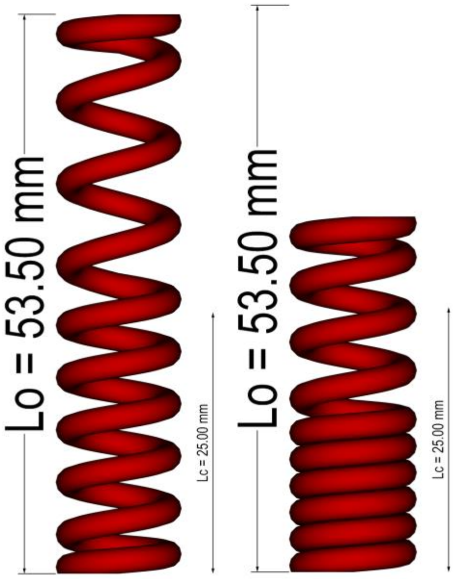


Illustration 59. Dual-rate spring, from normal to soft-rate side compressed

The second set of loads would simulate high stress, for example, by tipping the stroller onto the back wheels and pushing it down stairs or on sideroads. In this case the firm part of the spring should be taking the hits to protect the stroller from the large impact forces. The firm part of the spring activates when the soft part of the spring is fully compressed as shown in Illustration 60 below.

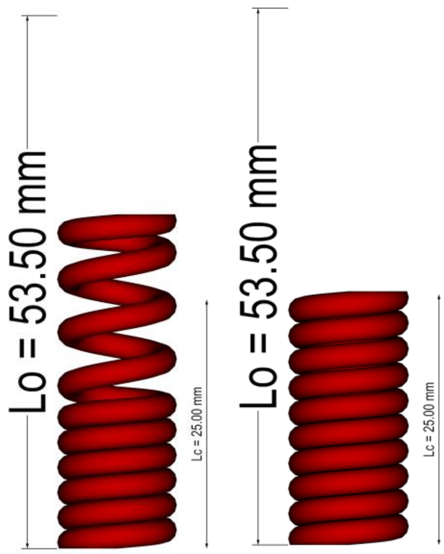
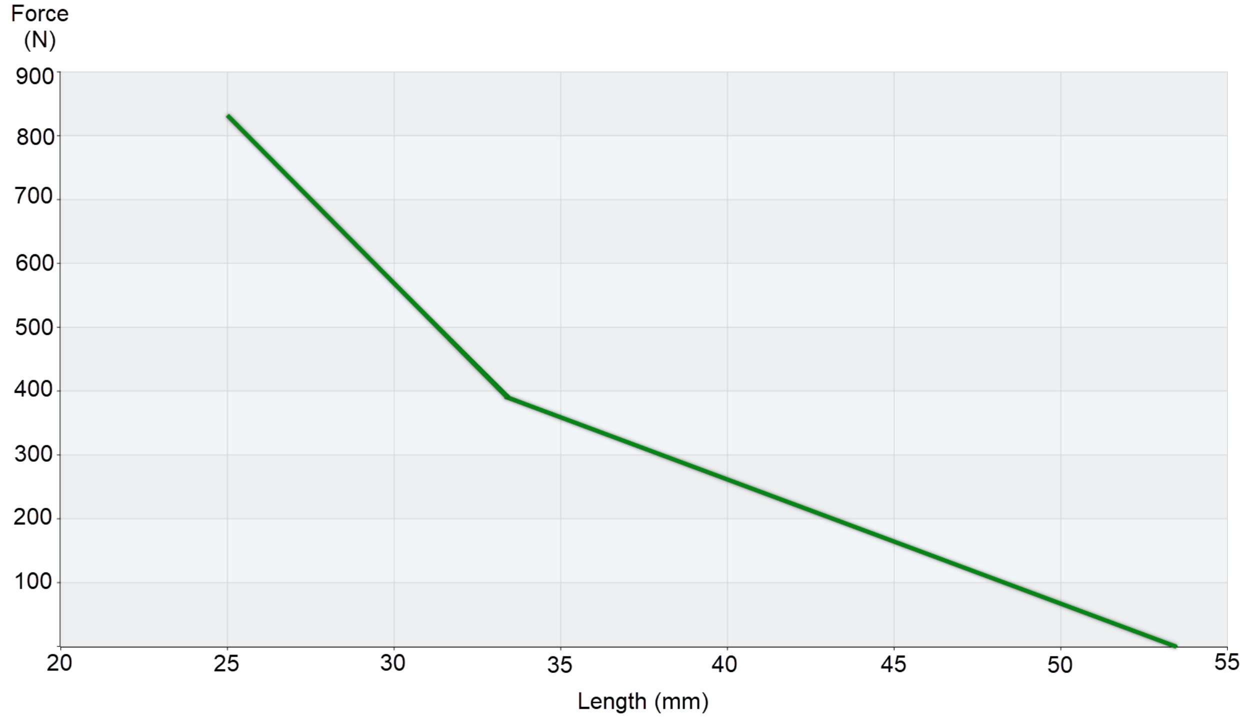


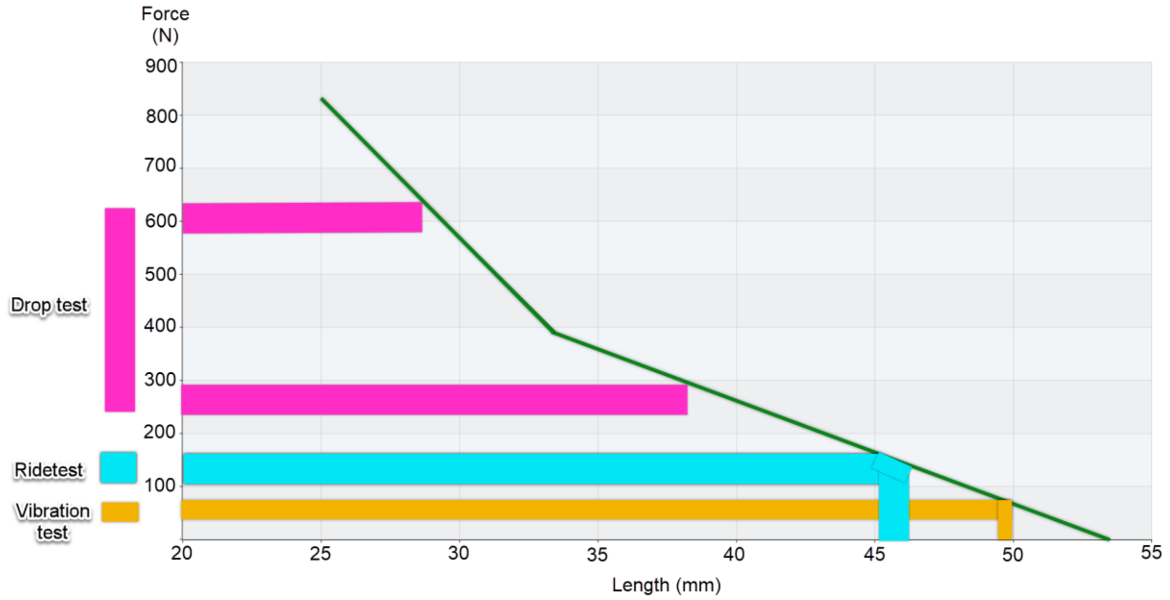
Illustration 60. Firm rate compression

This SCP load/length graph shows the compression of a dual-rate spring. The turn of the line at around 33mm means that the firm part of the spring activates when the load is more then 380N.



Graph 4. Dual rate Force-lenght

All test results were plotted into the SCP graph. Graph 5 illustrates the stages of the spring during the tests.



Graph 5. Overview over force-length graph, with respect to user tests

This confirms that the duel rate spring would act as it was intended when it is exposed to different type of loads and stresses.

2.5 PRODUKT TEST

Stokke's standards require running several tests on the strollers and their components before they are approved.

2.5.1 VIBRATION TEST

The stroller is put on a roller machine. The back wheels are placed up on the roller, as shown in Illustration 61 and Illustration 62. The roller rotates at a speed of 100 turns/min, which is equivalent to 3.8km/h. The bump on the roller is 1 cm high.
An accelerometer was attached to the back of a 9kg doll. The doll was placed on its back in the seat. To pass the test the vibratory acceleration must be under $9.8 m/s^2$ by law in Korea, and the maximum permissible range is $10.8 m/s^2$ (10% of the base value of $9.8 m/s^2$)
This test is done according to the (European standard, 2018).

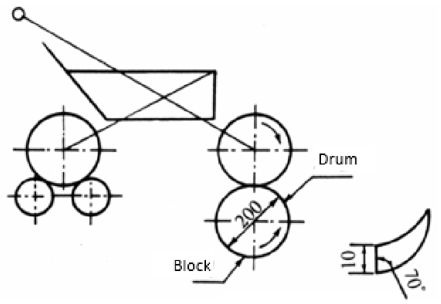


Illustration 61. Vibration test setup

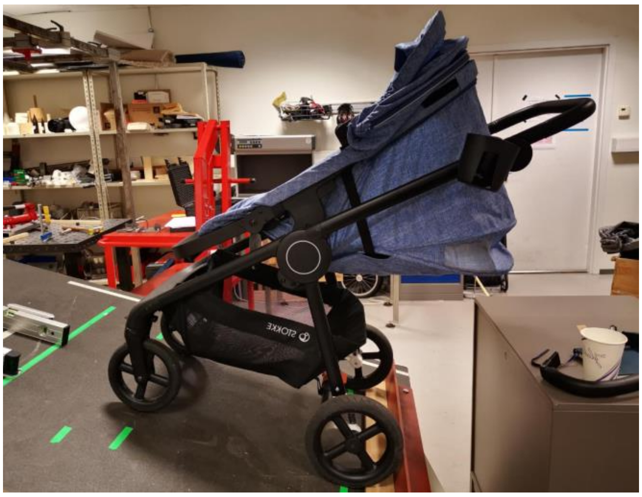
Illustration 62. Ride test.

2.5.2 STABILITY TEST

The table for the stability test is angle adjustable, one side of the table can be controllably lifted or lowered. The stroller is placed up on the table, then the angle of the table can be adjusted until the stroller starts to tip over. The angle of the table at the tipping point would be the result of this test. The test runs several times when the stroller would be tilted sideways, on the back wheels and on the front wheels with 22kg in the seat. To pass the test, the worst result must be better than 12 degrees. This test follows (European standard, 2018).

Backwards.

The stroller with a 22kg load in the seat is placed on the table. The brakes are off to put the rotation point closer to the centre of mass.



Picture 29. Backwards stability

A coffee mug holder must be attached to the handle to get more weight in the back. The back wheels lean on a 25mm high wooden stop. The tilting started at 16.8°. This result was within the standard expectation.

Sideways, child facing away.

The stroller is placed on the outer side of the wheel and leans on a 1cm high wooden stop. The front wheels are turned to the worst possible position as shown in Picture 30. The instructions from the institute say that the weight should be in the centre of the seat. That is why the styrofoam is placed in the seat as shown in Picture 30.

Picture 30. Sideways stability shown from the front

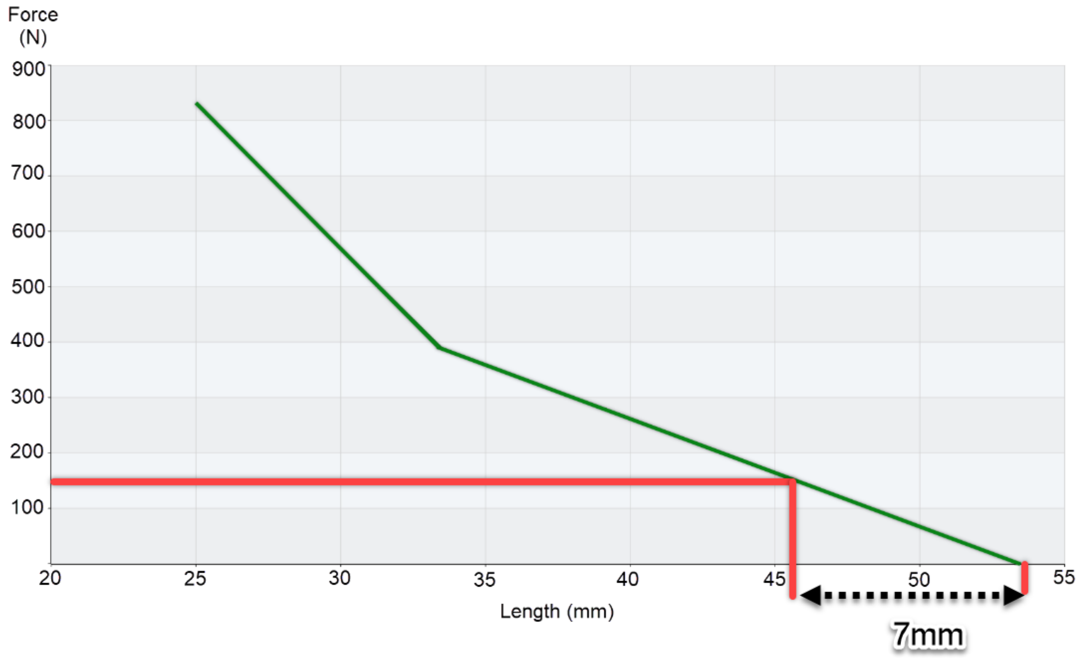
Picture 31. Shown from the back

Picture 32 below shows that when the stroller is loaded with 22kg in the seat, the table set at 17° and the back of the seat set to the lowest position, the right suspension is fully compressed to the internal end stop.

Picture 32. Suspension under sidewais stability.

The weight of the stroller is placed on the two right wheels of the stroller, as shown in Picture 32. That means that each of the wheel holds around 150N.

This graph shows how contracted the spring would be with a 150N force acting on it if the suspension system had an optimal spring like the one that was calculated in the section 2.4.4 INSTITUTE OF SPRING TECHNOLOGY.



Graph 6. Spring state with all the weight on two wheels.

Sideways child facing towards

The same sideways test, but this time the seat and the child are facing the rider.
The result of the test was the same, 17°.

Picture 33. Sideways

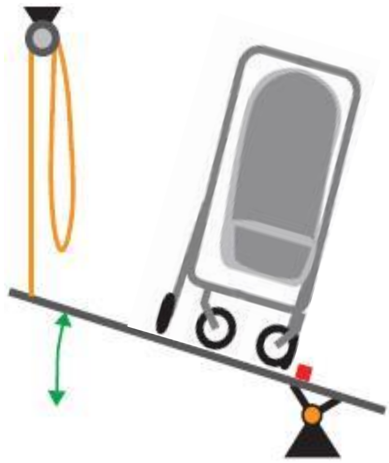


Illustration 63. Stability test setup.

2.5.3 HANDLE TEST

The handle test was performed by attaching the stroller handle to a cylinder that frequently goes up and down. The back wheel lifts up 120mm from the ground when the cylinder is in the highest point. In the same way, the front wheel lifts 120 mm up over the ground when the cylinder is in the lowest point as shown in Illustration 65.This test is meant to check the handle strength according to the (European standard, 2018).

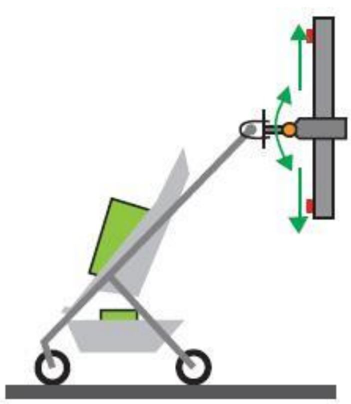


Illustration 64. Handle test setup

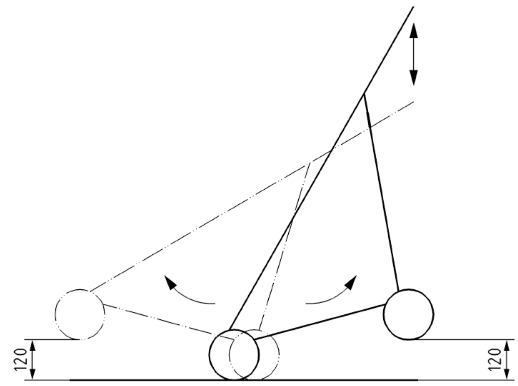


Illustration 65. Shows the dynamic motion of the test

This test was run with two different sets of loads. One set with 15 kg in the seat plus 10 kg in shopping basket, and one set with 22kg in the seat plus 10 kg in the shopping basket. The standards for this test require to run 10000 cycles with 15kg in the seat plus 10kg in the basket, and 3300 cycles with 22kg plus 10kg in the basket.
The test was run with the worst-case scenario (22kg and 10 in basket). During the test, the suspension mechanism was significantly deformed. The test showed some flaws in the design or in the material properties. The deformation happened at the very beginning of the test. The left side of Illustration 66 shows a normal position for the wheel and the suspension mechanism, the right side of Illustration 66 is an exaggerated sketch of the mechanism’s deformation during the test.

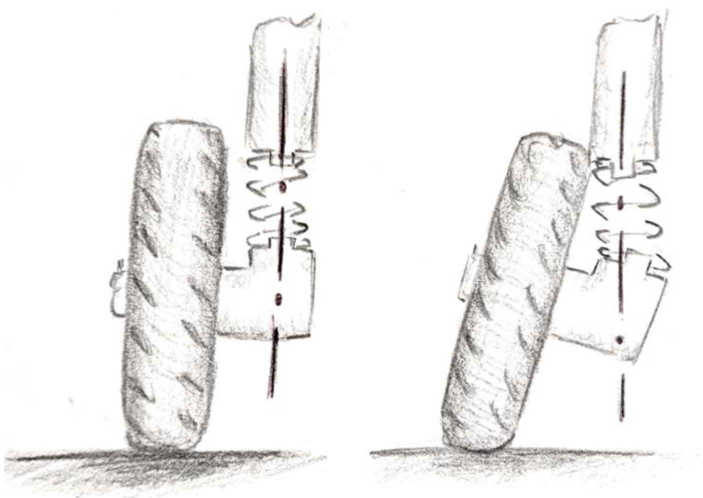


Illustration 66. Deformation of the wheelbase

Each part of the new system deforms at some degree, but the major deformation happened to the wheelbase part of the mechanism.
This problem with the stiffness might be resolved by using a harder material. The currently used PA12 is not as stiff as for example PA6 GF30, and as it was mentioned before the PA6 GF30 is 4 times stiffer than the 3D printed PA12. The base part could also be molded with a metal plate inside.
The design of the parts could also be improved to make the mechanism stiffer.

2.5.4 DYTRAN ACCELEROMETER TEST

The accelerometer test would help to see what difference there is between strollers with and without suspension. To get a clear picture of the improvement of the stroller's durability and the comfort while strolling on bumpy roads.

The accelerometer was attached to the back of a 9kg doll. The doll was laying on its back in the seat, and the back was fully extended as shown in Picture 34.

Picture 34. Seat back fully extended

The accelerometer is placed 80mm +- 10mm from the crotch of the doll and towards the head section, as shown in Illustration 67.

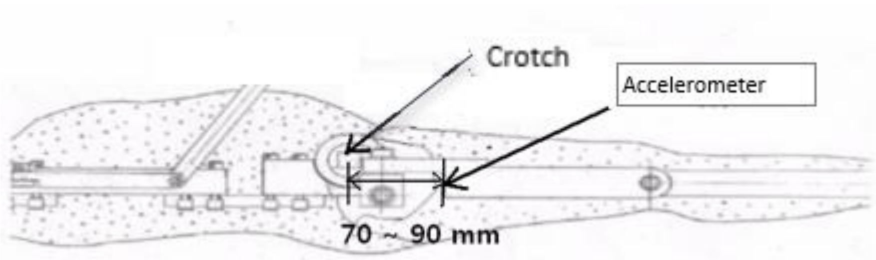
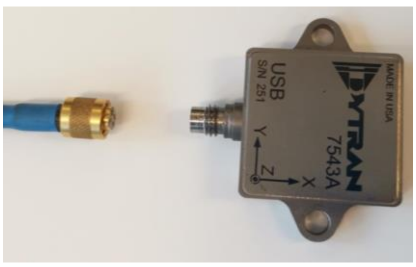


Illustration 67. Accelerometer placement

The accelerometer logs motions and acceleration in m/s^2 of the respective vectors (X,Y,Z) as shown in Illustration 69 below. The accelerometer is placed according to the Korean safety standard (Korean safety standard baby carrige, 2015).

Illustration 68. test setup



Picture 35. Dystan Accelerometer

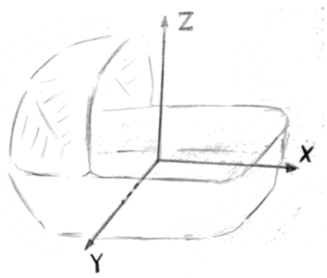
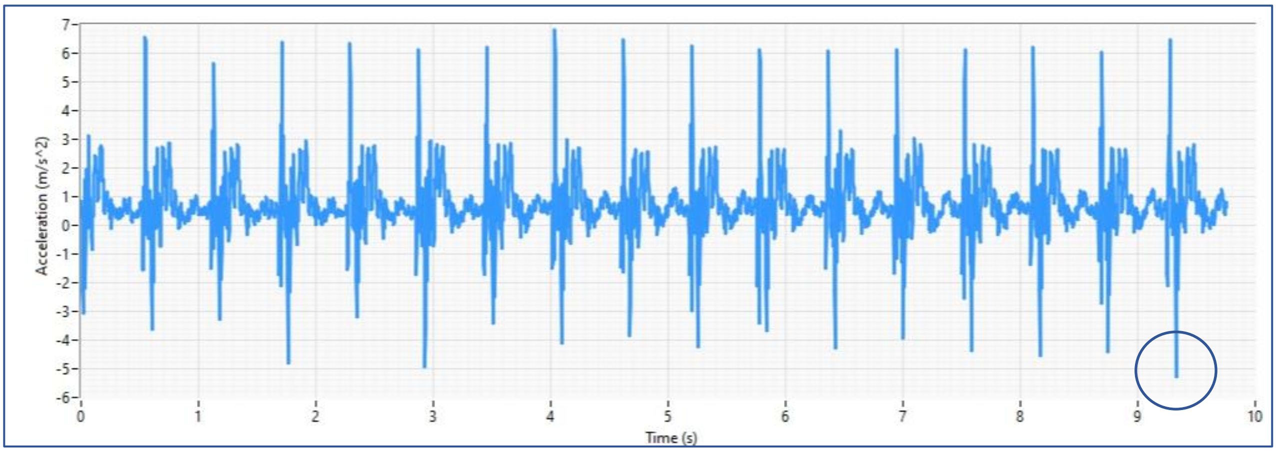


Illustration 69. Accelerometer vectors with respect to the seat

Comparison Results

The first test that was run was the vibration test. You can read about the setup in **2.5.1 VIBRATION TEST**.
Every vector output from the same test was compared with and without suspension in an interval of 10 sec.

X-axis Without suspension.



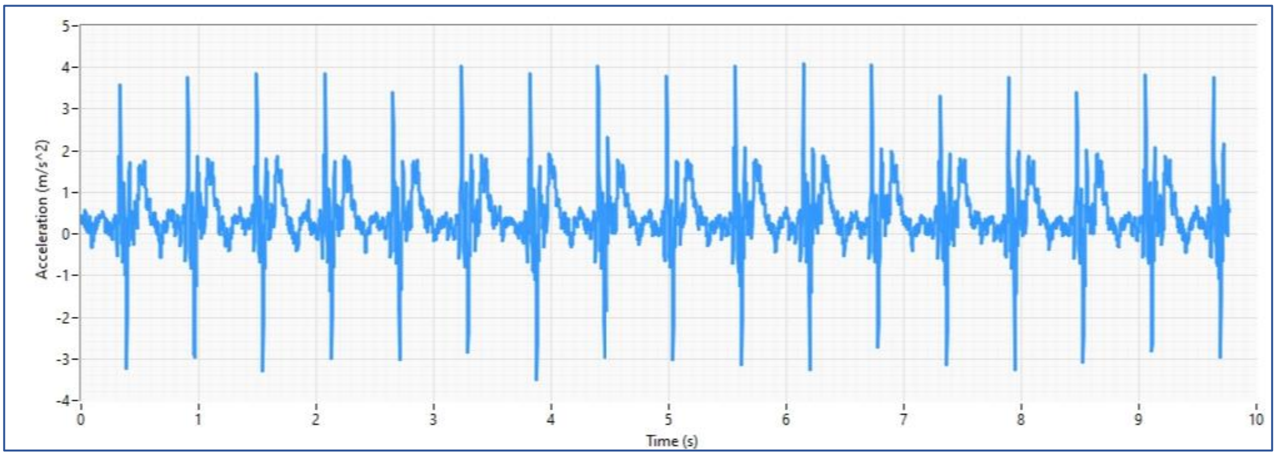
Graph 7. X-axis without suspension

The values for the test were exported into excel and analyzed with a max/min value lookup. The looked-up value from the negative side -4,9m/s^2 does not match with the plotted value. The extremal value on the negative side on the plot is -5.2m/s^2

Maks,Min lookup			
	time(s)	G	m/s^2
Max	4.0375	0.697813	6.845546
Min	2.93	-0.50358	-4.94014

Table 10. Min, Max lookup without suspension

X-axis with suspension.



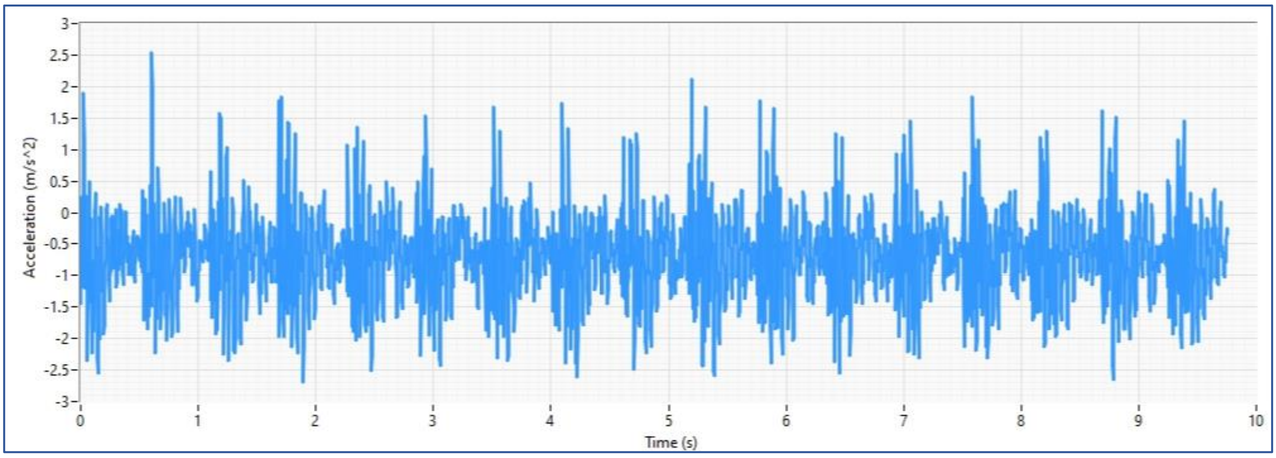
Graph 8. X-axis with suspension

The excel file gives us peak points at 6.1 sec and 3.8 sec, the acceleration peaks are 4.1m/s^2 and -3.5m/s^2 and this corresponds with the plotted graph from the Vibrascout software.

Maks, Min Lookup			
	Time	G	m/s^2
Maks	6.14375	0.418144	4.101993
Min	3.8725	-0.35784	-3.5104

Graph 9. Max, min lookup with suspension

Y-Axis Without Suspension



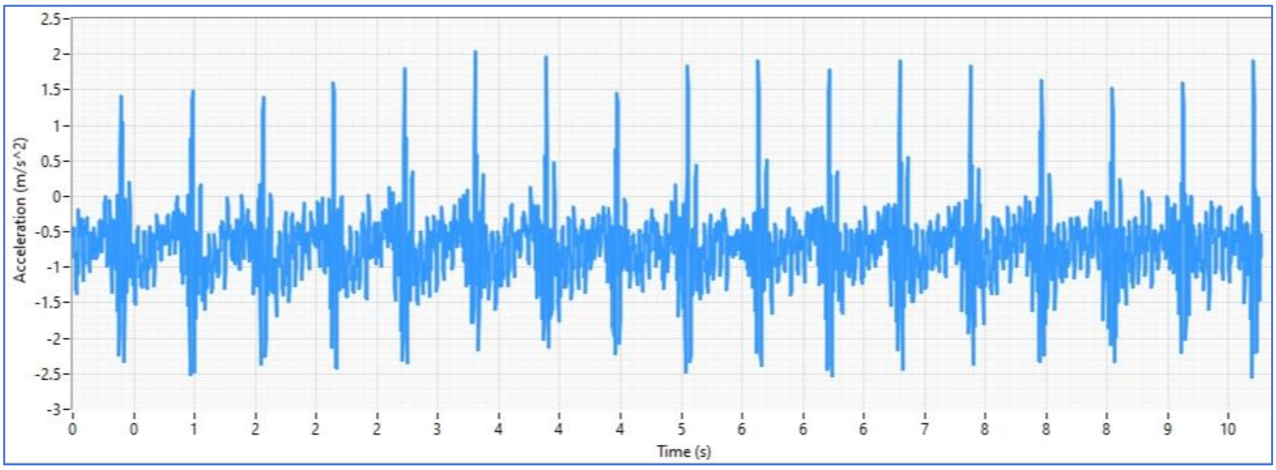
Graph 10. Y-Axis without suspension

The Y-axis represents the sideways motion. The graph above shows that there was some sideways acceleration during the vibration test. This vector is not that important considering the impact forces on the suspension, but they are more like a component that must be absorbed by the chassis and friction in the tires.

Maks, Min Lookup			
	time (s)	G	m/s^2
Maks	0.6025	0.25824	2.533334
Min	1.88875	-0.2761	-2.70853

Table 11. Max, min lookup without suspension

Y-Axis with Suspension



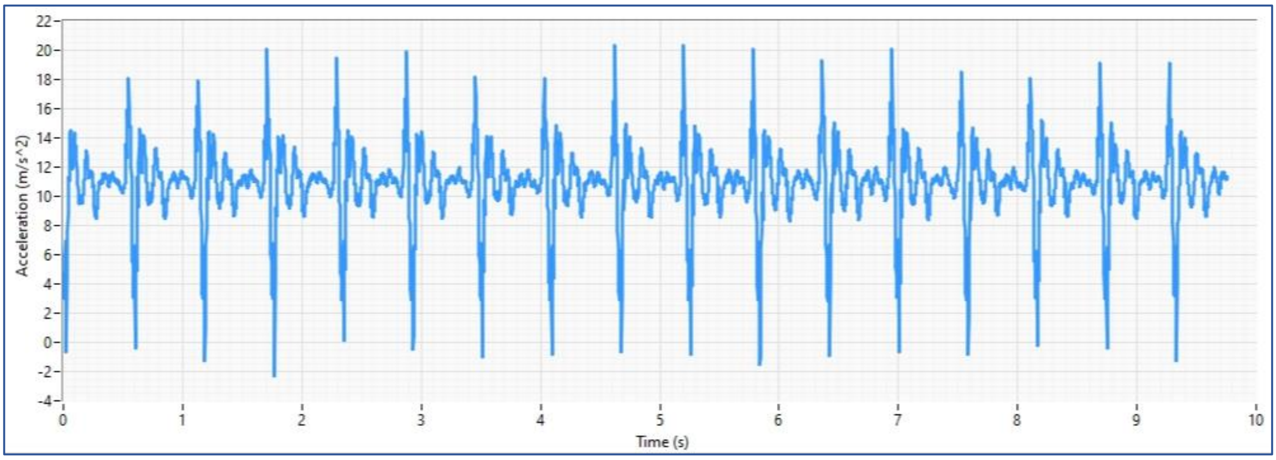
Graph 11. Y-axis with Suspension

It looks like there are less "noisy" vibrations on the Y-axis of the stroller with suspension than without suspension.

Maks. Min Lookup				
	ROW	Time	G	m/s^2
Maks	2647	3.30625	0.207189	2.032524
Min	4994	6.24	-0.25929	-2.54363

Table 12.Max, min lookup with suspension

Z-Axis without suspension



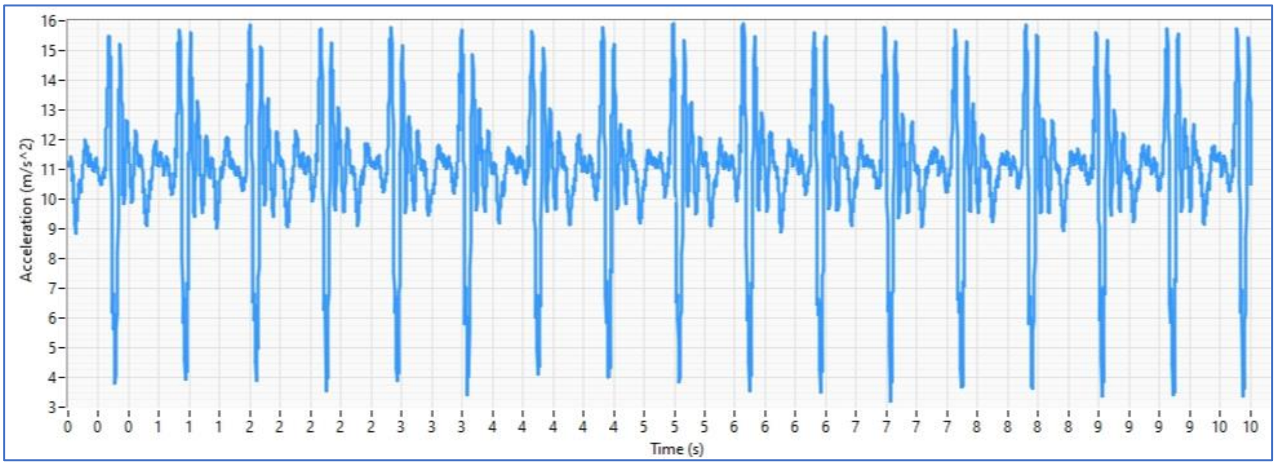
Graph 12. Z-axis without suspension

The reason the graph is shifted above the 0 in the y-axis is because of the natural earth gravitation that is around 9.81 m/s^2. Since the accelerometer is placed so that the z-vector is pointing upwards, it makes the neutral line to be around 9.81 m/s^2. This can also be a way to check if the accelerometer is placed correctly.

Maks, Min lookup				
	Row	Time	G	m/s^2
Maks	4162	5.20	2.078447	20.38957
Min	1417	1.77	-0.23601	-2.31524

Table 13. Max, min lookup without suspension.

Z-Axis with suspension



Graph 13.Z-axis with suspension

In this graph, the peaks in the positive and negative direction are reduced compared to the peaks on the z-axis without suspension. But there are more and smaller pulses in between the peaks. That is because the energy from the big peaks will be stored, then released into smaller negative and positive pulses in between.

Maks, Min Loopup				
	Row	Time (s)	G	m/s^2
Maks	3996	4.9925	1.621913	15.91097
Min	5431	6.78625	0.32567	3.194823

Table 14.Max, min lookup with suspension

The biggest positive peak is logged at 4,9s with an acceleration of 15,9-9.81 =**6.1 m/s^2**
The biggest negative peak is logged at 6,7s with an acceleration of 3.19-9.81= **-6.62m/s^2**

Final comparison and potential

The vibration test showed peaks in the positive and negative direction, both with suspension and without suspension. The improvement that the new suspension system gains is illustrated in Table 15 below. The result is calculated by comparing the stroller with and without suspension.

Positive direction

$$Improvement\ Positive\ = \frac{Amax - Amin}{Amax} * 100$$

$$IP = \frac{10{,}57\frac{m}{s^2} - 6.10\frac{m}{s^2}}{10{,}57\frac{m}{s^2}} * 100 = 42\%$$

Negative direction

$$Improvement\ Negative = \frac{Amax - Amin}{Amax} * 100$$

$$IP = \frac{-12{,}12\frac{m}{s^2} - (-6.60\frac{m}{s^2})}{-12{,}12\frac{m}{s^2}} * 100 = 45\%$$

X-axis					
Without			With		
Max	6.81	m/s^2	Max	4.10	m/s^2
Min	-4.94	m/s^3	Min	-3.51	m/s^3

Improvement max	40%
improvement min	29%

Y-axis					
Without			With		
Max	2.53	m/s^2	Max	2.03	m/s^2
Min	-2.70	m/s^3	Min	-2.54	m/s^3

Improvement max	20%
improvement min	6%

Z-axis					
Without			With		
Max	10.57	m/s^2	Max	6.10	m/s^2
Min	-12.12	m/s^3	Min	-6.62	m/s^3

Improvement max	42%
improvement min	45%

Table 15. Axis comparison and improvement

The significant peak reduction in the z-direction is important for this project, it is this vector that impacts the child the most. Table 15 above shows an improvement of acceleration by 42% in the positive Z-direction, and a 45% improvement in the negative direction.

The improvement of peak acceleration is around 40 percent in both directions with a home-made dual-rate spring. For further development and testing it is worth installing a spring with the perfect specifications, as calculated in the section 2.4.4 INSTITUTE OF SPRING TECHNOLOGY.

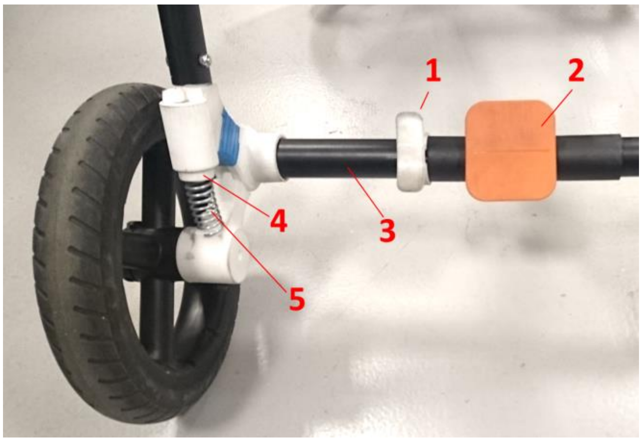
2.6 TWO MODE SUSPENSION

2.6.1 CONCEPT

Two mode suspension would allow the user to choose one of two stiffness modes for the suspension, a soft or a firm suspension according to the type of road.

The soft mode is active when both springs are operating. Cylinder (4) between spring (5) and spring (6) is freely gliding.

The harder mode activates when the rider flips the suspension pedal (1) This pedal is placed by the brake pedal (2). The pedal transfers moment to a steel pin inside tube (3). A simple mechanism with a little arm and a steel pin (see Illustration 70 and 71) blocks the gliding cylinder (4) and deactivates the soft spring (6). It allows only the bottom spring (5) to suspend, which provides a harder but steadier ride.



Picture 36. Two mode, part overview

Picture 37. Dual functioning spring

All parts are visual in the cross section of the fork. The lock pin is driven by a latch forcing it in and out. The latch is operated by a switch (1) near the brake pedal. The mechanism can therefore switch between two modes. one with only a soft spring, the other with a dual rate function.

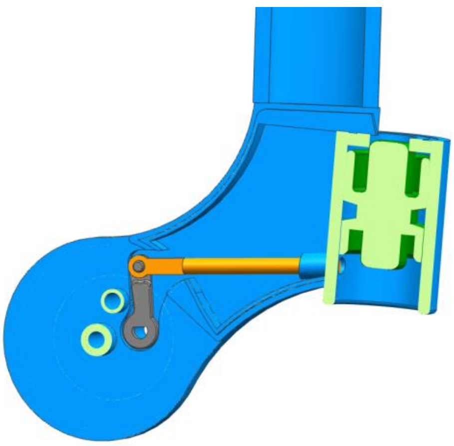


Illustration 70. disengaged mode, dual rate

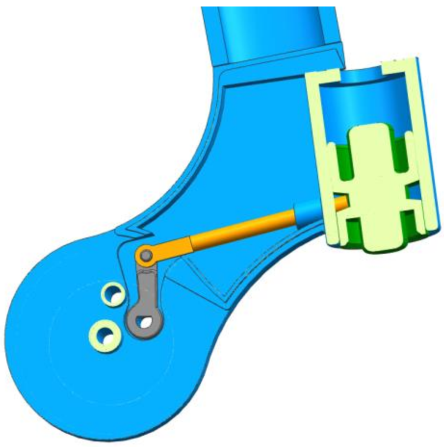
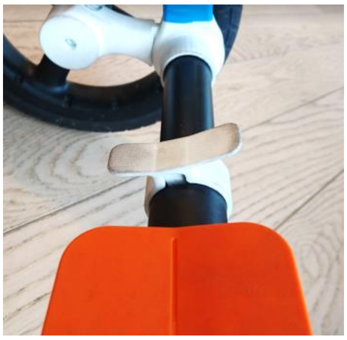


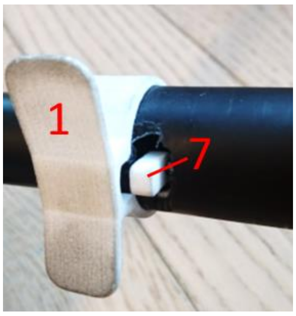
Illustration 71. Engaged mode, Single rate

The pedal design is similar to the brake pedal but has only 1/3 of the brake pedal's width and has a different color. It is made this way to visually separate the pedals and to prevent misusing them.



Picture 39. Switch for two mode suspension

Pedal (1) has the rotation axle in the center of tube (3). But part (7) rotates with pin (8) This means that pedal (1) slides inside the pedal when the pedal is flipped.



Picture 38. Pedal with rotation pin

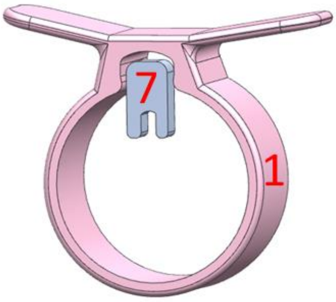


Illustration 72. Pedal function

The assembly of the pedal mechanism is simple but effective.
A steel pin goes through the horizontal bar between the two back wheels, leaving the brake system barely touched. The pin has three notches. One notch is made to connect pedal switch (7) and two on the ends are for transferring rotational force to arm (9).

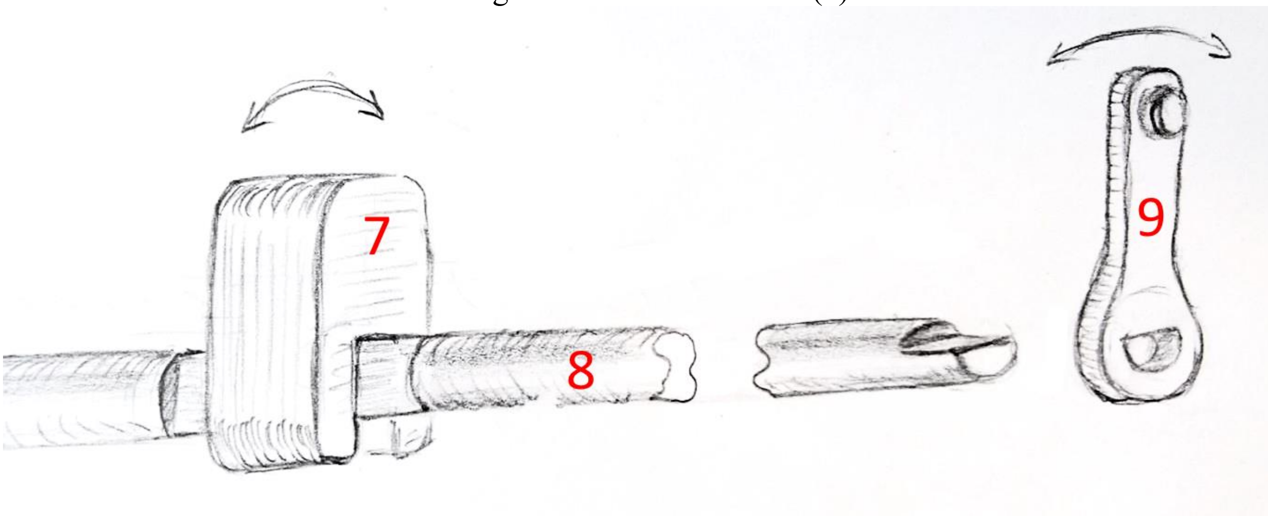


Illustration 73. Function map

2.6.3 FEEDBACK

During a debrief with Stokke's engineers and designers, this concept received good feedback as a potential future developing project. For the moment however, the simpler concept was considered preferable. Nevertheless, the lead project engineer encouraged continued work on this project parallel to the main concept if there is extra time.
From an idea to a working prototype took only 3-4 days. With such an outcome, this can be considered a successful tryout.

3.CONCLUSION

3.1 RESULT

Picture 40. Project result

Picture 41. Project result closeup

The result of this project was a functional prototype of a suspension system for the back wheels of the Beat stroller made of PA12. The suspension does not compromise the brake system and does not hinder the folding of the stroller. With this new suspension, the vibration peaks of the stroller were reduced by approximately 40 %.

Even a 3D printed PA12 prototype passed almost all the necessary tests, it's only the handle test that the mechanism is not stiff enough for. Better material would most likely resolve this problem. If it is needed, the design of the parts could still be improved to provide better stiffness.

There were a lot of research about springs and their properties and multiple tests were run to find the best solution for the springs. The dual-rate suspension system is unusual for a stroller. One part of this spring reduces the peaks of small vibrations, the other reduces impacts on the stroller from bigger bumps. This makes the ride more comfortable for the baby and the rider, it also increases the longevity of the stroller.

3.2 DISCUSSION

A suspension mechanism with better material and proper springs would give slightly different, and most likely better results. It is hard to say what the potential for this suspension system is before it is properly manufactured with planned materials.

In the middle of this project it was announced that Stokke has canceled the production of almost all their strollers, including the Beat stroller. This news did not change the fact that this project will be finished as planned, but it did influence the motivation in a negative way.

The epidemical situation in spring 2020 stopped certain processes for a while because there was no access to the company office and test labs for several weeks.

3.3 THOUGHTS ON FURTHER DEVELOPMENT

Further development would require making the model out of better materials. The material of the 3D printed model has approximately 4 times less stiffness then the material that is usually used for such parts. The next step for the project would be producing the parts out of PA6 GF30. The base part might need to be molded with a metal plate inside to provide better stiffness.

In this project there were many theoretical calculations and physical tests on springs to find a good balance between suspension and stability of the stroller. To find the best spring option it would require running more actual tests with different springs.
The currently used springs on the suspension are “home-made” and have different properties then the ideal spring that is factory produced.

A two-mode suspension system is an interesting project and has good potential. The switch pedal should probably be moved farther from the brake pedal to avoid misusing it.
Even though the designers did not require covering the spring, it would be interesting to see how it would work and look.

3.4 EDUCATIONAL EXPERIENCE

This project required getting familiar with both international standards and Stokke’s standards.
Stokke’s standards are more conservative than the international standards.
Learning about the whole process from a concept to a prototype was necessary for running this project.
It was relatively easy to come up with many concepts for suspensions but evaluating them and picking one was a good learning experience.
After making sure that the new suspension, the brakes and the folding of the stroller are working well, it was time to apply theoretical calculation int practice: developing and optimizing the design of the system.
During the project there were several evaluation meetings with Stokke’s engineers and designers. Casual meetings and small chats during the project period gave us a lot of constructive feedback as well.
- DFM was a good practice for designing a part that could be manufactured right away without redesigning.

The spring research took a lot of time and energy. It required learning about different types of springs and their properties, to find out which spring would be the best for this suspension system.

Buying dual rate springs is expensive and has a long delivery time, so several springs were manufactured at Stokke for this suspension prototype. The calculation of an ideal dual rate spring to a self-manufactured one was a all in all a good learning experience.
To do a topology optimization study on the wheelbase was interesting, we learned to use a new software that can optimize designs to use as little material as possible. All in all, this was a new and good experience.

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FIGURES

GRAPHS

Illustrations

SKETCHES

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