Design and evaluation of a sit-snowboard for advanced users, focusing on comfort and control

By

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Abstract

Sit-snowboarding is a new adaptive sport[1]. A sit-snowboard is a mechanism that allows people with lower extremity impairments to perform the sport of snowboarding by supporting their weight at the buttocks, knees and feet. The only sit-snowboard available on the market at the moment (Twinrider) is solely suitable for beginners. Comfort and control are insufficient for advanced riders who reach higher speeds and ride more bumpy slopes. The goal of this study is to design a sit-snowboarding mechanism that provides sufficient comfort and control for advanced users.

In the new mechanism design (Snowcruiser), vertical suspension is added between the seat and the board using two mountain bike forks. Independent compression of the forks, nose/tail translation of the seat and board flex are allowed. These alterations prevent visional and vibrational discomfort due to seat tilt, vibrations or shocks on the seat. Minimizing seat tilt and vibrations will also minimize control interference. A continuous interaction of the snowboard with the surface though board flexion and less vibrations on the board also improves control.

With a quantitative test the performance of the new design is evaluated by a straight descent from a bumpy, artificial slope. The prototype carried a dummy weight and the descent is guided by a skier. Using four accelerometers of which two were placed on the board and two on the seat, accelerations were measured. To assess the severity of these vibrations and shocks the standard BS 6841 is used. Vibration Dose Values (VDVs) for the board and the seat are determined after weighting the accelerations to the frequency and direction as described in the standard. Seat tilt and contactless distance were determined using data from high speed cameras. Setting each combination of maximum and minimum height, compression and rebound speed resulted in eight Snowcruiser models. With analysis of the variables, speed dependency is checked and an insight is gained on the behavior of the different combinations of settings. Also a qualitative test is performed in which two riders actually sit in the prototype and slide over hills while turns are made.

The measurements show that the VDVs on the seat are lower for all Snowcruiser models than for the Twinrider, indicating less discomfort. The riders of the qualitative test confirmed this by experiencing a smooth run: No shock is felt when landing after a hill. The Seat Effective Amplitude Transmissibility (S.E.A.T.) is not lower for the Snowcruiser than for the Twinrider, so vibration isolation is not more efficient for the Snowcruiser. However, the Snowcruiser shows reduced accelerations on the board, taking away the source of vibration at the board. The Snowcruiser is able to keep the seat horizontal for small inclines, preventing visional discomfort and control interference. The qualitative test showed that limited seat tilt also occurs for the Snowcruiser when passing a big hill at low speed. Measurements show that increased seat tilt occurs after passing a hill with the quantitative test, but this disadvantage did not occur with the qualitative test, which may be explained by the lower riding speed. The qualitative test shows that more board flexion is possible, leading to a more continuous board-surface interaction. The variable of contactless distance is strongly depending on riding speed, and therefore not a useful variable in this study.

Both tests show that comfort and control are improved for the Snowcruiser and that the goal is achieved: The Snowcruiser provides sufficient comfort and control for advanced users. A height of 500mm, maximum compression and fast rebound form the most promising combination of settings. The similar results from the two tests show that the measurement method presented in this study is a valid method for performance evaluation of comfort and control for a sit-snowboard, using the variables VDV and seat tilt.

Keywords

Sit-snowboarding, adaptive sports, suspension, board flexion, design, performance evaluation, whole body vibration, vibration dose value, seat tilt

[1] Sport for people with a disability

1 Introduction

1.1 What is sit-snowboarding

Sit-snowboarding is a new adaptive sport. A sit-snowboard is a mechanism to support the body of people with lower extremity impairments, enabling them to perform the sport of snowboarding. It reduces the gap between disabled and able bodied people, offering disabled people the possibility to enjoy winter sports and increasing their life quality. Sit-snowboarding is not yet a competitive sport and there is only one company developing and selling sit-snowboards.

The Twinrider (van der Werf, Klauss, & Helming, 2014) is a sit-snowboard developed by Gina van der Werf, owner at Prodaptive B.V., that allows people with impaired lower extremities to perform snowboarding while being supported below their buttocks, knees and feet, only using their trunk and arms (Figure 1) . The Twinrider is the only sit-snowboard available on the market at the moment. There is an adult and children's version.

Figure 1: Twinrider: sit-snowboard for beginners

1.2 Not sufficient for advanced users

Multiple videos from various users show that the Twinrider is functional for novice riders (ProdaptiveSnowsports). Making turns is possible and surface lifts such as the magic carpet, rope tow, J-bar or T-bar can be used to get on top of the slope. However, van der Werf points out that the Twinrider is not sufficient to be used by advanced riders who are likely to reach higher speeds and ride more bumpy slopes. Van der Werf explains: "An advanced boarder wants to be able to snowboard in all circumstances. So not only on freshly groomed slopes, but for instance also on the lower slopes at the end of the day. Extended use throughout the day will create bumps on these slopes. This happens very frequently and cannot be solved. To a certain extent, it is possible to compensate for bumps with the model for beginners by adapting speed and directional track. This has been shown in practice with riding the Twinrider in bumpy terrain." However, van der Werf, who is an advanced user, has experienced that when the speed is higher and the chosen track is more bumpy, the control is harder and comfort is worse.

An advanced rider who has been using the Twinrider during his holidays, experienced failure of the construction due to high forces. The type of forces the sit-snowboard needs to withstand when being used by advanced users is comparable to those with downhill mountain biking. At downhill mountain biking mechanisms are built in to be able to resist extreme forces. It is therefore plausible that it is a good idea to adapt the Twinrider for more extreme use on bumpy terrain.

When the Twinrider is adapted such that it is suitable for advanced users, sit-snowboarding might become more popular and winter sporting possibilities for people with impaired lower extremities will be broadened.

1.3 Performance evaluation

In order to evaluate if the sit-snowboard is sufficient for advanced users, performance needs to be judged. Performance of a sit-snowboard can be judged with the criteria ‘comfort’, ’control’, ’ease of use’, ‘appearance’ and ‘costs’. An overview of the performance evaluation criteria, factors and indicators is shown in Figure 2. Next to the performance criteria also several requirements exist that ensure safety and define the act of sit-snowboarding. These can be found in appendix I.

Hoogwout (2014) already focused on ‘ease of use’, creating a sit-snowboard that could be used in chairlifts and allowed propelling forward with the handlebars. In this study a focus is applied to a comfortable and controlled descent by taking into account the criteria ‘comfort’ and ‘control’. The criteria ‘appearance’ and ‘costs’ do not have priority at this stage of the development and are therefore not included in this study.

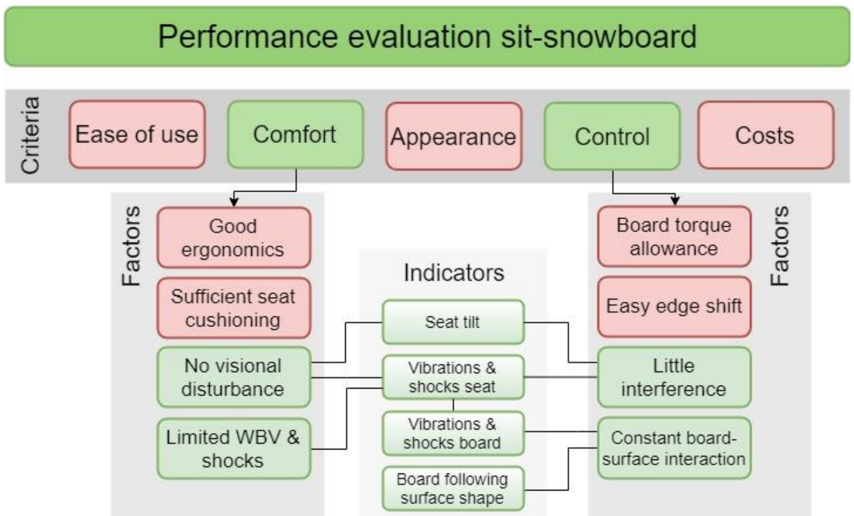

Figure 2: Performance evaluation criteria, factors and indicators

1.3.1 Comfort

Comfort is a term describing the experience of the user. A descent is comfortable when one feels relaxed and pleasant and does not experience any pain or fear. Comfort is improved by several factors like good ergonomics, sufficient body support cushioning in the seat, no visional disturbances and limited vibrations and shocks on the body. In this study focus is applied to visional discomfort and (dis)comfort due to vibrations and shocks, because these are the factors that are influenced by the basic mechanism design which is being redesigned in this study.

Sliding down a slope is a continuous exposure to disturbances resulting in a series or combination of free vibrations. It is expected that vibrations will increase with higher speeds which are reached by advanced users (Ismail, Nuawi, Kamaruddin, & Bakar, 2010; Mayton, Jobes, & Gallagher, 2014; Nahvi, Fouladi, Jailani, & Mohd Nor, 2009; Nahvi et al., 2006). Vibrations are defined by the frequency and amplitude of the oscillation (Harris & Piersol, 2002). Vibrations transmitted from the seat to the body of the rider are called whole body vibrations (WBV) (Griffin, 1996; Griffin et al., 2006; Jöhnsson, 2002). The term ‘shock’ is used to describe non-periodic short excitations (Harris & Piersol, 2002). Shocks are experienced when the construction regains contact with the surface after contact surface is (partly) lost. Exposing a seated person to vibrations and shocks might cause discomfort. It may lead to tiredness, disturbed perception and it makes a user more susceptible to back injury (Bovenzi & Hulshof, 1999; Cavacece, Smarrini, Valentini, & Vita, 2005; Mayton et al., 2014; Nahvi et al., 2006). Depending on direction and frequency, WBV are causing more or less discomfort (Griffin, 1996). More detail on the dependency of direction and frequency can be found in chapter 2.2.2.

To decrease WBV and shocks, the source of the vibrations can be eliminated. This means that vibrations and shocks on the board should be minimized, which can be achieved by keeping the board in continuous contact with the slope. Another possibility is to make sure that vibrations and shocks on the board are not transferred to the seat and body by applying vibration isolation with a mechanism between the board and the seat.

Vibrations on the head might result in shaky vision which may be experienced as discomfort (Cavacece et al., 2005). In earlier studies on the performance in sit-skiing, it is stated that when the seat is kept parallel to the slope, no visional discomfort is expected (Burkett, 2012; Cavacece et al., 2005; Cho, Kim, Cho, & Mun, 2013). An important addition to this statement is that this is only true when the seat is kept parallel to the main slope of the surface, and not following bumps and pits in the slope. Also the speed of the seat tilting is influencing the degree of discomfort experienced: When seat tilting happens slowly, the brain has no trouble adapting and no discomfort is expected. Another way to determine the amount of visional discomfort is by using the fact that WBV are also transmitted to the head. The less vibrations and shocks on the seat are present, the less the visional discomfort is expected to be.

1.3.2 Control

Good control is a requirement to be able to safely perform the sport of snowboarding. Control contributes to the joy the rider experiences. Riders are in control of their own safety and excitement. Riders need to control the direction and speed while descending. Control is improved by several factors like the possibility to torque the board, making edge shifting easy, prevention of control interference caused by certain unwanted movements of the body and enabling a constant interaction between the snowboard and the surface. In this study a focus is applied to the factors 'control interference' and 'board-snow interaction', because these are the factors that are causing the insufficient control performance of the Twinrider. Board torque and easy edge shifting is already successfully incorporated in the current design.

Directional control of the sit-snowboard is achieved by making turns. Turns can be made by torqueing the board and balancing the board on the long edges using center of mass (COM) shift in x-direction which is also called heel/toe direction (Anastasiadis, Haest, Jenkins, Langbroek, & Leenders, 2012) (Figure 3). The long edges of a snowboard are called heel-side edge and toe-side edge (Figure 4). The name of the edge depends on the feet placement (or body position for sit-snowboarding). COM shift can be achieved by leaning with the trunk.

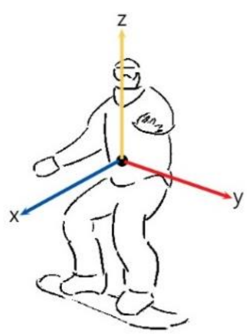

Figure 3: Axis defnitions

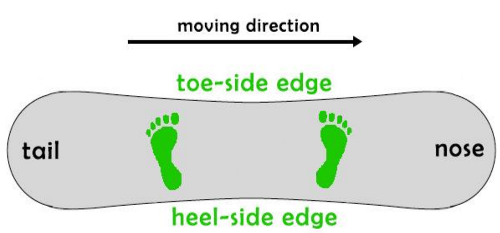

Figure 4: Illustration of the top view of a snowboard

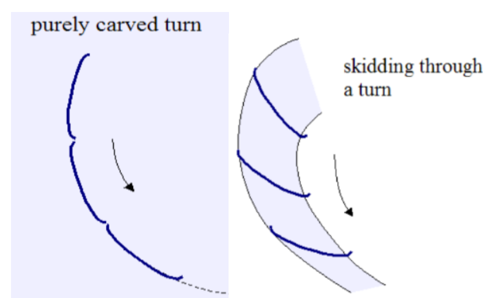

Figure 5: Illustrations of carved(left) and skidded turn(right)

When the snowboard touches the surface with one long edge only, the curved shape of the edge makes the board turn. This is called carving, and the edge of the snowboard is parallel to the moving direction (Figure 5). When the snowboard is not purely pointed in the direction of its velocity, the edge is slipping. This is called a skidded turn (McNab, 2005; Normani, 2009).

When a skidding turn is made, friction of the long edge with the snow results in deceleration. When, during skidding, the board is tilted more with respect to the surface, more friction is created and more deceleration occurs (Anastasiadis et al., 2012). Purely carved turns do not decelerate the snowboard because the direction of the velocity is in line with the snowboard edge, not resulting in friction.

The nose and the tail of the board are the front and back area of the snowboard (Figure 4). In standing snowboarding, also COM shift in nose/tail direction (y-direction) and up/down direction (z-direction) are used to control turns (Anastasiadis et al., 2012). It is unknown to what extent COM shifting in these directions is necessary for good control, but enabling them both will mimic standing snowboarding more. A user is capable of shifting the weight in nose/tail direction by leaning with the trunk, but up and down COM shift by just using the trunk is very limited.

No research is available on sit-snowboarding, so literature on sit-skiing is analyzed to learn about the degrees of freedom in the sit-skiing mechanism (Fioole, 2017). In sit-skiing research, Koo, Eun, Hyun, and Kweon (2014) note the importance of the up and down motion of the COM to make turning motions easier. Goodman, Charron, and Barlett (2000) state that having a spring in the mechanism may be beneficial for the control of a sit-ski. He states that having a spring, biased in extended position, propels the mono-ski out of a turn into the next one.

Shifting the COM up and down not only supports the turning motions, but is also used when a bump is passed. Controlling direction and speed can only be done when there is interaction between the board and the snow. Decrease of pressure when sliding over a hill is caused by less normal force than gravitational force and results in decrease of control. Advanced standing snowboarders can compensate for the height of the bumps by shifting their COM up and down such that they do not experience centripetal acceleration and contact with the snow is maintained. Able bodied snowboarders go over hills by bending their knees to let the mass of the body continue at the same height while the board is going over the hill (Lind & Sanders, 2004; McNab, 2006). A sit-snowboarder does not have this option with the Twinrider, because there is no up/down motion possible with the construction and the up and down COM shift with the trunk is very limited.

The decrease of board-surface interaction can be explained by modelling the situation as a partial circular motion around a circle with radius r (Figure 6) (SantoPietro, 2016).

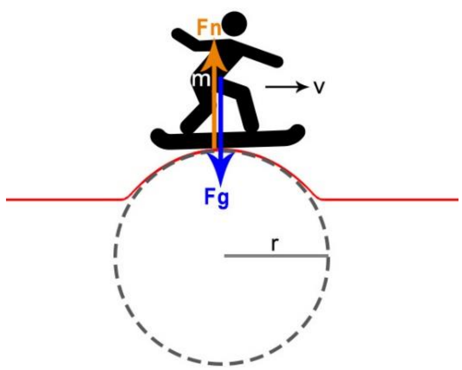

Figure 6: Model of a sit-snowboarder passing a hill

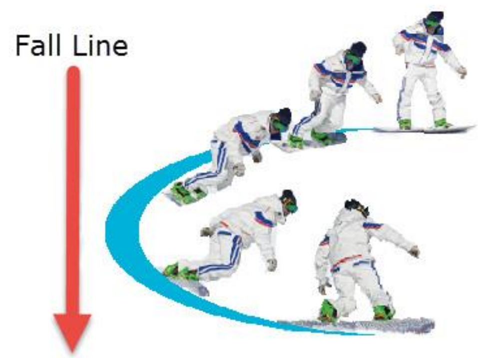

Figure 7: A closed turn adapted from (mementoski.com, 2017; Pont, 2016)

When looking at the instant the sit-snowboard is at the top of the circle, Newton's 2nd law for the vertical direction states that:

$$a_c = \frac{\sum F_c}{m} \quad (1)$$

Where a_c is the centripetal acceleration caused by the moving speed and F_c is the centripetal force, defined as the net force pointing toward the center of the circle. When filling in the formula for centripetal acceleration this becomes:

$$\frac{v^2}{r} = \frac{\sum F_c}{m} \quad (2)$$

Gravitational force (F_g) is pointing into the circle and normal force (F_n) is pointing out of the circle. Using these gives:

$$\frac{v^2}{r} = \frac{F_g - F_n}{m} \quad (3)$$

Using $F_g = mg$ with $g = 9.81\ m/s^2$ and isolating the normal force results in:

$$F_n = mg - m\frac{v^2}{r} \quad (4)$$

When the normal force is less than the rider is used to, the rider experiences a feeling of weighing less at that moment (the same feeling as every child has experienced when using a swing). The faster the moving speed or the bigger the hill radius, the smaller is the normal force and the lower is the pressure of the board on the surface. This decreases the board-snow interaction and thereby the control. When the sit-snowboarder going over het hill is acting as a rigid body, the theory above applies. But when the COM is lowered, the radius is decreased and the normal force becomes bigger, resulting in a good board-surface interaction.

Speed control

Gravity causes the rider to accelerate while sliding down a slope. Speed can be reduced by friction of the board with the snow or by steering to a part of the hill without decline (or even incline) (Anastasiadis et al., 2012; McNab, 2005).

Making closed turns decreases the acceleration due to gravity. A closed turn is defined as a turn in which the snowboard starts and ends perpendicular to the fall line and switches edge (Figure 7). Halfway through a closed turn, the snowboard is headed towards the bottom of the slope (parallel to the fall line) which makes the snowboard and rider accelerate. When the closed turn is completed, the snowboard is rotated until it ends up perpendicular to the fall line. Now the snowboard is traversing horizontally over the slope, which means that the snowboard is moving over slope without any decline, and deceleration occurs. The slope change which comes with directional change is comparable with slope change due to hills on the slope. When deceleration is wanted, a rider can choose a path with inclined slope or steer such that the board is perpendicular to the fall line (or even going uphill).

Good control

Directional and speed control are closely related, so the performance evaluation of control in general is discussed in this paragraph.

Besides causing discomfort, WBV and shocks may also result in temporarily inability to control the sit-snowboard because the controlling movements of the body are interfered (Harris & Piersol, 2002) To prevent control interference, minimal vibrations and shocks on the seat are desired. Control interference may also occur when sudden or extreme seat rotations are present during the ride. The seat should have a continuous tilt angle or tilt slowly. When seat tilt is too far from horizontal or changing too fast, compensation with the body is required to maintain balance and control interference occurs.

For good control, it is important that the board applies pressure on the surface continuously. Better control will be achieved when vibrations of the board are reduced. Also obstacles like bumps, hills, pits and drops in the slope may cause parts of the board to lose contact with the surface. A change of mechanism design may allow the board to better follow the shape of the slope and decrease the (partial) loss of contact with the surface.

1.4 Goal and deliverables

The goal of this study is to design a sit-snowboard working mechanism for advanced users, such that it has sufficient performance regarding comfort and control when sliding over a bumpy slope. Two prototypes are produced to perform both quantitative and qualitative test. The quantitative test will be performed to evaluate if the prototype performs better than the Twinrider on a bumpy slope and to give insight in the different settings of the mechanism. A measurement protocol for quantitative evaluation of the sit-snowboard regarding comfort and control is designed. The qualitative test may validate the results from the quantitative test. The quantitative test and qualitative test together form a conclusion on the performance of the new design for advanced users regarding comfort and control. No calculations are done in this research to guarantee the structural durability of the construction.

2 Method and Materials

In this chapter, first it is explained how the new design has formed: What are elements of the current Twinrider design that are re-used and what alterations are made? Next, the experimental methods are explained for the evaluation of the new design.

Figure 8: Elements included in the current Twinrider design

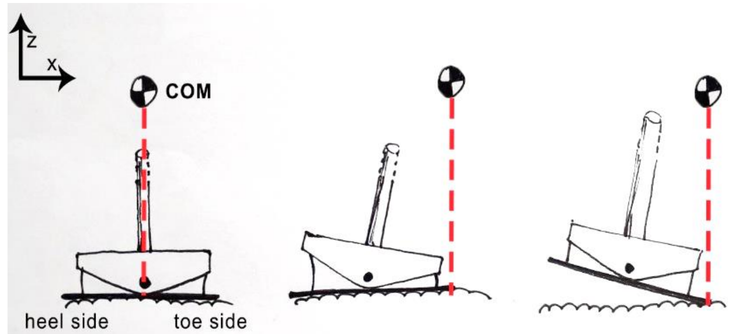

Figure 9: Working principle of the 'limiter'

2.1 Design

A new working mechanism of the sit-snowboard is developed for advanced users. The advanced sit-snowboard is called Snowcruiser.

2.1.1 Current design

Body weight support

The Twinrider contains a seat, kneepads and footrests to support the body weight of the rider (Figure 8). Using a 3 point pressure method, even paralyzed riders will be supported in the semi-sitting position. It is essential that this support is included in the final design as well, but for the mechanism design in this project, the design and locations of the seat, kneepads and footrests are not taken into account. The seat, kneepads and footrests from the Twinrider can be copied to the new design once the final design is finished. Connection methods should be determined taking into consideration the degrees of freedom in the mechanism.

Limiters

In order to tilt the board to one edge, the rider needs to shift the COM across the edge. To prevent falling over, balance can be maintained by minor COM shift above the edge. However, achieving enough heel/toe COM shift might require extreme body positions which might require too much muscle force (while leaning back) or are not possible to reach, due to limited range of motion (appendix II). Once enough COM shift is achieved, balance is hard to maintain because the exact positioning of the COM is critical. The COM will change a lot when the board is tilted due to the fact that the seat is rigidly connected at a distance of about 60 cm from the board. This amplified seat displacement will cause a COM which might cause loss of balance.

A sit-snowboard design can simplify edge shifting and balancing by supporting the COM shift with a mechanism that moves the seat in heel/toe direction. The current design, the Twinrider, has elements implemented at the bottom of the construction to allow tilting the seat in heel/toe direction. These elements are called ‘limiters’. A limiter consists of a hinging plate which is limited in range of motion by silicon rubber blocks below the plate on both heel and toe-side. This silicon rubber has exponential resistance, meaning that the further the COM is shifted, the more resistance is created. The increasing resistance gives the rider feedback on how far the COM is shifted. Once the COM is above the edge, the rider can use the handlebars to tilt the board. The board is tilting, but due to the hinges included in the limiters, the seat will stay at the same location (Figure 9). Also the limiters allow for torsion in the board because the tilting of the limiters is not coupled, so if one handlebar is pushed and at the other is pulled, torsion in the board occurs. The limiters have shown in practice to be functional for the Twinrider. The limiters define how the snowboard motion for the sit-snowboard works and feels. To maintain this same sit-snowboard basic control method, the limiters are also included in the Snowcruiser design.

Handlebars

The handlebars are rigidly connected to the snowboard and reach up to just above seat height. Riders holding the handlebars with their hands are in direct connection with the snowboard. Riders can keep their trunk in balance while holding the handlebars, but they can also use the handlebars to influence the tilting angle of the board and even apply torsion to the snowboard to initiate a turn. The handlebars are also essential for the final sit-snowboard product, but their design is not taken into account in this project.

2.1.2 Alternative design

Multiple concepts are formed using some brainstorm sessions. A selection of the most promising concepts is made together with Gina van der Werf according to the expected pros and cons of the concepts. A Harris Profile is a graphic representation of the strengths and weaknesses of design concepts that helps in making a decision on which concept to continue with (van Boeijen, Daalhuizen, van der Schoor, & Zijlstra, 2014). For the selected concepts, Harris Profiles were created to determine the most promising concept. The concept sketches and the corresponding Harris Profiles can be found in appendix III. Concept 'shortening legs' is selected for further development because it is the only concept meeting all the requirements together with a good score on all comfort and control criteria.

2.1.2.1 Mechanism changes

As the name of the concept shows, the mechanism has two shortening legs. A schematic drawing of the mechanism design is shown in Figure 10. The limiters are the red blocks at the bottom. Regarding to the Twinrider mechanism, two main alterations are made in the Snowcruiser mechanism design.

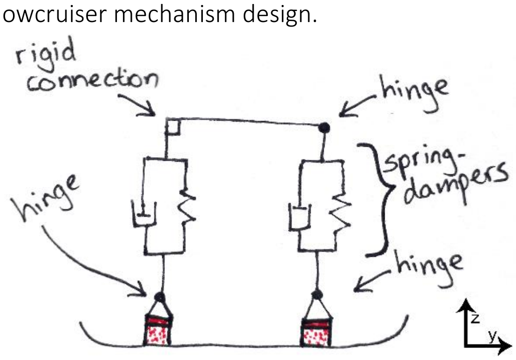

Figure 10: Schematic drawing of the mechanism design

Spring-dampers

To isolate vertical vibrations and shocks on the seat (and thereby also on the body), spring-dampers are added in the mechanism. The compression and extension of the springs isolate vibrations between the surface and seat. Damping causes the amplitude of free vibrations to decay, dissipating energy (Harris & Piersol, 2002).

Two mountain bike front forks are used as spring-dampers because they contain a spring and a damper which are expected to have appropriate characteristics and compression and extension is limited to a single degree of freedom in the up/down z-direction. COM shifting in x- and y-direction will not have any influence on the forks.

Hinges

A side view (yz-plane) of the mechanism can be illustrated in 2D as a box containing four bars and four connections (Figure 10). The bottom and upper bars are rigid (resp. the board and seat). The two vertical bars on the sides can be compressed and extended because forks are added there. In order to allow flexion in the board, the two bottom connections should be hinges. To allow independent fork compression, the top connections should be hinges as well. However, if all four corner joints of the construction are hinges, the construction is instable, and will collapse without any limitations. As solution to create a stable construction, the front top connection is chosen to be rigid. The other three connections are hinges with bearings rotating around the x-axis (in heel/toe direction). When compression of the front fork occurs, the rigid angle forces the seat to rotate and translate to the nose of the board. These linked motions mean that, besides in up/down direction, movements in nose/tail direction are regulated by the forks compressing and extending.

2.1.2.2 Functionality changes

The Snowcruiser mechanism design introduces four main functionality changes. A schematic drawing of a sit-snowboard going up a hill is shown in Figure 11. The green sketch represents the Snowcruiser design and the black sketch is the rigid Twinrider. It can be seen that the Twinrider does not allow board flex and thereby the middle of the board is not in touch with the surface. The Snowcruiser allows board flexion and when the nose of the board is raised due to a hill, the leading fork will compress, resulting in rotation of the seat with respect to the board (to keep the tilt minimal) and horizontal translation of the seat. The functionality changes are further described in this section. The final design is shown in Figure 12.

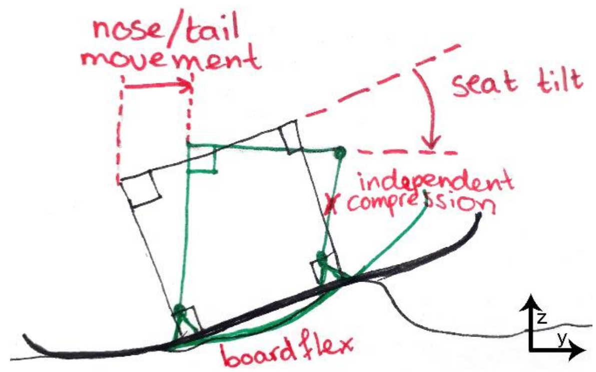

Figure 11: Schematic drawing of the functionalities of the Snowcruiser. Twinrider is shown in black, Snowcruiser is shown in green.

Board flexion

The Twinrider does not allow flexion in the board around the x-axis between the two connection points of the rigid construction with the board. Allowing flexion in the board around the x-axis, allows the board to better follow curved surfaces, improving the control through better board-surface interaction.

Seat movement up and down

Most vibrations occurring to the sit-snowboard will be in vertical direction. A degree of freedom in the mechanism in this direction might isolate these vibrations between the board and seat and decrease the vibrations on the seat (Griffin, 1996), thereby improving the vibrational and visional comfort for the rider and preventing control interference.

Independent compression and extension

As described in chapter 1.3.1, COM motion in up/down direction is actively used for control in snowboarding. According to the Austrian method of snowboard teaching, the COM is moved up and down by extending and bending both legs at the same time and the Canadian method teaches to use separate foot action (van der Werf, 2018). To stimulate improved board-surface interaction, it is chosen to focus on the Canadian method. To mimic standing snowboarding with two independent legs, independent nose and tail compression and extension is implemented in the mechanism.

Due to the independent compression and extension, seat rotation with respect to the board is possible. Visional discomfort and control interference are minimized when the seat is kept still. It is expected that when a bump is passed, the Twinrider shows respectively backward and forward seat tilting but the Snowcruiser models are able to keep the seat horizontal thanks to the independent compression and extension of the forks.

Movement of seat in nose/tail direction

COM shift in nose/tail direction is not essential for making turns, but when movement of the seat in nose/tail direction is also allowed in the mechanism, it would more closely mimic the standing snowboarding motion. It might also decrease horizontal accelerations on the seat and thereby decrease WBV. Imagine a snowboard to be abruptly decelerated by bumping into a big hill. The COM will continue moving due to inertia. When no degree of freedom in nose/tail direction is allowed, the COM is forced to brake in a very short distance, leading to very high decelerations which might lead to discomfort or loss of control. Allowing translation of the seat in nose/tail direction will elongate the braking distance of the COM, reducing the decelerations leading to discomfort and loss of control.

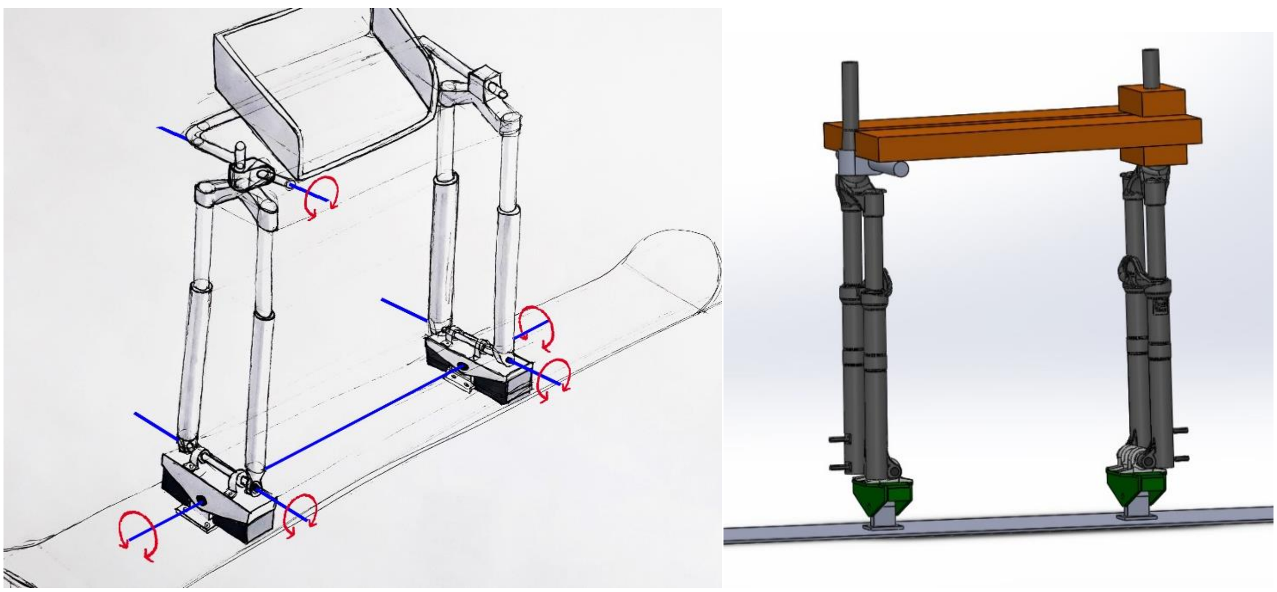

Figure 12: Final design. Left: Sketch. Right: Digital drawing

2.1.3 Prototypes

Enduro mountain bike forks are ready to use spring-dampers with guided straight movements. There are two main types: air spring or coil spring. Coil springs are best to use for the sit-snowboard because the behavior of coil springs is not influenced by altitude, temperature or humidity and coil springs have consistent compliance. An overview of the pros and cons of these types are shown in appendix IV.

The quantitative test will consist of a straight descend over a bumpy slope and the qualitative test will be performed by riders actually using the sit-snowboard. For the quantitative test no movement in heel/toe direction is desired, therefore the heel/toe movement is eliminated using wooden blocks instead of silicon rubber blocks in the limiters. A platform is created as connection between the legs to be able to fixate a dummy weight on top. The same is done for the Twinrider model, such that the same dummy mass can be fixated above the center of the board. The footrests and kneepads are not connected to the prototypes. The prototypes used during the qualitative test are shown in Figure 13. For the qualitative test, the prototype should be ready to be used by a person sitting in the sit-snowboard. A seat, kneepads and footrests are added to the prototype (Figure 14).

Figure 13: Prototypes for quantitative test. Left: Snowcruiser. Right: Twinrider loaded with dummy weight.

Figure 14: Prototype for qualitative test

2.2 Evaluation

2.2.1 Model versus experimental research

An advisory report is written by a student Human Kinetic Technology on the optimal characteristics for a sit-snowboard with suspension (Idzerda, 2017). While he states his research question is whether or not the settings and design of shock absorbers for the Twinrider can be determined by measuring a human on a normal snowboard, he does not support his assumption that this is possible with any reasons or prove. Idzerda (2017) translates the behavior of two people snowboarding over a hill into characteristics of the human legs with a simple passive, single degree of freedom, one-body, mass spring damper (MSD) model. This model is not validated using experimental observations.

It is expected that the model is simplified too much to model a complex movement of snowboarding over a hill. The simplicity of using MSD models instead of musculoskeletal models to model biomechanical behavior comes at the cost of accuracy (Nikooyan & Zadpoor, 2011). The biomechanical behavior of the legs is actively controlled by the muscles, regulated by the central nervous system, which a passive MSD model does not take into account. Also the accuracy of a model increases when multiple dimensions are added or when multiple bodies are included. The model by Idzerda (2017) only has one body and dimension.

The development of active MSD models is complicated. Making an accurate, active model and calculating the desired mechanical characteristics for snowboarding over hills is therefore a very difficult and time consuming process, which will probably take years.
For this project, a quantitative test and a qualitative test are conducted to analyze the effectivity of the alterations in the design. The methods of these evaluations will be further explained in the next sections.

2.2.2 Quantitative test

This chapter will explain in detail the methodology of the quantitative test. The objective of the quantitative test is to determine whether the new design (Snowcruiser) has improved performance regarding control and comfort with respect to the control design (Twinrider) and to give insight on the performance of the different suspension characteristics.

2.2.2.1 Experimental set-up

Because it is unknown how the mechanism will react on riding over bumpy terrain, a dummy weight is used during the quantitative test to avoid bringing people into danger. The prototypes to test are each loaded with three sandbags weighing 75 kg in total. The mechanisms are fixated to snowboards with length 165 for the Twinrider and 155 cm for the Snowcruiser.

The experiment is conducted on an artificial slope which is not changing shape over time. The part of the slope used has five hills and a sudden drop. Moist decreases the friction of the slopes, so the weather conditions should be the same for all tests. High speed cameras are placed next to two important obstacles, giving a side view (yz-plane) from an external, fixed reference frame. The important obstacles are the highest hill and a sudden drop. An illustration of the slope section and the placement of the cameras is shown in Figure 15.

A descent is guided by a skier behind the model, holding the back handlebar. The skier is given instructions to balance the model and guide a straight descent (no turns) without influencing the model's speed (pushing or breaking). The skier has a weight of 85 kg and is the same person for all measurements. At the top of the slope the sensors are activated. Then the skier guides the model to the starting location and breaks to stand still at the start. To start the measurement, the skier stops breaking and the skier and model starts sliding down.

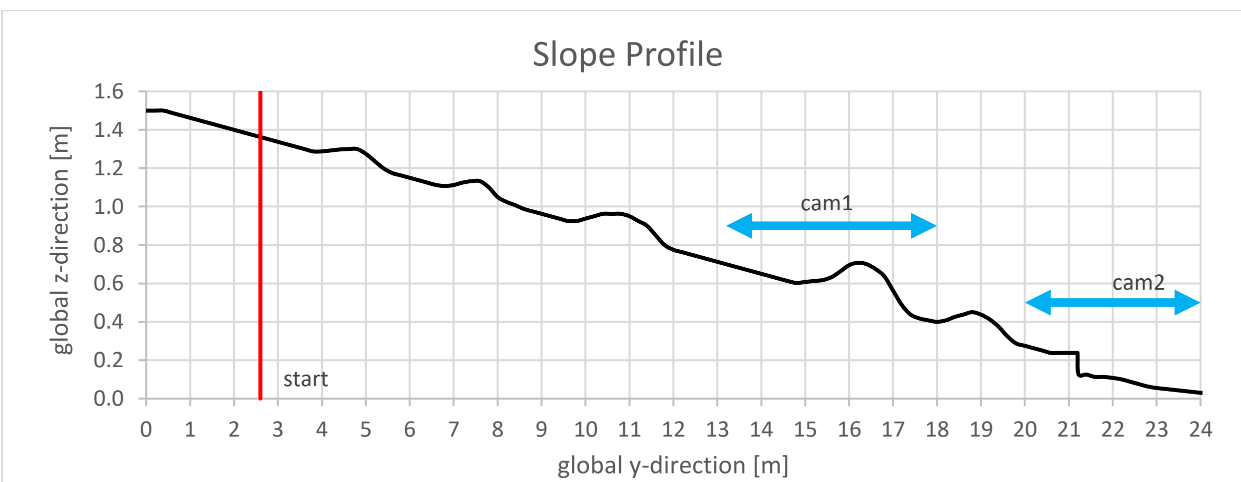

Figure 15: Section of the slope profile during the qualitative test.

Independent variables

Independent variables during this test are the slope profile, initial speed, weight, path of descend and mechanism model (Table 1). The mechanism model is the only variable to be changed, while the other independent variables are kept constant. The model options consist of the Twinrider as control model and the Snowcruiser as testing model.

Table 1: Independent variables during the quantitative test.

Variable	Constant/varied	Control options
Slope profile	Constant	Artificial slope with hills.
Initial speed	Constant	Starting at the same position on the slope from stance.
Weight	Constant	75 kg added weight.
Path of descend	Constant	Straight descend by slight steering.
Mechanism model	Varied	• Twinrider (control, without suspension) or Snowcruiser (with suspension) • Compression set to maximum and minimum. • Rebound speed set to maximum (fastest) and minimum (slowest) • Height set to 530 mm or 500 mm

The forks of the Snowcruiser can be tuned by changing three settings: compression, rebound and height. It is unknown what behavior the prototypes will show with the different settings of the forks. Also, no absolute values of the ranges of the settings are known. To be sure to include a big range of characteristics, the maxima of the three setting options are combined into testing conditions. In this research, the two forks are set to have identical characteristics.

- The forks have a 'dual position' option, which means that the spring can be set at two heights. The amount of maximum travel depends on the fork height. At maximum height, the forks are 530mm and the maximum travel is 150mm. At shortened height, the forks are 500mm and the maximum travel is 120mm.
- Compression can be set to be more or less with five steps. With maximum compression, less force is needed to compress the fork (the damping coefficient in Ns/m is lower).
- Rebound is the extension of the fork after compression. Rebound speed can be set to fast or slow with 22 steps.

In total eight combinations of settings exist. All testing conditions are shown in Table 2. Testing conditions are coded respectively by the compression, rebound an height values. For example, testing condition one is called 'maxfast500' because this condition has maximum compression, fast rebound and a height of 500mm. Every testing condition is executed two, three or four times.

Table 2: Experimental design matrix with testing conditions for the Snowcruiser based on different settings. A grey field marked with a X selects an option.

	Compression		Rebound		Length		Code
	Min	Max	Slow	Fast	500	530	
1	X		X		X		minslow500
2		X	X		X		maxslow500
3	X			X	X		minfast500
4		X		X	X		maxfast500
5	X		X			X	minslow530
6		X	X			X	maxslow530
7	X			X		X	minfast530
8		X		X		X	maxfast530

Dependent variables

In chapter 1.3 is explained how good performance regarding comfort and control can be achieved. The dependent variables used to determine the performance are:

- Comfort
  - Accelerations of seat: Vibrations and shocks can be measured using accelerations. Accelerations of the seat are an indication for the amount of whole body vibration and shocks experienced by the rider. WBV and shocks may cause vibrational discomfort.
  - S.E.A.T.: Seat Effective Amplitude Transmissibility (S.E.A.T.) can be used to indicate the efficiency of vibration isolation.
  - Seat tilting: A constant seat tilting position prevents visional discomfort. Seat tilting is defined as the angle in the yz-plane between the seat and the global horizontal expressed in degrees.
- Control
  - Accelerations of seat: Vibrations and shocks can be measured using accelerations. Accelerations of the seat are an indication for the amount of whole body vibration and shocks experienced by the rider which might cause control interference.
  - Seat tilting: A constant seat tilting position prevents control interference.
  - Contactless distance: While passing a hill or drop, the nose of the board is contactless for a while. Measuring this distance is an indication for the board-surface interaction performance.
  - Accelerations of board: Less accelerations on the board indicate good board-surface interaction which improves control.

These dependent variables will be clustered in variable groups in the continuation of this chapter and in the results chapter: The variable groups are: Accelerations, contactless distance and seat tilt.

2.2.2.2 Data acquisition

- Angular and linear accelerations on the seat and board are measured in three directions with four accelerometers (x-IMU sensors from IO-technologies). To obtain the accelerations at the bottom of the mechanism, two accelerometers are fixated on the top surface of the snowboard. They are located on the middle part of the snowboard, close to the limiters, to avoid measuring flapping of the nose or tail of the board. Sensors on the board are numbered as sensors 1 and 2. To obtain the accelerations at the seat, two other accelerometers are fixated to the bottom of the wooden seat construction. These are numbered as sensors 5 and 7. The x-IMU sensors give calibrated linear accelerations in *g*, angular velocities in *deg/s*, and 3x3 rotation matrices as output.
- Contactless distance is measured for the two most important instances during the run. High speed cameras are placed next to these two obstacles, recording with 120 frames per second. Video analysis is done using the program Kinovea. The frame is selected in which the nose of the board touches the surface again after the obstacle. For the contactless distance after the big hill, the contactless distance is defined as the distance from the nose of the snowboard which touches the surface to a certain cone on top of the hill. It is measured in cm, and called 'dist1'. For the contactless distance after the sudden drop, the distance between the nose of the board and a recognizable location on the slope is measured. This is called 'dist2' and is also measured in cm. Two example screenshots are shown in Figure 16.

Figure 16: Measurement of contactless distances after hill (left) and sudden drop (right). Screenshots from 'minslow500 run 1'.

- Seat tilting position is defined at several moments while crossing the two important obstacles. This is done analyzing the video footage with the program Kinovea. For the big hill, four locations and a certain moment in time are used. The four locations at which the seat rotation is defined are shown in Figure 17. The fifth measuring moment is the instant the nose of the board is pushed onto the surface again after losing contact with the surface. For the sudden drop 3 locations are used. These locations include a location just before, just after and far after the drop. The exact locations can be found in appendix V.

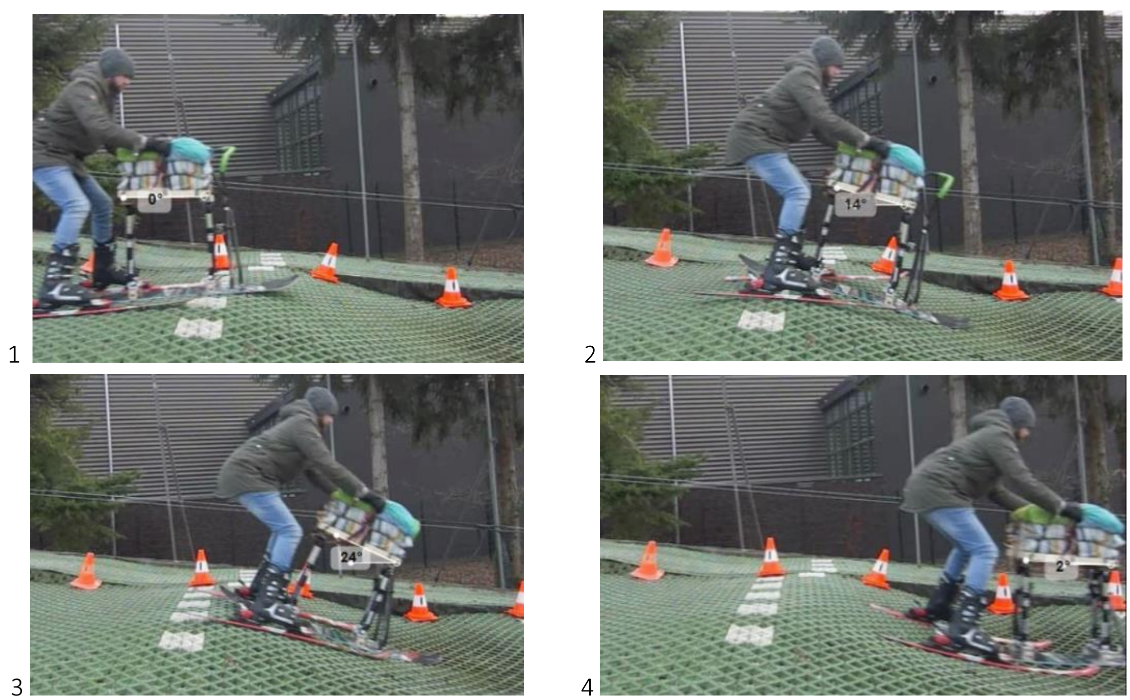

Figure 17: Measurement of seat tilt at 4 locations when passing the hill. Screenshots from 'maxfast500 run1'.

2.2.2.3 Data processing

No further data processing is needed for the contactless distance and seat tilt values after acquisition.

The accelerations are transformed into a single value that gives information on the vibration magnitude. This measure is called the Vibration Dose Value (VDV). This section discusses why VDV is chosen, how it is calculated and interpreted.

Measures

Crest factor (CF) is a number to describe the amount and magnitude of peaks in the acceleration data (Griffin, 1996). The CF is the ratio of the absolute peak weighted acceleration $(a_{w,peak})$ to weighted root mean square (r.m.s.) acceleration $a_{w,rms}$.

$$CF = \frac{|a_{w,peak}|}{a_{w,rms}} \quad (5)$$

A CF of 1 indicates a flat signal without any peaks. The CF will be high if shocks are included in the measurement period (increasing the peak value) or if a lot of low accelerations are included in the measurement period (low r.m.s.).

For vibrations with low CF, the r.m.s. is a useful measure to describe the vibrations severity. However, the r.m.s. does not deal with non-stationary vibrations, shocks or transient vibrations (Figure 18), because the period of time over which r.m.s. is determined affects the magnitude (Griffin, 1996).

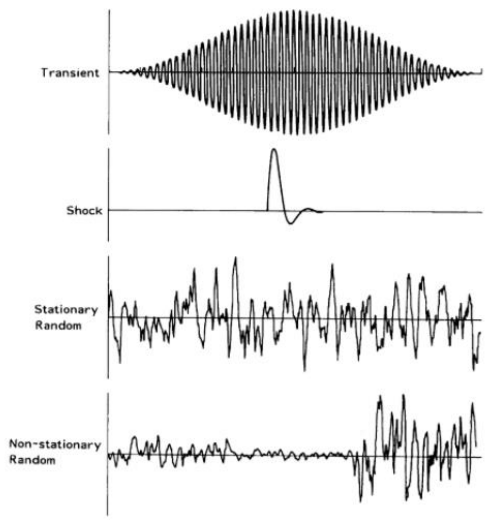

Figure 18: Examples of waveforms of different types of oscillatory motion.(Retrieved from Griffin, 1996)

When the crest factor is high, the human response is mainly determined by the peak values. The VDV is developed as a measure that gives a better indication of the risks from vibrations that include shocks. The VDV provides a single-number dose value which presents the cumulative effect of the vibration over time using a fourth power. Root mean quad (r.m.q.) is an alternative fourth power method, but the VDV offers a more robust method of assessing the severity of vibrations including shocks (Griffin, 1996). The VDV is the r.m.q. value multiplied by the fourth root of the duration. “The r.m.q. value is intended for the comparison of motions which contain high peak values but can only be quantified over a fixed period of time.” (Griffin, 1996). Maximum Transient Vibration Value (MTVV)(Spång & Arnberg, 1990: cited in Stayner, 2001) is another value that can be used, but MTVV is dominated by the magnitude of the most intense event, while VDV integrates the contribution from each transient event to form a time and magnitude dependent dose (Griffin, 1998; Harris & Piersol, 2002). An alternative measure of vibration exposure, which does not rely on frequency weightings, is absorbed power (S_{ed}), but this is very hard to measure in the field (Mansfield, Holmlund, & Lundström, 2000). It is applicable for vibrations that contain mainly shocks.

Sliding over bumpy slopes creates non-stationary vibrations, shocks and transient events. The VDV is used as a measure for acceleration severity, because it is a robust measure for all types of vibrations including shocks.

Standards

Several standards are available to evaluate the human response to WBV. These standards are based on subjective tests to determine comfort level and on research about health problems being caused by WBV. Accelerations are weighted according to their direction and frequency before parameters are calculated to assess the severity of the vibrations and shocks. The methods of weighting and assessment differ between standards. The most common standard to assess seated human exposed to WBV are ISO 2631-1 or the recently published ISO 2631-5 (International Organization for Standardization, 1997, 2004) and BS 6841 (British Standards Institution, 1987). Table 3 gives an overview of standards to assess WBV severity (Stayner, 2001).

Table 3: Standards for assessment of WBV.

Standard	Year	Name	Method
BS6841	1987	Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.	CF<6: r.m.s. CF>6: VDV
ISO2631-1	1997	Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 1: General requirements	CF<9: r.m.s. CF>9: MTVV or VDV
ISO2631-5	2004	Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 5: Method for evaluation of vibration containing multiple shocks.	S_{ed} (daily equivalent static compression dose)

ISO 2631-1 states that above a CF of 9, MTVV or VDV should be used, but no guidance is given on the decision between these two measures. The standard BS 6841 takes away the confusion of choosing between the MTVV and VDV (Griffin, 1998; Mansfield et al., 2000). Also Griffin (1998) argues that the maximum CF of 9 to use r.m.s. is too high. BS 6841 states that above a CF of 6, one should use VDV to assess the comfort. ISO2631-5 is a rather new standard to assess the effects of WBV and shock which is based on the biomechanical response of the lumbar spine, rather than subjective evaluations (Alem, 2005; Cvetanović, 2013; Park, Fukuda, Kim, & Maeda, 2013). Only few extensive epidemiological studies have been carried out to determine the acceptable exposure action and limit values for this new standard (Aye, 2010). ISO2631-5 is based on health effect only, and not on subjective comfort evaluations, which is a very important aspect in this research. The method of VDV proposed in BS6841 is recommended as the most appropriate for assessment of discomfort from continuous vibration with repeated shocks when comparing it with ISO2631-1 (Mansfield et al., 2000). This method for evaluating comfort regarding WBV described in BS6841 is mainly used in automobile industry, but it is also been used in the sit-ski performance evaluation research that is conducted (Cavacece et al., 2005; Cho, Park, Kim, Mun, & Kim, 2015). BS6841 is applicable to the evaluation of all types of vibrations, including non-stationary random vibrations and transient vibrations or shocks.

The standard BS6841 is used to evaluate the vibrations on the seat. This method is also used for the accelerations of the board to give an indication of the amount of vibrations on the board given as a dose value and to be able to compare the vibrations between the board and the seat.

Calculation and interpretation

The accelerations over time are measured with a sample frequency of 256 Hz. In accordance with BS6841, weighting is applied to the accelerations depending on frequency and direction (Griffin, 1996) (appendix VI). To apply this weighting, the data is converted to frequency domain using the fast Fourier transform. After weighting, the inverse fast Fourier transform is applied to get the frequency weighted time history of the accelerations.

VDV is defined as:

$$VDV = \sqrt[4]{\int_0^T a_w^4(t)dt} \qquad (m/s^{1.75}) \tag{6}$$

where $a_w^4(t)$ is the frequency-weighted acceleration at time t in m/s^2 and T is the exposure time in seconds. The unit of VDV is $m/s^{1.75}$.

The VDV is calculated for the accelerations in each direction (3 linear and 3 angular directions). These six directional VDV's are combined into one VDV using:

$$VDV_{total} = \sqrt[4]{\sum VDV^4} \tag{7}$$

High VDV will cause severe discomfort, pain and injury, so a low VDV is desired (Griffin, 2004) "The 'maximum safe exposure' is set as a VDV value equal to $15\ m/s^{1.75}$. Above this limit a further expose to vibration will be accompanied by an increased risk of injury." (Griffin, 1996).

To calculate the effectivity of isolating vibrations with the mechanism between the board and the seat, the vibration measures at the board and the seat are compared. The seat effective amplitude transmissibility (S.E.A.T.) is a measure to express this vibration isolation efficiency. It is defined as the ratio between the VDV on the seat and the VDV on the floor, which is the board in this case (Equation 8) (Griffin, 1996). The lower the S.E.A.T., the better the vibrations are isolated, resulting in a more comfortable descent. The S.E.A.T. values of the Snowcruiser models with different settings give insight in the shock absorbing performance of the suspension mechanism incorporated in the Snowcruiser models.

$$S.E.A.T.[\%] = \frac{VDV_{seat}}{VDV_{board}} * 100 \tag{8}$$

2.2.2.4 Hypotheses

The following is hypothesized regarding the dependent variables:

- Accelerations
  - VDV for the seat will be lower for the Snowcruiser than for the Twinrider.
  - VDV for the board will be lower for the Snowcruiser than for the Twinrider.
  - The S.E.A.T. will be lower for Snowcruiser models than for the rigid Twinrider.
- Contactless distance
  - Contactless distance will be lower for the Snowcruiser than for the Twinrider.
- Seat tilt
  - The Snowcruiser will be able to keep the seat horizontal for small bumps: No seat tilt will occur.
  - After a big hill is passed, Snowcruiser models will show more seat tilting than the Twinrider.

2.2.3 Qualitative test

The objective of the qualitative test is to subjectively assess the comfort and control for the Snowcruiser. The results of this qualitative test will be used to validate the results of the quantitative test.

The prototype with seat, kneepads and footrests is tested in an indoor snow slope (De Uithof, Den Haag) by two riders. During the test, the Snowcruiser is set to a height of 500 mm, maximum compression and fast rebound. The Twinrider model is also used during the test in order to compare the two models. Several hills were passed while making a turn by both riders using both prototypes. Video footage is recorded when obstacles are traversed. Opinions of the riders were documented after the testing day.

3 Results

3.1 Quantitative test

In total 21 runs were executed with the Snowcruiser and two with the Twinrider. Due to sensor errors, five runs have missing acceleration data. The sensor errors were caused by a bad connection of the SD card in the accelerometer, not being able to store the data for some random measurements. Data between the two sensors on the board (1 and 2) and between the two sensors on the seat (5 and 7) is averaged. The only sensor giving errors is sensor 5, so the VDV can still be calculated for the board and the seat for all runs.

Accelerations

All crest factors can be found in appendix VII. The mean crest factors for accelerations are bigger than 6 (15.7 for the Snowcruiser and 6.7 for the Twinrider), so the method of working with VDV is applicable. The crest factor for the Twinrider is lower than expected due to limited range of sensors (see chapter 4.1.1).

All VDVs and S.E.A.T.s can be found in Table 4. The VDV's are averaged for the board and the seat, resulting in two VDV's for each run: one for the board and one for the seat. These are shown in Figure 19. Figure 20 shows the S.E.A.T. values for each run. Figure 21 shows the average S.E.A.T. values per run with the corresponding error bars.

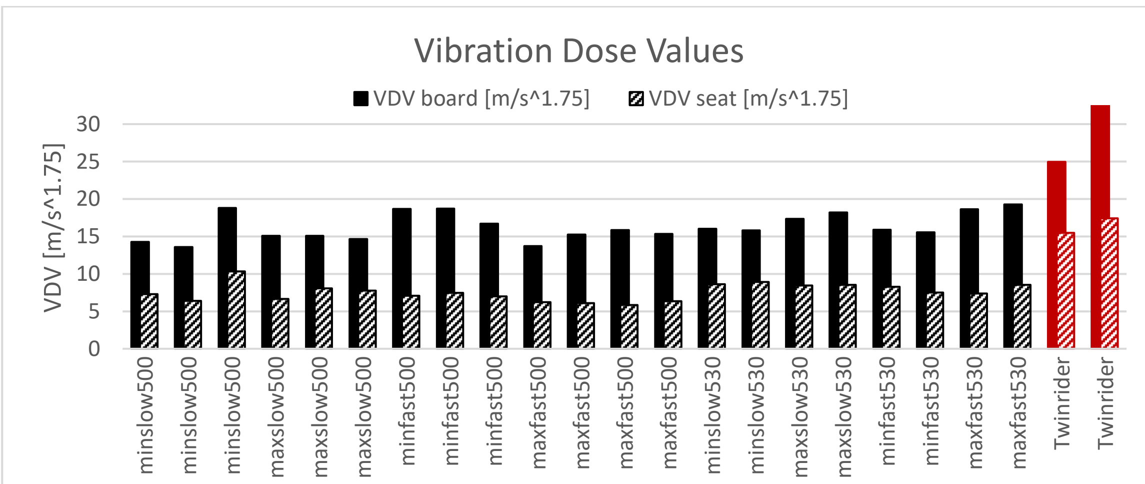

Figure 19: Vibration Dose Values of all runs.

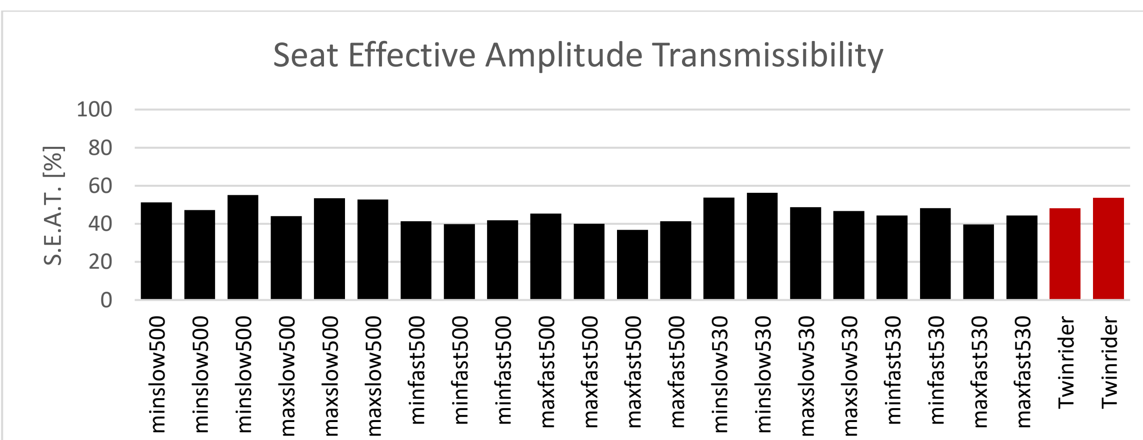

Figure 20: Seat Effective Amplitude Transmissibility values of all runs.

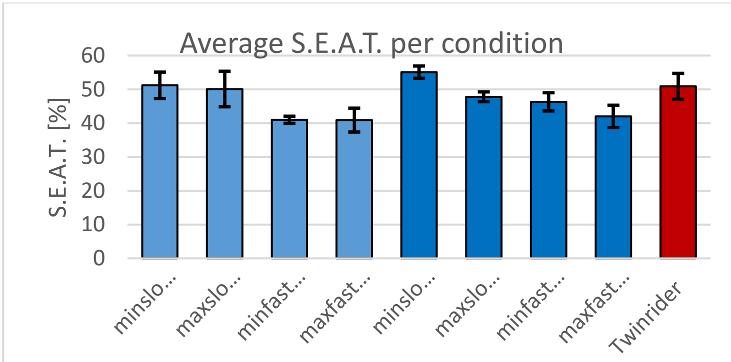

Figure 21: Seat Effective Amplitude Transmissibility averaged per condition.

Contactless distance

All contactless distances per run are shown in Table 4. Four runs are excluded in further analysis because the snowboard was located further away from the camera than in the other recordings, leading to a different perspective: minslow500 run3, maxfast500 run3, minslow530 run2 and maxfast530 run2. More information about this perspective difference can be found in chapter 4.1.1.

Seat tilt

The seat tilts for all runs are shown in Table 4. The first five columns under the heading 'seat tilt' are measured at the passing of the hill. The last three columns are measured at the sudden drop.

Table 4: Overview of results of all variables.

Con-dition	Code	ACCELERATIONS			CONTACTLESS DISTANCE [cm]		SEAT TILT [degrees]							
		VDV board [m/s^1.75]	VDV seat [m/s^1.75]	S.E.A.T. [%]	hill	drop	h1	h2	h3	h4	land	d1	d2	d3
1	minslow500	14.3	7.3	51.3	117.2	200.8	0	21	23	2	21	5	12	13
	minslow500	13.6	6.4	47.2	115.1	210	1	20	23	5	20	5	12	12
	minslow500	18.8	10.4	55.0	~~122.8~~	~~247.7~~	0	15	23	0	20	6	14	14
2	maxslow500	15.1	6.7	44.0	121.4	203.4	1	16	24	0	16	7	13	14
	maxslow500	15.1	8.1	53.4	116.5	206.2	1	22	25	1	19	6	12	12
	maxslow500	14.7	7.7	52.8	117.2	202.5	0	21	24	3	21	5	12	13
3	minfast500	18.7	7.1	41.4	117.1	208.1	0	20	24	0	20	6	15	14
	minfast500	18.7	7.5	39.8	116.4	206.2	1	22	23	1	20	6	12	12
	minfast500	16.7	7.0	41.8	117.1	204.4	1	23	23	0	21	6	14	13
4	maxfast500	13.7	6.2	45.4	123.1	227.9	0	14	24	2	14	5	15	8
	maxfast500	15.3	6.1	39.9	124.2	210.9	0	14	27	3	16	4	16	8
	maxfast500	15.9	5.8	36.8	~~119.3~~	~~215.7~~	2	16	25	0	17	5	15	8
	maxfast500	15.3	6.3	41.4	124.3	215.7	2	17	26	0	17	6	15	8
5	minslow530	16.0	8.6	53.8	129.1	234.5	2	16	26	7	23	6	15	14
	minslow530	15.8	8.9	56.3	~~118.7~~	~~224.1~~	2	18	25	6	21	6	14	15
6	maxslow530	17.3	8.5	48.8	125.4	232.6	3	20	27	7	22	7	17	16
	maxslow530	18.2	8.5	46.8	126.8	231.7	2	17	27	5	22	6	15	16
7	minfast530	15.9	8.3	44.4	142.1	231.7	3	15	24	7	18	6	14	13
	minfast530	15.6	7.5	48.2	145.8	235.4	5	16	24	8	22	6	15	14
8	maxfast530	18.6	7.4	39.7	136.3	217.5	3	14	25	9	17	5	16	13
	maxfast530	19.3	8.5	44.4	~~126.1~~	~~210.9~~	6	16	27	3	18	5	17	12
9	Twinrider	25.0	15.5	48.2	158.6	225.1	-3	12	18	1	18	0	5	7
	Twinrider	32.5	17.4	53.6	147.6	215.5	-4	11	15	2	16	0	7	8

3.2 Qualitative test

An overview of the reactions of the subjects after the subjective test can be found in appendix VIII.

It has shown that going over hills with the Snowcruiser while leaning on the heel side edge is easier with the Snowcruiser. The advanced rider (Gina van der Werf) has done three unsuccessful tries with the Twinrider of going over two consecutive high hills while leaning on the heel side edge. With the Snowcruiser it was possible to pass the hills without falling!

Also it was experienced by the riders that their trunk makes less sudden movements with the Snowcruiser model at the top of a hill. With the Twinrider a big and fast rotation of the riders trunk was experienced, but the seat rotates slower with the Snowcruiser and the riders were able to keep their trunk vertical.

With the Twinrider, a shock was felt after passing the hill and with the Snowcruiser this shock was absent.

Board flexion for the Twinrider has shown to be limited and the Snowcruiser has shown to allow much more flexion in the board (Figure 22). The flexion in a pit of the Snowcruiser was limited because the handlebars collided with the seating construction. For the Twinrider, this collision also occurred, but just slightly: Not the collision with the handlebars, but the rigid construction was limiting the flexion for the Twinrider.

Figure 22: Board flexion is bigger for the Snowcruiser(left) than for the Twinrider (right).

4 Discussion

4.1 Limitations

4.1.1 Quantitative test

Amount of data

No statistical analysis has been performed since not enough data is gathered. Each testing condition only had two, three or four repetitions leading to a total of 21 runs of which five do not contain data from all four sensors. Nevertheless, the experimental results give a lot of information on the Snowcruiser performances.

Speed not constant

It is desired that the riding speeds are the same for all runs. This is attempted by starting with an initial speed of zero, starting at the same position on the slope and having the same weight sliding down the slope. To check whether the speeds were really the same for all runs, the speed is measured using video footage at the two important obstacles: The hill and the sudden drop. The amount of milliseconds to cross a known distance is measured and the speed is calculated in km/h. The speed per run is shown in Table 5 for both obstacles named speed1 and speed2. Also the average speed per run is shown. The results in this table are sorted chronically. The speed is not the same for all runs, but varying between 3.2 km/h and 5.4 km/h. This may be caused by the fact that moist on the slope has changed during the progress of the test. Another big influence on speed differences is the lubrication on the mat on the top of the slope. Unfortunately, new oil was poured on the mat by the owner of the ski slope halfway the test (before 500minslow run 3). This moment can be clearly seen in the table: All speeds increased after this moment. The assumption that speeds are the same for all runs is incorrect.

Table 5: Riding speed per run sorted chronically.

Condition	Run	Speed1 [km/h]	Speed2 [km/h]	Av. speed [km/h]
maxfast500	1	3.2	4.4	3.8
	2	3.2	4.4	3.8
	3	3.0	4.1	3.6
	4	3.0	4.2	3.6
minfast500	1	2.9	3.9	3.4
	2	2.7	3.8	3.2
	3	2.7	3.7	3.2
maxslow500	1	3.0	3.7	3.3
	2	2.8	3.8	3.3
	3	2.8	3.9	3.4
minslow500	1	2.9	3.9	3.4
	2	3.0	4.0	3.5
	3	3.7	5.0	4.4
minslow530	1	4.2	5.1	4.6
	2	3.9	4.8	4.3
maxslow530	1	3.7	4.8	4.2
	2	4.0	4.9	4.4
maxfast530	1	4.0	5.1	4.6
	2	3.6	4.8	4.2
minfast530	1	4.7	5.1	4.9
	2	5.1	5.0	5.1
Twinrider	1	5.3	5.4	5.4
	2	4.8	5.1	5.0

It is not known whether different behaviors for the different conditions is due to different moving speeds, or the different moving speeds are a result from the different model settings. The influence of speed on the variables is investigated in the results part of the discussion. Variables that do not depend on riding speeds will give an insight in the influence of the different suspension settings on this variable. For the variables which are depending on moving speed, the results should be analyzed with more care, and maybe further research is required to investigate the influence of speed and different settings on these variables.

Data acquisition

Accelerometers

The accelerometers that were available for the quantitative test have a range of ±8g. During the measurements, accelerations were outside this range, which can be seen from the many peaks at ±8g in the raw data in Figure 23 and Figure 24. It seems that these peaks were limited by the range of the sensor. For sensor 5 at the Snowcruiser, the accelerations do not reach this maximum of ±8g, but at sensor 5 for the Twinrider measurement, the accelerations still reach the maximum values. When looking at the VDV results in Figure 19 it is suspected that the range of the accelerometers corresponds with a VDV of about 15 m/s^1.75. When the range of the sensors would have been bigger, the VDVs on the board for the Snowcruiser, and on the board and seat for the Twinrider would probably be higher. This should be kept in mind when comparisons are made during further research. For this research, results can still be used, because accelerations on the seat with the Snowcruiser do not reach the max.

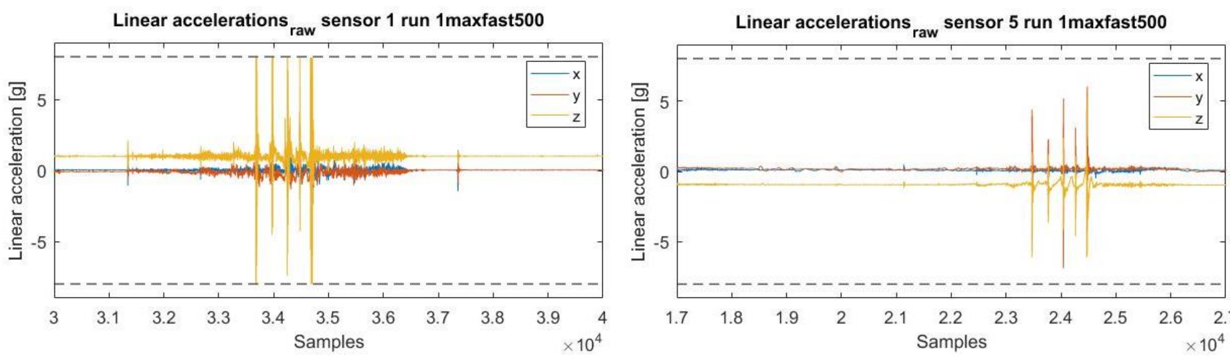

Figure 23: Raw linear accelerations of sensors 1 (left) and 5 (right) during a run with the Snowcruiser. In the left graph it can be seen that the sensor reaches the maxima of ±8g.

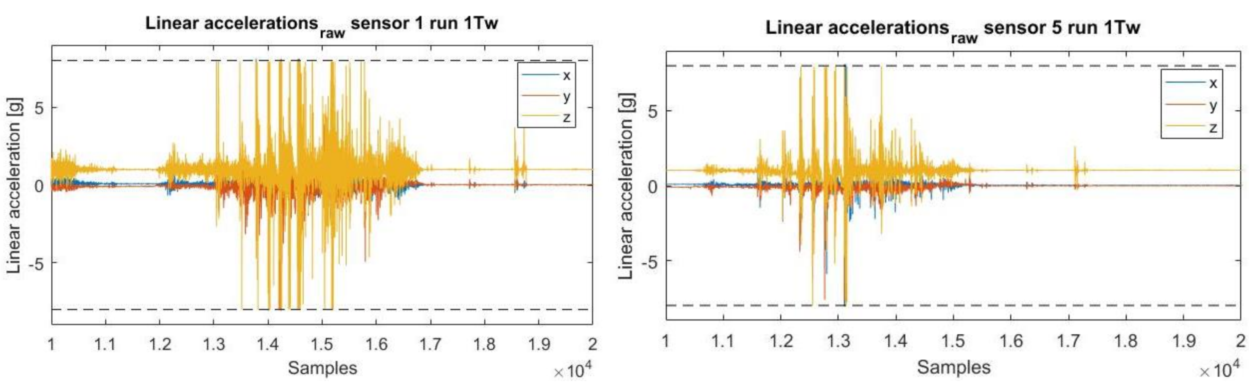

Figure 24:Raw linear accelerations of sensors 1 (left) and 5 (right) during a run with the Twinrider. Both sensors reach the maximum of ±8g.

The accelerometers measure with a very high sample frequency (256 Hz). If the maximum occurring frequency is higher than half the sampling frequency (Nyquist frequency), aliasing might occur (Schouten, 2010). This means that an error is introduced during analog to digital conversion, because the sample frequency is not high enough. To prevent aliasing, the sample frequency should be at least 2.5 times the cut off frequency or an anti-aliasing filter can be applied before digitizing. There is no cure to get rid of the aliasing error once it is introduced in the signal. I used the highest possible sampling frequency that is supported by the sensors available to minimize the risk of aliasing (higher sampling frequency gave an SD card error).

<u>Cameras</u>
The measurement distance is about 22 m from the starting point. This big distance makes it hard to capture everything on camera. It is chosen to use two cameras, placed perpendicular to the travelling direction at two important obstacles. To capture the whole obstacles, the cameras still needed to be placed pretty far from the actual object without zooming in. This causes distortion.

The path of the rider was not fixed, making it possible to pass the cameras at different distances. Sideways movements may have influenced the results because of different perspectives. Chapter 0 describes that runs are excluded for the variable 'contactless distance' because of the different perspective.

The resolution from the high speed cameras is not very high. The fact that measurements were done outside did not improve the quality of the videos because of limited light. The quality could have been improved if a lower frame rate is chosen, but then the movements were too fast to capture without blur. The limited video quality causes the variables gathered from video footage to be less reliable.

Because of the highly dynamic movement, it is very hard to quantify all interesting behavior from video footage. Visually a lot of interesting behavior can be detected, but it is hard to capture this behavior in certain parameters at certain moments in time. For instance, at the bottom of the slope it could be observed that some models lacked the inability to extend the front fork such that the seat became horizontal again; their resting seat position was still tilted. The seat tilt measurements do not tell which models lacked the capability of full extension at the end and which models were just slow in restoring the height.

Using other variables such as velocities could improve the performance evaluation, but also makes it more complicated to measure. As alternative, qualitative performance evaluation can be done instead of trying to capture the complicated movements in numbers. This emphasizes the benefit of qualitative experiments to assess the performance of a sit-snowboard.

4.1.2 Qualitative test

Because of tight schedules and the prototype starting to have slack connections, the test had limited duration. More feedback can be gathered when more and extended testing is done. The seating position of the rider is suboptimal because the prototype has a higher seat than the Twinrider and the seat is positioned almost horizontal. This makes the rider sit like in a chair instead of having a semi-sitting position (Figure 25). This made control harder and the subjects experienced more fear than in the (lower) Twinrider. The amount of subjects (only two riders) is very limited. These riders are both connected to the project, and therefore might be biased.

Figure 25: Height and posture difference between Snowcruiser (left) and Twinrider(right).

4.2 Discussion on results

Despite the limitations, it is possible to learn from the data, evaluate the hypotheses and conclude if the goal is achieved. The objective of the quantitative test is to determine whether the new design (Snowcruiser) has improved performance regarding control and comfort with respect to the control design (Twinrider) and to give insight on the performance of the different settings of the suspension characteristics. The objective of the qualitative test is to subjectively assess the comfort and control for the Snowcruiser and validate the evaluation method for comfort and control performance.

4.2.1 Quantitative test

In this section I will discuss all the variables that were measured to assess the comfort and control. For each variable, I will determine whether the variable is depending on speed and analyze what can be said about the different suspension settings. I will also discuss how these variables impact comfort and control. The variables are grouped into comfort and control again, as in the 'methods and materials' section.

4.2.1.1 Results quantitative test: Comfort

Accelerations of seat

The accelerations are used to calculate the VDVs. In Figure 26 the VDVs on the seat are plotted in red against the average speed per run. For the VDVs on the seat of the Snowcruiser models, slightly increasing linear relationships can be seen. These are depicted with the dashed lines. The influence of the different settings is not taken into account with this linear relationships. The Twinrider is excluded from the calculation of the linear relationship, because it can be clearly seen that the VDVs from the Twinrider are much higher and deviating from the VDVs of Snowcruiser. Although the VDV is depending on speed, the high VDVs of the Twinrider are not just caused by a higher riding speed. As hypothesized, the Snowcruiser has lower VDVs at the seat for all combinations of settings than the Twinrider, which means vibrational and visional discomfort are less for the Snowcruiser.

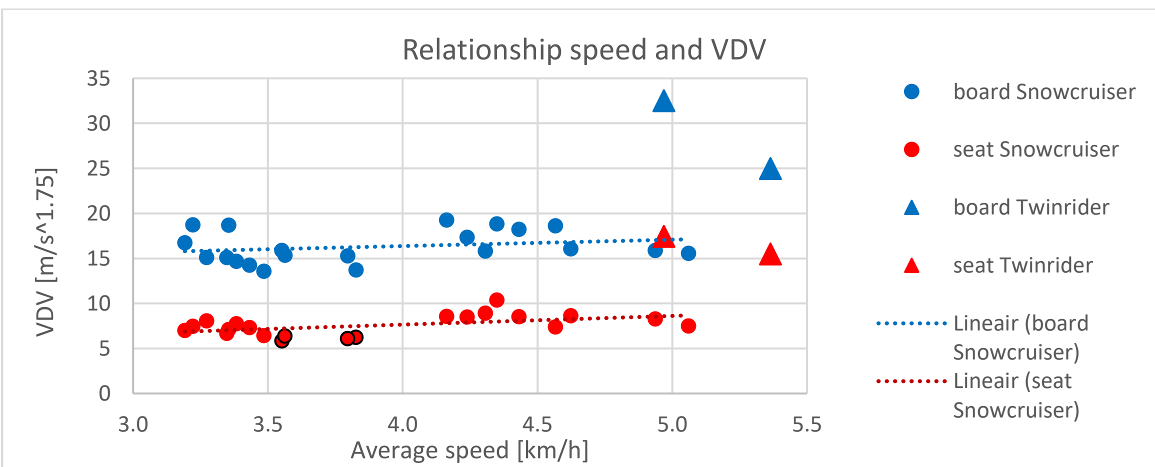

Figure 26: Vibration Dose Values plotted against riding speed for each run.

The increasing linear relationship shows that the VDVs are increasing with speed, which was also found in earlier research (Ismail et al., 2010; Mayton et al., 2014; Nahvi et al., 2009; Nahvi et al., 2006). This means that it are not simply the suspension settings with the lowest VDV that are the best regarding accelerations. All settings are pretty close to the relationship line, meaning that the choice of settings does not have much influence on the VDV. There is one combination of settings with VDVs under the dashed line for all runs (shown with a black outline). This is the model with a height of 500mm, maximum compression and fast rebound. Table 6 shows that these settings score the lowest VDVs. It is expected that these settings are leading to the best performance when low accelerations on the seat are desired.

It is remarkable that the speed dependency for the Twinrider shows opposite behavior: the higher the speed, the lower the VDV. It is not known what causes this contradictory behavior. It would be interesting to do further research on the VDV for the Twinrider with different and higher riding speeds.

Table 6: Vibration Dose Values on the board and seat averaged per condition.

	VDVboard [m/s^1.75]	VDVseat [m/s^1.75]
minslow500	15.5	8.0
maxslow500	15.0	7.5
minfast500	18.0	7.2
maxfast500	15.0	6.1
minslow530	15.9	8.8
maxslow530	17.8	8.5
minfast530	15.7	7.9
maxfast530	18.9	8.0
Twinrider	28.7	16.5

Table 7: S.E.A.T. for each condition with the improved efficiency with respect to the Twinrider.

	S.E.A.T. [%]	Improved efficiency w.r.t. Twinrider [%]
minslow500	51.2	-0.3
maxslow500	50.1	0.8
minfast500	41	9.9
maxfast500	40.9	10.0
minslow530	55.1	-4.2
maxslow530	47.8	3.1
minfast530	46.3	4.6
maxfast530	42.0	8.9
Twinrider	50.9	

Vibration isolation: S.E.A.T.

The S.E.A.T. is a number to express the vibration isolation efficiency. S.E.A.T. values are plotted against speed in Figure 27. It can be observed that the data points form a cloud, so no speed dependency seems to be present. To dig into the figure a bit deeper, the conditions are given their own color, the models with height 500 having lighter colors and the models with height 530 having dark colors with a black outline. All conditions show different relationships with speed. Also, the condition with the biggest speed difference (minslow500) does not show an extreme big variance in S.E.A.T. values when comparing with the other conditions. This means that the S.E.A.T. is not depending on speed and differences and vibration isolation performance can be related to the different mechanisms. Critical note is that the condition 'maxslow500' shows a big variance with a very small variance in speed. It is unknown what might be causing this variance.

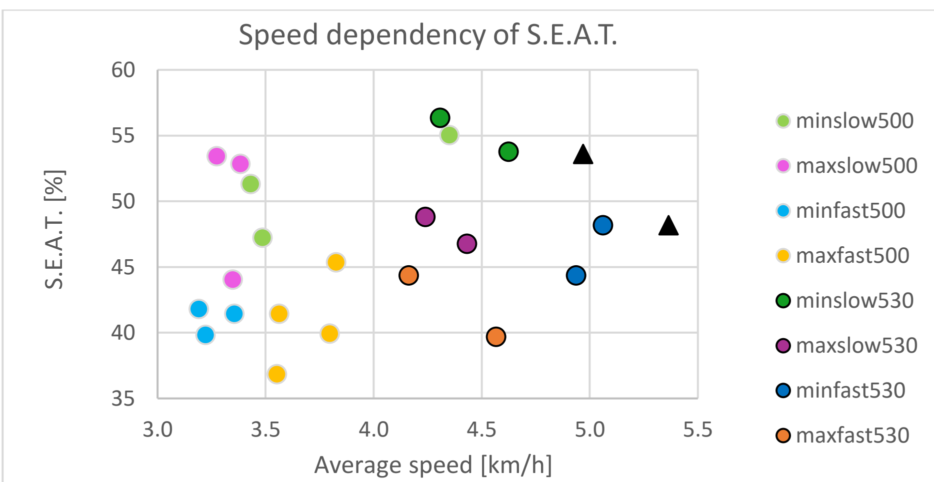

Figure 27: S.E.A.T. values plotted against riding speed for each run.

In Figure 21 and Table 7 it can be seen that the S.E.A.T. values aren't much lower for the Snowcruiser models than the Twinrider model, which is against expectations. Apparently vibration isolation exists between the board and the seat for the rigid Twinrider model as well. The S.E.A.T is not improved for all Snowcruiser models in comparison to the Twinrider.

The models with maximum compression and fast rebound seem to have the lowest S.E.A.T. values, which means the best efficiency. In Figure 27 these are shown with the yellow and orange dots. Even with high speeds (model with height 530mm), these settings still have a good vibration isolation performance. The vibration isolation efficiency is increased with approximately 10%. The settings with minimal compression and fast rebound also show a big increase in efficiency (9.9%). With a height of 530mm and higher speeds, the increase in efficiency is lower (4.6%).

Seat tilt

Rotation of the seat with respect to the board is desired to keep the seat horizontal at small bumps. It also adds an extra control method: Nose/tail translation in combination with rotation of the seat in the sit-snowboard adds an extra control method for the rider in addition to trunk leaning in heel/toe direction. Controlling the COM in nose/tail direction requires certain core and arm strength and coordinative skills of the rider. However, seat tilt might introduce some unwanted issues as well. Too fast or too much seat tilt may cause discomfort and loss of control.

In this section, the quantitative results are discussed, dealing with the seat tilt behavior while passing obstacles. Seat tilt is defined as the angle of seat with the horizontal in the camera reference frame. It is measured at several locations while passing a hill and a sudden drop. Can small bumps indeed be compensated with the Snowcruiser? What is the seat tilting behavior after an obstacle is passed and how fast is the recovery of this compression? What does this mean for the comfort and what are the influences of the different settings on these results?

Hill

Figure 28 shows the seat tilt plotted against the speed for measuring locations 1 to 4 at the hill.

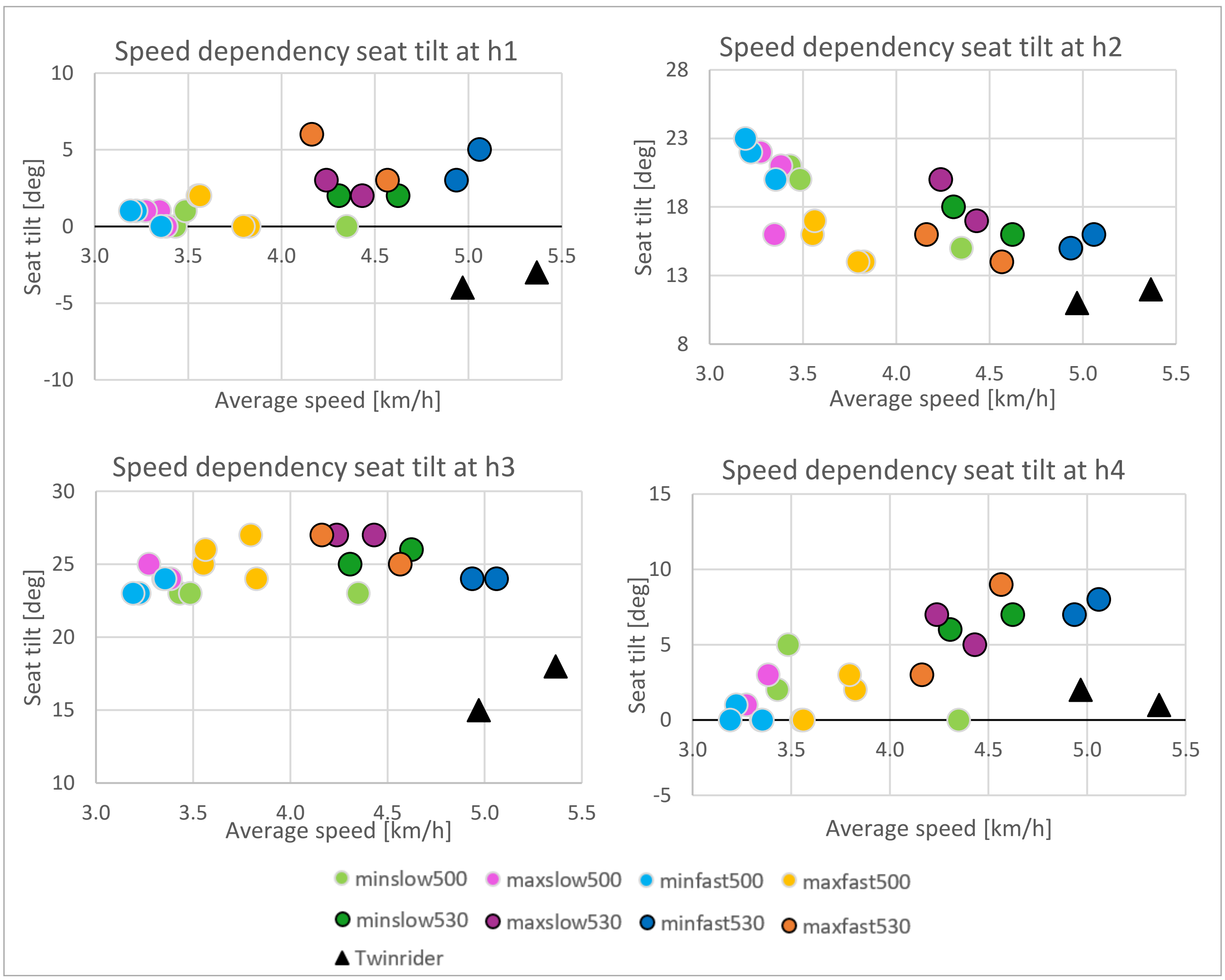

Figure 28: Seat tilt plotted against the speed for measuring locations 1 to 4 at the hill.

The seat tilt at h1 seems to be independent of speed because the seat tilt does not increase with increasing speeds. Three clusters can be remarked: one with models with height 500mm, one with models with height 530mm and the Twinrider. The 500mm models show a seat tilt between 0 and 2 degrees, which is desired. The Twinrider shows negative seat tilting, which is undesired, because this may lead to control interference or visional discomfort. It is shown that the Snowcruiser will be able to compensate for small and fast slope changes by keeping the seat horizontal, especially the models with a height of 500mm.

Just after the top of the hill, location h2 is defined. At h2, decreasing speed dependencies can be seen for most conditions of the Snowcruiser. This can be explained with the following theory: The faster the snowboard travels, the more centripetal acceleration is present and the more the board continues the straight movement forward instead of rotating as soon as the COM is in front of the contact area with the hill. The Snowcruiser model with maximum compression, fast rebound and a height of 500mm is deviating from this expected seat tilt with all four runs. Extension of the front fork causes the seat to rotate less.

At the steepest part of the decline of the hill (h3) no speed dependency is shown for the Snowcruiser models because the main shape of the data points is moving horizontally to the right. Minimal compression and a height of 500 mm give least seat rotation at this stage (light green and light blue) , but the differences between the different settings are small (average of 24.7° with st.dev. of 1.5°). Overall, the seat tilt is much higher for all Snowcruiser models than that for the Twinrider which has an average tilt of 16.5°.

In the pit after the big hill, location h4 is defined. At first sight, location h4 shows an increasing speed dependency for the Snowcruiser models. This can be explained by the fact that a higher speed causes the sit-snowboard to 'fly' over the hill. The sit-snowboard is only compressed when it lands again on the surface. When speed is higher, this compression occurs at greater distance after the hill. At the location of h4, the models with higher speeds have not been fully restored yet from the compression that just occurred. An exception to this is the fast descend from minslow500. This particular run shows no seat rotation at all, although the speed is pretty high. This might be caused by the fact that the combination of minimum compression and a height of 500mm is not allowing a lot of front fork compression. For limiting the seat tilt, this is a good setting. But the other variables should give more insight in the performance of these settings, because minimal compression might also lead to more shocks and vibrations.

Another remarkable issue is that for the run at speed 3.5 km/h, with minimal compression and slow rebound, the seat tilt is higher than expected according to the observed relationship. This shows that results with different settings are really hard to interpret when they are depending on the speed. The dynamic behavior of the forks in combination with the exact slope profile and specific speeds might cause the sit-snowboards to be humping up and down or back and forth, while changing one of these variables just slightly, might change the behavior drastically.

It is hard to determine the real speed dependency, because not much speed variance is present. However, when also the fast descend of the Snowcruiser with minimal compression and slow rebound is taken into account, again two clusters can be seen between the 500mm and 530mm Snowcruiser models. The Snowcruiser models with height 530 show more seat rotation (average of 6.5°) than the models with height 500 (average of 1.3°) and the Twinrider (average of 1.5°).

Increased forward rotation illustrates the risk on the phenomena of 'bottoming out' at the front. Forks have the risk on bottoming out. Bottoming out means that the suspension does not have the time to return to original extended position before a next compression occurs, leading to a more and more compressed spring, until the spring is completely bottomed out, or compressed. In compressed state, the fork is not functional anymore and discomfort may be experienced. Also the bottoming out may result in loss of control because sudden seat tilt is occurring because no compression is allowed anymore. One would expect the slow rebound to cause bottoming out, but the models with slow rebound and a height of 500mm (green and pink) show no increased seat rotation at h4, while the models with slow rebound and a height of 530mm have increased forward seat tilt. This shows that the height of 530 increases the forward seat tilt after consecutive bumps and therefor has a higher risk on bottoming out at the front fork. This increased forward seat tilt for the 530mm models may be an explanation for the higher seat tilt at h1: Due to previous bumps at the beginning of the run, the front fork has not been able to fully restore the seat horizontally. On the other hand, with a bigger height, a longer travel is allowed, again reducing the risk on bottoming out.

The seat tilt is also determined at the moment the nose of the board touches the surface again after passing the hill. Figure 29 shows this seat tilt plotted against the speed. The scattered results show that they are not speed dependent. The models with a maximum compression and fast rebound are performing best: Their seat tilts forward as much as the Twinrider does. Since the Twinrider cannot be compressed, the seat tilt of the Twinrider indicates the slope angle. The model with these settings and a height of 500mm even shows less seat tilt, meaning that the independent extension of the forks has done its job: The contact is regained as fast as possible while keeping the seat as horizontal as possible.

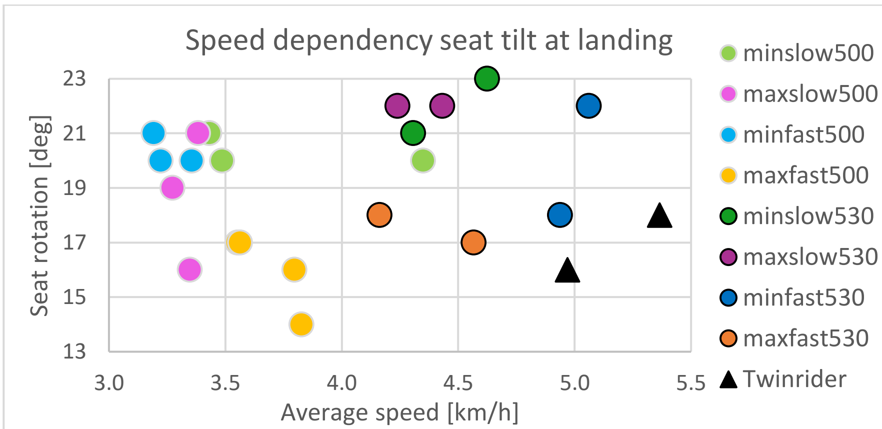

Figure 29: Seat tilt determined at the moment of landing after the hill is passed, plotted against speed.

<u>Sudden drop</u>

The sudden drop is the last obstacle in the descent. Figure 30 shows the seat tilt plotted against the speed for measuring locations 1 to 3 after the sudden drop.

When looking at the seat rotations just before this obstacle (d1), it can be seen that the seat tilt is independent of speed. It is remarkable that all Snowcruiser models have comparable seat tilt with an average of 5.7° (st.dev.=0.57°), while the Twinrider shows that the slope angle is 0° at that spot. This implies that all the Snowcruiser models have the same amount of recovery at that moment, regardless of their settings. Because no movements are captured in this measurement, it is unknown to what extend the forks are still extending or already at rest.

Just after the drop has occurred the second seat tilt is measured (d2). A slight increasing relationship can be seen. Besides, the values are not widely spread. Because of these reasons, no further insight is gained on the different settings of the suspension. It can be seen that all Snowcruiser models show more seat tilt than the Twinrider, but this is expected due to the shock absorption: In the Snowcruiser, seat rotation is appearing when compression of only one spring-damper is occurring. Absorbing energy after a landing with compression of the front fork automatically leads to forward seat rotation.

At the end of the measurement (d3), after the sudden drop, the slope has a continuous decline of about 7° (based on the Twinrider seat rotation in Table 4). However, many Snowcruiser models show more seat rotation at this stage. The bottom graph in Figure 30 clearly shows one condition to have the seat tilted parallel to the slope (yellow: maxfast500). It is remarkable that the model 'maxfast500' is the only one capable of returning the seat parallel to the slope at that stage.

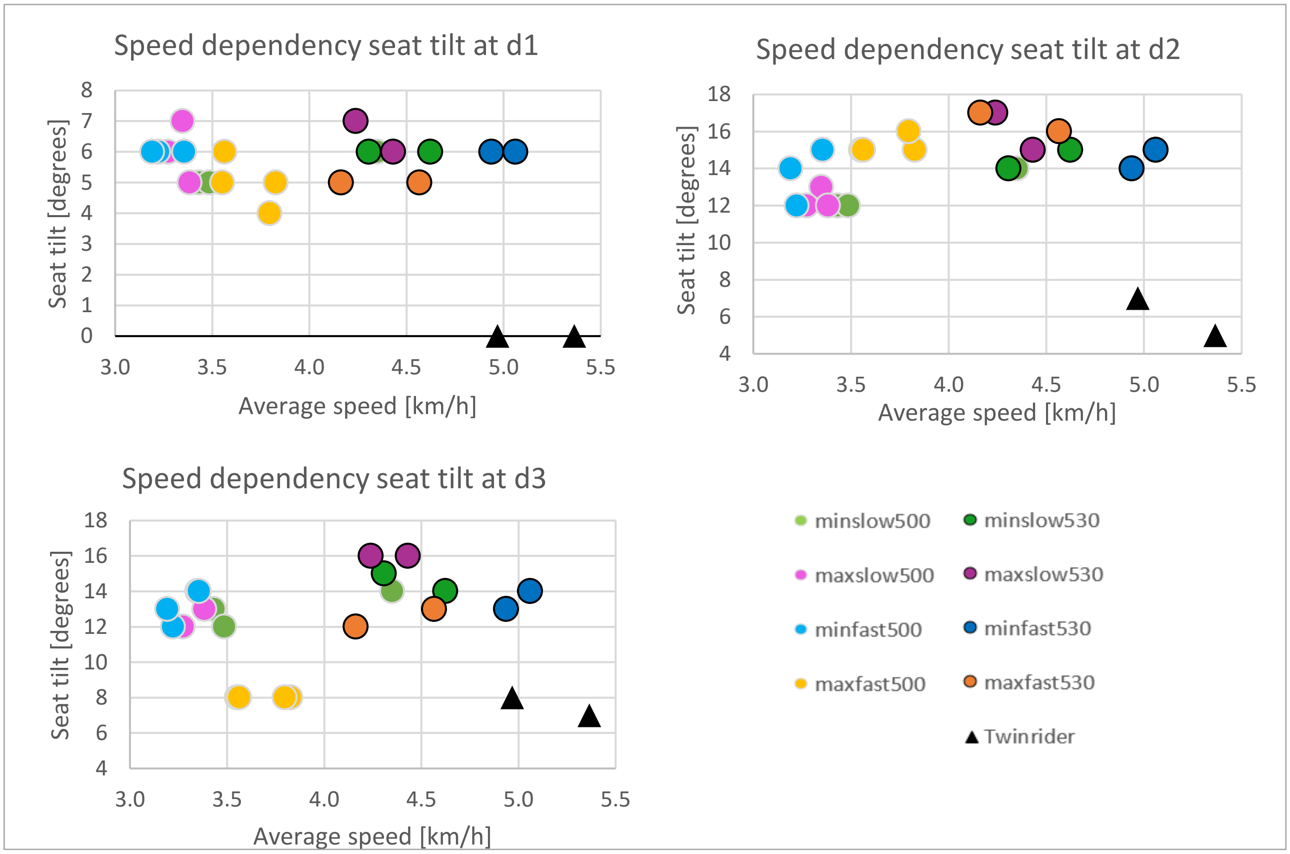

Figure 30: Seat tilt plotted against the speed for measuring locations 1 to 3 after the sudden drop.

Comfort optimization

Visional discomfort is avoided when the seat tilting is minimal. It is shown that the Snowcruiser is able to compensate for small and fast slope inclines by keeping the seat horizontal. It is expected that the Snowcruiser is able to keep the seat horizontal while passing small bumps including consecutive inclines and declines.

The shock absorbing mechanism in the Snowcruiser automatically introduces more seat tilt than is desired (parallel to slope) after a hill is passed. It is important to find the settings that lead to the optimal tradeoff between shock absorption and seat tilt, leading to minimal discomfort.

After an obstacle, minimal compression and a height of 500mm give least seat rotation, but the minimal compression setting also allows less shock absorption. This results in higher VDVs on the seat than the same conditions with maximum compression (see Table 6). The Snowcruiser with maximum compression, fast rebound and a height of 500mm performs well regarding minimum seat tilt, and also performs well in decreasing vibrational discomfort due to accelerations (described in the previous discussion sections on comfort about accelerations on seat and S.E.A.T.)

The setting ‘maxfast500’ also shows a quick recovery of seat tilting angle after an obstacle is passed. On video footage it can be seen that this quick returning of ‘maxfast500’ causes a slight oscillation of the seat. The accelerations caused by this oscillating did not lead to a high VDV on the seat. On the contrary, the VDV on the seat performed best for this condition.

4.2.1.2 Results quantitative test: Control

Accelerations of seat

This variable is already discussed in the previous section on 'comfort' because it also has effect on the comfort. The Snowcruiser has lower VDVs at the seat for all combinations of settings than the Twinrider, which means less body interference is expected for the Snowcruiser, leading to improved control.

The model with maximum compression, fast rebound and a height of 500mm is the only model having a lower VDV on the seat than expected for all runs. It is therefore expected that these settings are best when good vibrational comfort and little body interference is desired.

Seat tilt

Seat tilt is extensively discussed in the 'comfort' section (chapter 4.2.1.1). Besides comfort, also control is improved when seat tilting is minimal because no control interference is occurring. Control interference can occur in the form of fast tilt changes or a large continuous seat tilt. Extra muscle force is needed to keep balance when the seat is tilted. It is possible that not all riders have this required muscle force. Also it might cause fatigue, muscle ache or difficulty controlling the board because of a specific, non-optimal body position. The Snowcruiser model with maximum compression, fast rebound and a height of 500mm shows least seat tilt of all Snowcruiser models.

The seat tilting speed is not directly measured with the quantitative test. The change in tilting angle between several moments is not useful because a lot of the seat tilting data is speed dependent and not enough speed variation is applied.

On video footage it can be seen that the quick extension of the front fork when using 'maxfast500' causes a slight oscillation of the seat. This did not affect the VDV results negatively, but qualitative tests are recommended in order to investigate the amount of loss of control due to control interference caused by the oscillating.

Contactless distance

The contactless distances are plotted against the speeds for the two obstacle crossings (Figure 31). The triangles represent the Twinrider measurements. The dotted lines show the relationships between the speed and the contactless difference.

For the contactless distances after the hill, the best fit is a polynomial relationship. The R^2 values shows that this relationship fits well, however these statistics should be used with care because of the limited amount of data. This relationship includes the Twinrider data points, which means that this variable is solely depending on speed and it is not possible to draw conclusions on the board-surface interaction performance using contactless distance after the hill.

For the sudden drop, the best fitting trend line is the linear increasing relationship without the Twinrider data points. The Twinrider shows smaller contactless distance, which means the contactless distance after a sudden drop is worse for Snowcruiser models. This might be due to a catapulting effect: The extending springs are moving the COM up at the location of the sudden drop, causing the sit-snowboard to 'fly' further.

The lower the contactless distance, the better, because the board regains contact with the surface faster. Improving the board-surface interaction improves control performance. Results indicate that the Snowcruiser does not improve the surface contact. On the contrary, the Snowcruiser is even contactless for a bigger distance than the Twinrider after the sudden drop. It is hypothesized that the distance would be decreased because of the independent extension of the forks, but this hypothesis is shown to be incorrect. However, the catapulting effect which is occurring is strongly depending on the slope profile and riding speed. Changing the slope profile or speed will change the behavior of the Snowcruiser.

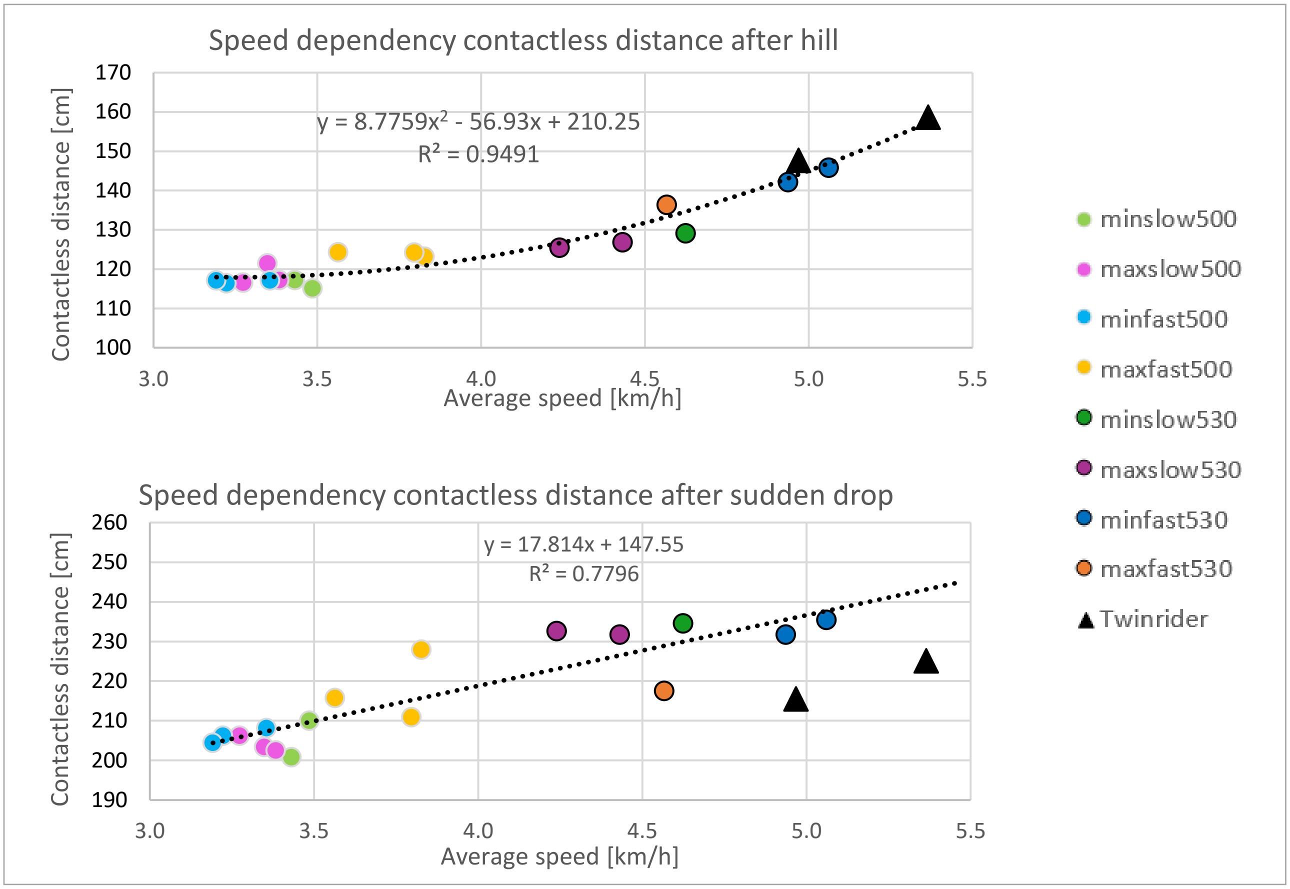

Figure 31: Contactless distances plotted against speed after passing the hil (top) and sudden drop (bottom.)l

Accelerations of board

The accelerations are used to calculate the VDVs. In Figure 19 the VDVs on the board are plotted in blue against the average speed per run. The discussion on the accelerations on the seat also applies for the accelerations on the board.

As hypothesized, the Snowcruiser has lower VDVs at the board for all combinations of settings than the Twinrider, which means the board-surface interaction has improved for the Snowcruiser, leading to a better control. The contactless distance has not decreased for Snowcruiser models, meaning that the decrease of vibrations on the board were probably caused by the flexion possibility and the vertical shock absorbers.

VDVs on the board are also depending on the speed, so the VDVs do not give a clear insight in the performance of the different suspension settings. This time, many data points score a VDV lower than expected based on the linear relationship. Nothing can be said on the performance of different suspension settings regarding accelerations on the board influencing the control.

4.2.2 Results qualitative test

The results of the qualitative test coincide with the results from the quantitative test: The Snowcruiser leads to a better comfort and control compared to the Twinrider.

Regarding the comfort, the qualitative test confirmed that the vibrations on the body were lower. This is also found with the quantitative test with the lower VDV on the seat.

Also control is better when going over a hill while making a turn. The quantitative test learned that the board of the Snowcruiser would not regain faster contact with the snow, but this does not mean that the goal of improving surface contact is not achieved. During the qualitative test it was noted that flexion in the board, occurring at the Snowcruiser, created contact with the full edge length. With the Twinrider it could be seen that a gap existed between the board and the snow when going over a hill. This degree of contact with the surface was not evaluated with the quantitative test, but in practice improved surface contact for the Snowcruiser has been shown. This enabled the rider to keep control going over a hill while this was not possible with the Twinrider.

The Twinrider caused a rather fast seat tilt after the top of a hill was passed, resulting in discomfort and harder control due to body interference and a shock at the landing (Figure 32). The Snowcruiser showed the independent extending and seat tilting mechanism to be functional at this stage of passing the hill, by reducing the seat tilt while the board was gliding over the hill (Figure 33 b and c). This was experienced as a smooth ride. This experience coincides with the result from the quantitative test that the Snowcruiser can keep the seat horizontal for small bumps. However, the hills passed during the qualitative test were not small, but as high as during the quantitative test. The fact that the seat was kept horizontal during the qualitative test, but not during the quantitative test may be caused by a difference in riding speed: The riding speed during the qualitative test is expected to be lower than during the runs of the quantitative test, but it is not measured. The settings used during the qualitative test were maximum compression, fast rebound and a height of 500mm. With the quantitative test, it is found that these settings showed less seat tilt than expected from a Snowcruiser after just passing a hill (chapter 4.2.1). This is supported by the results found in the qualitative test. The Snowcruiser is even able to keep the seat nearly horizontal when a bigger hill is passed with a low speed. No excessive seat tilt occurred after the hill was passed: The seat was parallel to the surface (Figure 33d).

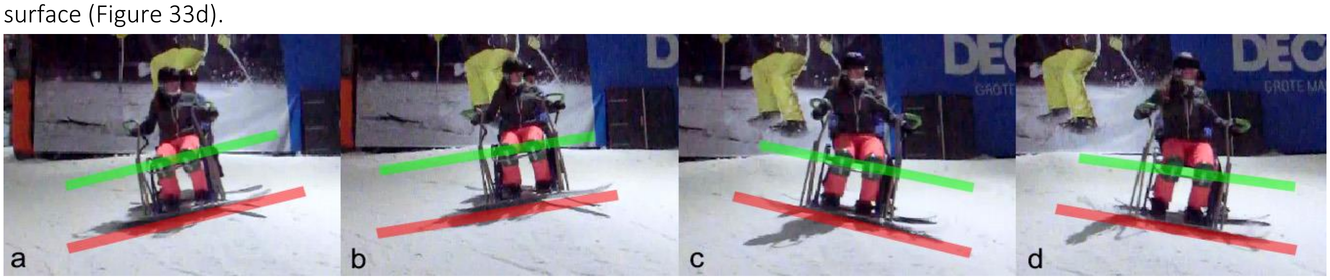

Figure 32: Passing a hill with the Twinrider during the qualitative test.

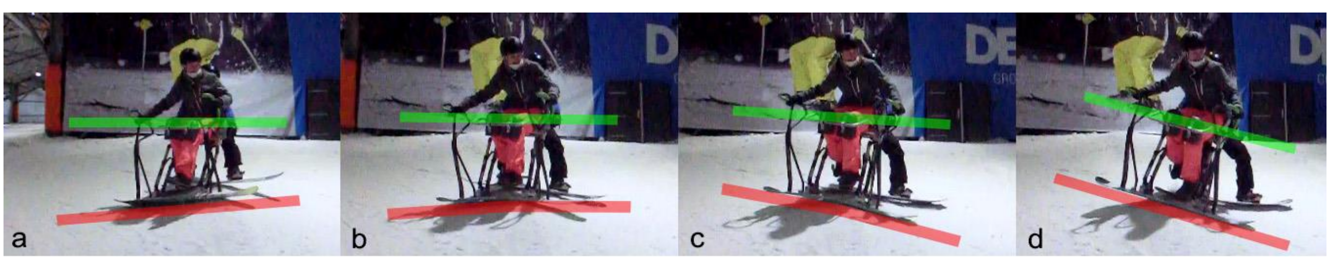

Figure 33: Passing a hill with the Snowcruiser during the qualitative test.

4.2.3 Hypotheses

To summarize, the hypotheses are repeated in Table 8 with indications on whether the hypotheses are accepted or rejected.

- Comfort and control are improved because the VDV on the seat is lower. This is confirmed with the results from the qualitative test.
- The Snowcruiser has decreased vibrations on the board, reducing the source of WBV and improving the board-surface interaction .
- Surprisingly, the S.E.A.T. is not lower for the Snowcruiser than for the Twinrider, so vibration isolation is not more efficient for the Snowcruiser.
- The contactless distance is not decreased by the independent fork extension of the Snowcruiser. However, the qualitative test shows improved board-surface interaction due to board flex which is limited for the Twinrider.
- The Snowcruiser is expected to be able to keep the seat horizontal for small bumps, preventing visional discomfort and control interference.
- According to the quantitative test, the mechanism for shock absorption is introducing more seat tilt after a big hill is passed. However, the qualitative test does not show this increased seat tilt. This is probably due to a lower riding speed.

Table 8: Hypotheses with the results from the tests

Hypotheses	Quantitative	Qualitative
• VDV for the seat will be lower for the Snowcruiser than for the Twinrider.	accepted	confirmed
• VDV for the board will be lower for the Snowcruiser than for the Twinrider.	accepted	
• The S.E.A.T. will be lower for Snowcruiser models than for the rigid Twinrider.	rejected	
• Contactless distance will be lower for the Snowcruiser than for the Twinrider.	rejected	improved by board flex
• The Snowcruiser will be able to keep the seat horizontal for small bumps.	accepted	confirmed
• After a big hill is, the Snowcruiser will show more seat tilting than the Twinrider.	accepted	rejected

With the results from the qualitative test, the protocol for quantitative performance evaluation regarding comfort and control is validated: Both tests show improved comfort and control for the Snowcruiser. Vibration and shock data shows comparable results for both tests. The seat tilt does not exactly show the same results. The (unwanted) increased seat tilt after a hill is absent during the qualitative test. It is suspected that this is due to lower riding speed. It is recommended that this is further investigated to confirm this and to predict the behavior of the Snowcruiser at higher speeds. The inability to capture the improved board-surface interaction with the variable of contactless distance during the quantitative test has been compensated by the fact that board flexion occurrence shows during the qualitative test. A quantitative variable to capture the amount of board flex may be a good indicator for board-surface interaction.

4.3 Discussion on performance evaluation method

This study is combining the strengths of a reproducible quantitative test with a qualitative test giving insight in the user experience. This section is about the used method for quantitative performance evaluation.

Since sit-snowboarding is a new sport, no research has been conducted on this field yet. Some research has been conducted on sit-skiing, but these researches were inconsistent (Fioole, 2017). Performance indicators used in sit-skiing are inertia and location of COM for control, VDV and seat angle for comfort and moving speed. Many researches use VDV to evaluate comfort for vehicles but only three researches used VDV for comfort assessment in sit-skiing (Cavacece et al., 2005; Cho et al., 2015; Jang, Kim, Shin, & Mun, 2015). These researches used models and simulations, making a lot of assumptions and simplifications. The results were showing big differences, showing the weaknesses of these simulations. Koo et al. conducted a 3D field test focusing on the seat bucket for sit-skiing, using a complicated and expensive set-up containing of 24 infra-red cameras. With that method, only motion analysis is allowed and no vibration and shock data are gathered. In standing snowboarding and skiing, earlier research uses VDV to assess comfort (Spörri, Kröll, Fasel, Aminian, & Müller, 2017; Supej, Ogrin, & Holmberg, 2018; Tarabini, Saggin, & Scaccabarozzi, 2015). They conclude that the VDVs are much higher than the set exposure limit values by the standards ISO 2631 and BS 6841, but note that the current limits set in the standards are not applicable for extreme sports such as skiing and snowboarding. They mainly focus on health problems caused by vibrations rather than on rider experience and control issues. The different skiing techniques and body posture are taken into account, but the conditions of the slope are left out. The researches give insight in the attenuation of vibrations by the body but this not very useful for the development of a sit-snowboard, since no or very limited attenuation of vibrations can be done with the body during sit-snowboarding. Designing a good mechanism between the board and seat may contribute to the minimization of WBV. In this study special attention is given to the effect of the mechanism on the experience of the rider rather than in depth black and white research focusing on numbers being below a certain limit or frequency analysis of the vibrations.

This is the first experimental research in the field using the VDV for assessing comfort and control for sit-skiing or sit-snowboarding, only using four accelerometers and two high speed cameras. Besides VDV, also seat tilt is used. When seat tilt is calculated from the accelerometers instead of determined manually from video footage, the computation time will be much lower and room for error will be smaller, increasing reliability. When contactless distance, which has shown not to be an interesting variable due to the big speed dependency, is not used for performance evaluation, the two high speed cameras will be unnecessary, creating a cheap measurement set-up. For easy displacement between models, accelerometers are fixated using Velcro. This introduces some risk on random errors, reducing reliability. However, reliability is increased by averaging data over sensors on the same location (two on the board and two on the seat). Repeating the measurement with multiple runs per condition ensures the reliability even more. A cheap, fast, valid and reliable method for performance evaluation of comfort and control during sit-snowboarding is presented in this study.

The VDV calculated is the accumulative vibration dose value over the measured time. However, the measuring time was short, only covering about 22 meters and containing six obstacles. A run from a full slope or even a day of sit-snowboarding will result in higher VDV's, which will probably be above the 15 $m/s^{1.75}$ action level. However, a comparison between the models can still be made, even if the absolute values of the VDV do not seem to be correct. During the data processing it became clear that when a filter would have been used, the VDV's would have been much lower. The method of data processing is influencing the results a lot. I decided not to use any filtering so no information would get lost.

4.4 Future research

Future research on the exposure limit values of the VDV during extreme sports will make quantitative evaluations for sit-snowboarding easier and more straight forward. With the method provided in this research, comparisons can be done to evaluate comfort, but the interpretation whether comfort is high enough to prevent health problems is not possible yet.

It is recommended to do more qualitative tests with a good prototype and multiple unbiased subjects. Doing more research with other slope patterns and varying speeds will give valuable insight in the behavior of the Snowcruiser and the influence of the different fork settings. Tuning of settings should be done in combination with different riding styles, test riders and slope conditions. It is recommended that in future research, both quantitative and qualitative tests are performed to assess the performance of sit-snowboards.

Further development is needed to improve the other factors and criteria of the product as well, trying to maintain or even improve the comfort and control performance of the Snowcruiser.

5 Conclusion

The Snowcruiser has lower VDVs on the seat for all Snowcruiser models than for the Twinrider, reducing the discomfort and control interference. Also the Snowcruiser shows reduced accelerations on the board, taking away the source of vibration at the board and improving the board-surface interaction. The Snowcruiser is able to keep the seat horizontal for small inclines, preventing visional discomfort and control interference. More board flexion is occurring, leading to a better board-surface interaction.

Both the quantitative test and the qualitative test confirmed that the goal is achieved: The Snowcruiser is suitable as sit-snowboard for advanced users because it has improved comfort and control while being used on bumpy slopes.

According to the quantitative test, maximum compression, fast rebound and a height of 500mm form the optimal combination of settings. These settings were used during the qualitative test, and the riders indeed experienced better comfort and control.

A reproducible, cheap, fast and valid and reliable method for experimental performance evaluation of comfort and control during sit-snowboarding is presented in this study. The method is using the variables VDV and seat tilt.

6 Acknowledgement

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Appendices

I. Design Requirements

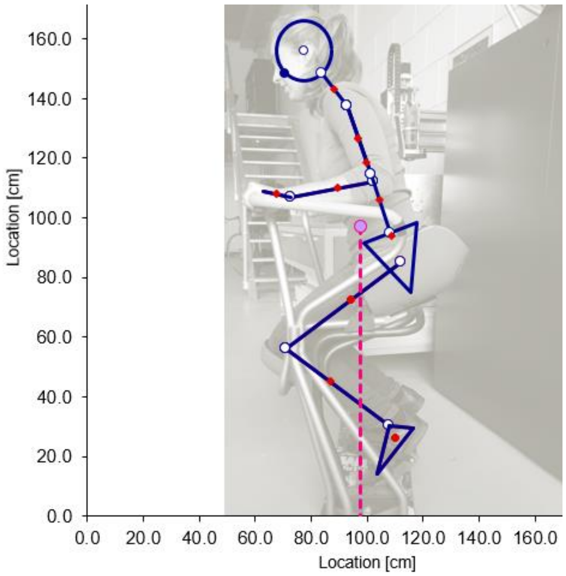
Design requirements make the product a functional and safe product. They do not directly contribute to a specific goal. A sit-snowboard needs to meet all the requirements.

- Act of snowboarding
  - Shoulders are parallel to travelling direction.
  - The system can be installed on a snowboard.
  - No active leg control required from the rider.
- Safety
  - Legs are fixated to the product.
  - No collisions between parts.
  - No sharp objects which may hurt the rider or others.
  - The product is able to function appropriately in snowy conditions at a temperature of -20°C.
  - Structural durability: does not break with extensive use and falling.

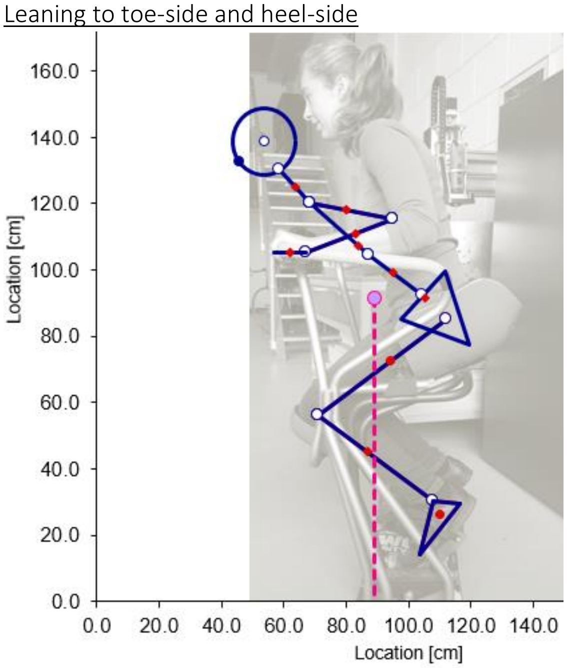
II. Kinematic Analysis heel/toe COM shift

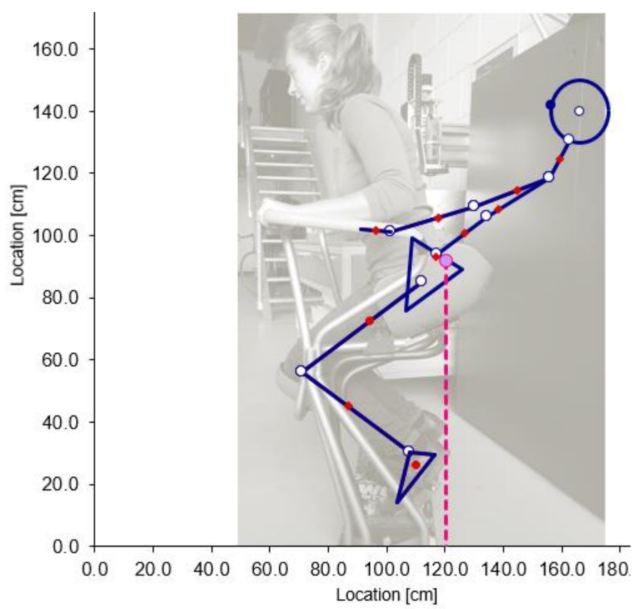
The center of mass (COM) should be shifted in toe- and heel side direction over the minimal distance of the width of the board. The widths of snowboard varies between 23 and 27 cm (McNab, 2006). From kinematic analysis, the COM shift that can be achieved while sitting in the sit-snowboard is predicted based on the dimensions of the design and the human (Winter, 1990) and the range of motion as stated in table 10.3. By rotation of the hips and leaning of the trunk the maximum COM shift is 29 cm (from 89cm to 120cm). This range should be just enough, however, such extreme body positions require a lot of body control and strength, which cannot be demanded from the user group.

Neutral body position



Leaning to toe-side and heel-side





x coordinate COM toe-side leaning: 89 cm
x coordinate COM heel-side leaning: 120 cm

TABLE 10.3 Average Range of Motion (ROM) Values for Healthy Adults

Joint	ROM (degrees)	Joint	ROM
Shoulder		Thoracic-lumbar spine	
Flexion	150-180	Flexion	60-80
Extension	50-60	Extension	20-30
Abduction	180	Lateral flexion	25-35
Medial rotation	70-90	Rotation	30-45
Lateral rotation	90	Hip	
Elbow		Flexion	100-120
Flexion	140-150	Extension	30
Extension	0	Abduction	40-45
Radioulnar		Adduction	20-30
Pronation	80	Medial rotation	40-45
Supination	80	Lateral rotation	45-50
Wrist		Knee	
Flexion	60-80	Flexion	135-150
Extension	60-70	Extension	0-10
Radial deviation	20	Ankle	
Ulnar deviation	30	Dorsiflexion	20
Cervical spine		Plantar flexion	40-50
Flexion	45-60	Subtalar	
Extension	45-75	Inversion	30-35
Lateral flexion	45	Eversion	15-20
Rotation	60-80		

Data from the American Academy of Orthopaedic Surgeons (Greene and Heckman 1994) and the American Medical Association (1988).

Retrieved from (Helming, 2012)

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III. Concept Choice

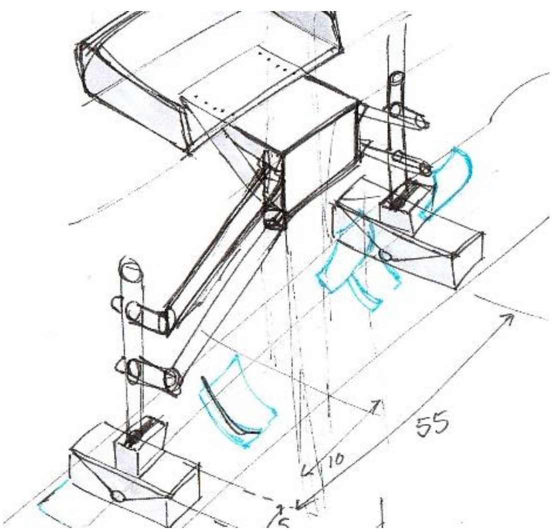
A Harris Profile is a graphic representation of the strengths and weaknesses of design concepts that helps in making a decision on which concept to continue with (van Boeijen, Daalhuizen, van der Schoor, & Zijlstra, 2014). For the selected concepts, Harris Profiles were created to determine the most promising concept. The design requirements and performance criteria on comfort and control are listed. Scores are given according to the expected performances.

To make the working mechanisms more clear, the kneepads and footrests are not drawn in the concept sketches.

All concepts meet the requirements:

Requirements		-	+
Snow-boarding	Shoulders parallel to travelling direction		
	Can be installed on a snowboard		
	No active leg control required		
Safety	Legs are fixated		
	No parts collide		
	No sharp objects		
	Withstand snow and -20°C		
	Structural durability		

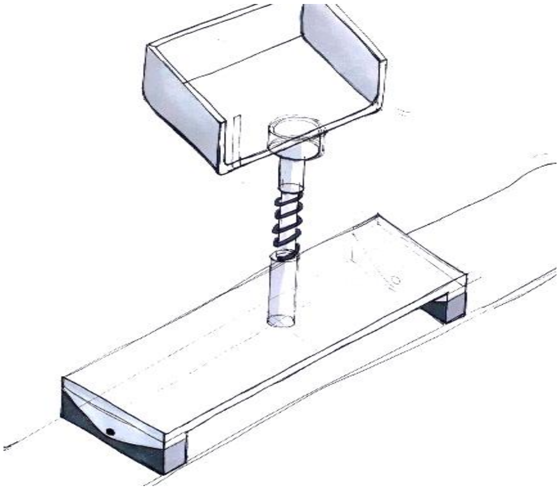
Concept 1: 2 times 4-bar mechanism



Perormance criteria		- -	-	+	++
Focus	Minimize seat tilt due to bumps				
	Minimize vibrations and shocks on seat				
	Board surface contact				
Other	Torsion in board is allowed				
	Easy edge shifting				
	Ergonomics: Support in semi-sitting position				
	Ergonomics: Maximum sitting height is 66 cm				

This concept can't support the body in semi-sitting position because the legs do not fit under the seat without colliding with the frame.

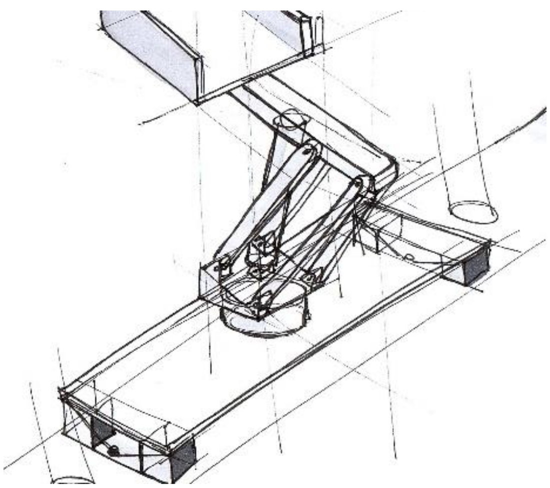
Concept 2: SnowGo2



Perormance criteria		- -	-	+	++
Focus	Minimize seat tilt due to bumps	(red)	(red)		
	Minimize vibrations and shocks on seat			(green)	
	Board surface contact	(red)	(red)		
Other	Torsion in board is allowed			(green)	(green)
	Easy edge shifting			(green)	(green)
	Ergonomics: Support in semi-sitting position			(green)	(green)
	Ergonomics: Maximum sitting height is 66 cm			(green)	(green)

This concept is basically the design by Hoogwout (2014), with a vertical spring-damper built in. Flexion in the middle of the board is not possible due to the baseplate connection between the two limiters, resulting in bad board surface contact. This mechanism is rigid in the travelling direction, causing the seat mechanism to rotate with the board tilting due to bumps. Also seat vibrations are only isolated in pure vertical direction and not in the horizontal direction.

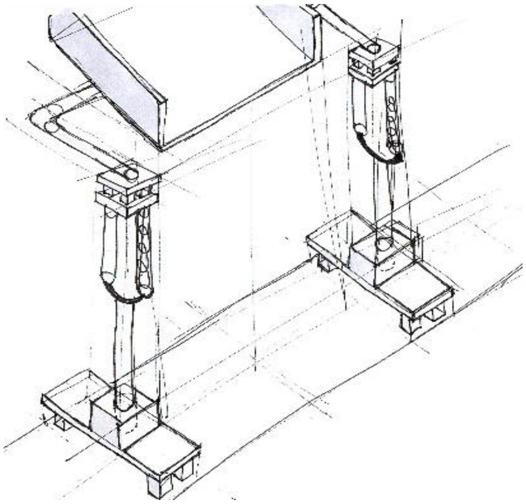
Concept 3: Sit-ski heel/toe



Perormance criteria		- -	-	+	++
Focus	Minimize seat tilt due to bumps	(red)	(red)		
	Minimize vibrations and shocks on seat			(green)	
	Board surface contact	(red)	(red)		
Other	Torsion in board is allowed			(green)	(green)
	Easy edge shifting		(red)		
	Ergonomics: Support in semi-sitting position			(green)	(green)
	Ergonomics: Maximum sitting height is 66 cm			(green)	(green)

This concept is a combination between the often used current sit-ski suspension mechanism and the SnowGo (Hoogwout,2014). The sit-skiing suspension mechanism allows for large seat travel with only limited spring compression. However, by placing it in x-direction, it will not be able to compensate for seat tilt due to bumps. Seat vibrations are only isolated in pure vertical direction and not in the horizontal direction. Flexion in the middle of the board is not possible due to the baseplate connection between the two limiters, resulting in bad board surface contact. When shifting the COM in x-direction to lean on one edge, the suspension mechanism might compress or extend due to this COM shift. This might decrease the vibration isolation performance or complicate control while making a turn. Placing the mechanism sideways is not possible due to limited space for the legs to be placed under to create a semi-sitting body position.

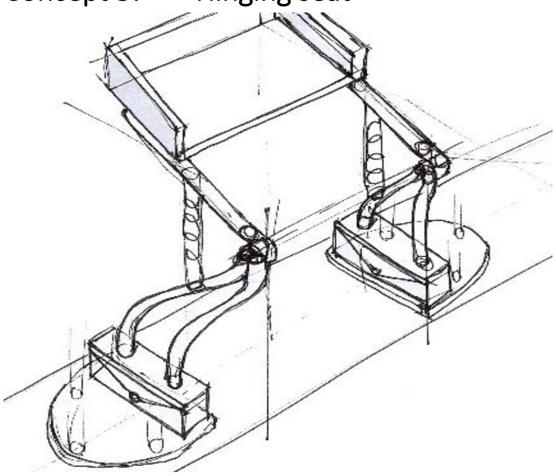
Concept 4: Shortening legs



	Perormance criteria	- -	-	+	++
Focus	Minimize seat tilt due to bumps			(green)	(green)
	Minimize vibrations and shocks on seat			(green)	(green)
	Board surface contact			(green)	(green)
Other	Torsion in board is allowed			(green)	(green)
	Easy edge shifting			(green)	(green)
	Ergonomics: Support in semi-sitting position			(green)	(green)
	Ergonomics: Maximum sitting height is 66 cm			(green)	(green)

This concept has two mountain bike forks for suspension. The connections with the board and seat supporting bar can rotate in both x- and y-direction. This allows board flex to occur between the two board connections. When the nose of the board is raised due to a bump, the leading fork will compress, resulting in minimal rotation of the seat.

Concept 5: Hinging seat



	Perormance criteria	- -	-	+	++
Focus	Minimize seat tilt due to bumps	(red)	(red)		
	Minimize vibrations and shocks on seat	(red)	(red)		
	Board surface contact		(red)		
Other	Torsion in board is allowed			(green)	(green)
	Easy edge shifting		(red)		
	Ergonomics: Support in semi-sitting position			(green)	(green)
	Ergonomics: Maximum sitting height is 66 cm			(green)	(green)

This concept is a simple concept which is very close to the current Twinrider design. The suspension mechanism may react on the heel/toe COM shift, while it should only react on the vibrational interference from the surface. This makes edge shifting harder. When, during a turn, the COM is above the heel-side edge, the mechanism is compressed and is not fully functional. Also, when the COM is above the toe side of the board (and above the rotation center of the suspension mechanism) no vertical vibration isolation will occur. The seating mechanism is rigid in nose/tail direction, allowing very little flexion in the board and rotating the seat when a bump is passed.

Final choice

Concept 'shortening legs' is the only concept meeting all the requirements and scoring well on all comfort and control performance criteria. This concept is chosen to be developed further into a prototype.

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Hoogwout, M. R. (2014). *Design and preliminary testing of a novel sit-snowboard, enabling chairlift usage.* (Master of Science), TU Delft,

IV. MOUNTAIN BIKE FORK CHOICE

Enduro mountain bike forks are ready to use spring-dampers with guided straight movements. They have two main types: air spring or coil spring. The pros and cons are shown below. A very important factor is the behavior being influenced by altitude, temperature and humidity, because this should be avoided in the sit-snowboard design. Also consistent compliance is desirable for the fork being used for a whole day on the slopes for several consecutive days. Therefore it is decided to use coil spring enduro mountain bike forks.

Table 1: Pros and cons of air and coil spring mountain bike forks.

Air	Coil
Easy to adjust spring stiffness	Adjustment only possible by changing the spring
Light	Heavy
Linear, can be made progressive with volume spacers to prevent bottoming out	Always linear spring and unable to make it more progressive
More expensive than coil spring	Cheaper than air spring
More maintenance	Less maintenance
Influenced by altitude, temperature and humidity	Not influenced by altitude, temperature and humidity
Bad small bump sensitivity	Good small bump sensitivity
Compliance and sensitivity fade with longer use	Consistent compliance

Reference

Patterson, J. (2016). Shock talk - the coil-sprung comeback. Retrieved from https://www.bikeradar.com/mtb/gear/article/trail-tech-shock-talk-the-coil-sprung-comeback-45004/

V. Measurement locations seat tilt

d1

d2

d3

VI. WEIGHTING BS 6841

The measured accelerations are weighted on the frequency and direction. As weighting factors, the asymptotic approximations in table 3.5 are used (Griffin, 1996). The weighting W(f) contains both the frequency weighting and the axis multiplying factor.

The approximations apply frequency weighting for linear accelerations in x and y-direction by the multiplying factor Wd. Wd is attenuating accelerations at frequencies higher than 2 Hz.
Linear accelerations in z-direction are attenuated at frequencies outside 5 to 16 Hz using the weighting factor Wb, depending on the frequency.

All angular accelerations are multiplied by a frequency weighting factor (We) and by an axis multiplying factor smaller than one depending on the axis of rotation.

Table 3.5 Asymptotic frequency weightings, $W(f)$, used to assess vibration discomfort (f, frequency of vibration, Hz; $W(f) = 0$ where not otherwise defined)

Input	Axis	Frequency weighting	Axis multiplying factor	Weighting, $W(f)$
Seat	x	W_d	1.00	$0.5 < f < 2.0$ $W(f) = 1.00$ $2.0 < f < 80.0$ $W(f) = 2.0/f$
	y	W_d	1.00	$0.5 < f < 2.0$ $W(f) = 1.00$ $2.0 < f < 80.0$ $W(f) = 2.0/f$
	z	W_b	1.00	$0.5 < f < 2.0$ $W(f) = 0.4$ $2.0 < f < 5.0$ $W(f) = f/5.00$ $5.0 < f < 16.0$ $W(f) = 1.00$ $16.0 < f < 80.0$ $W(f) = 16.0/f$
	r_x	W_e	0.63	$0.5 < f < 1.0$ $W(f) = 0.63$ $1.0 < f < 20.0$ $W(f) = 0.63/f$
	r_y	W_e	0.40	$0.5 < f < 1.0$ $W(f) = 0.4$ $1.0 < f < 20.0$ $W(f) = 0.4/f$
	r_z	W_e	0.20	$0.5 < f < 1.0$ $W(f) = 0.2$ $1.0 < f < 20.0$ $W(f) = 0.2/f$

Reference

Griffin, M. J. (1996). Handbook of Human Vibration: Academic Press.

VII. Results – Crest Factors

code	take	direction	sensor1	sensor2	sensor3	sensor4
500maxfast	1	rx	11.6	14.2	13.0	13.6
		ry	13.7	12.2	19.8	18.7
		rz	11.2	15.5	17.5	12.6
		x	16.3	10.1	20.3	9.9
		y	10.0	10.0	18.4	15.4
		z	6.3	9.8	12.8	10.6
	2	rx	9.7	13.9	21.5	14.5
		ry	14.6	16.5	16.0	21.8
		rz	9.4	16.9	14.1	18.7
		x	21.9	11.6	12.3	9.7
		y	8.6	11.7	18.8	15.1
		z	6.7	8.8	12.9	10.9
	3	rx	13.9	16.1	24.4	
		ry	23.9	16.5	19.5	
		rz	17.0	18.9	19.3	
		x	13.3	11.5	17.8	
		y	7.8	11.3	16.1	
		z	7.2	9.6	6.4	
	4	rx	18.7	15.7	20.3	25.2
		ry	18.9	15.6	19.0	23.7
		rz	13.3	20.2	35.5	24.7
		x	12.4	14.5	16.2	14.5
		y	8.5	8.3	23.3	19.9
		z	7.9	9.3	16.3	10.7
500minfast	1	rx	25.3	24.6	28.1	16.2
		ry	13.1	22.7	22.4	25.3
		rz	12.1	20.2	32.7	19.7
		x	16.8	14.5	19.9	16.9
		y	11.1	10.5	20.0	17.8
		z	7.7	9.7	11.7	12.5
	2	rx	23.0	18.2	25.6	22.3
		ry	16.1	21.0	22.8	24.7
		rz	15.6	15.2	34.3	22.0
		x	13.3	15.1	20.2	7.9
		y	12.1	9.7	21.5	21.3
		z	7.5	9.9	18.8	9.6
	3	rx	20.7	12.2	28.5	
		ry	17.9	19.7	16.5	
		rz	12.8	19.5	24.8	
		x	14.1	13.2	20.1	
		y	9.6	11.9	21.3	
		z	8.1	9.9	9.3	

code	take	direction	sensor1	sensor2	sensor3	sensor4
500maxslow	1	rx	15.2	20.9	19.4	23.5
		ry	19.2	16.4	28.9	24.7
		rz	15.0	14.4	23.9	29.5
		x	15.7	15.1	11.6	14.7
		y	12.0	8.6	23.4	23.0
		z	7.8	9.0	21.2	5.9
	2	rx	15.8	15.4	29.5	25.6
		ry	19.8	24.9	32.0	27.0
		rz	16.2	26.6	31.7	28.0
		x	22.3	23.7	20.5	18.3
		y	8.9	10.0	20.5	18.4
		z	8.1	9.3	17.8	19.6
	3	rx	26.6	21.0	26.9	
		ry	17.5	21.1	25.3	
		rz	18.7	20.9	23.9	
		x	19.1	18.5	18.2	
		y	10.6	11.6	22.5	
		z	8.4	9.3	8.6	
500minslow	1	rx	23.5	12.7	20.0	20.2
		ry	19.1	26.7	26.4	23.2
		rz	11.5	22.2	23.0	22.7
		x	21.6	22.9	19.4	16.6
		y	8.4	8.4	22.2	20.0
		z	8.0	10.1	19.9	18.3
	2	rx	15.0	21.8	10.0	18.0
		ry	13.1	12.1	19.9	13.8
		rz	12.0	13.4	21.1	17.8
		x	10.3	8.5	19.6	15.9
		y	10.6	9.3	17.0	11.9
		z	9.7	10.9	9.6	7.6
	3	rx	16.3	20.7	19.5	25.0
		ry	13.3	17.2	21.0	17.9
		rz	13.4	29.6	15.7	21.1
		x	15.1	17.0	12.5	12.6
		y	9.8	9.2	15.0	14.4
		z	6.1	7.6	13.7	14.4
530minslow	1	rx	15.0	21.5	15.3	14.2
		ry	11.8	16.6	17.8	20.0
		rz	9.3	17.0	21.7	13.9
		x	12.0	7.7	20.2	12.1
		y	10.1	8.8	18.1	15.5
		z	7.2	8.8	14.0	8.0
	2	rx	18.2	23.4	15.2	16.4
		ry	11.2	20.6	17.0	12.8
		rz	15.3	23.3	18.1	26.3
		x	12.9	8.7	8.4	18.5
		y	9.9	8.6	17.0	14.4
		z	7.0	8.8	14.3	12.7

code	take	direction	sensor1	sensor2	sensor3	sensor4
530maxslow	1	rx	19.9	15.7	23.7	17.6
		ry	13.6	17.3	16.5	23.8
		rz	9.5	12.1	17.6	18.1
		x	16.0	11.4	25.5	24.8
		y	9.0	8.7	15.2	15.6
		z	6.2	7.8	10.4	5.8
	2	rx	16.4	15.7	25.8	17.0
		ry	15.3	17.8	26.6	19.9
		rz	9.4	17.0	22.7	17.1
		x	16.4	9.3	11.7	16.4
		y	7.3	8.8	16.0	17.1
		z	5.8	8.2	14.0	12.0
530maxfast	1	rx	9.3	13.0	13.3	
		ry	15.1	11.7	13.9	
		rz	10.1	14.2	23.5	
		x	10.1	8.9	7.4	
		y	9.2	8.4	15.0	
		z	5.9	8.4	8.5	
	2	rx	11.9	18.1	17.8	16.6
		ry	11.8	13.4	23.4	12.1
		rz	11.8	13.1	28.1	23.9
		x	7.4	10.2	9.4	15.8
		y	7.6	8.6	19.6	20.6
		z	6.0	7.9	13.7	9.1
530minfast	1	rx	12.2	19.3	18.4	18.8
		ry	11.0	20.1	16.7	16.5
		rz	13.7	26.1	19.6	17.3
		x	21.3	13.5	15.2	15.0
		y	8.7	8.4	16.2	13.7
		z	6.7	9.2	12.2	15.7
	2	rx	11.9	18.2	18.8	18.9
		ry	11.6	19.6	15.8	27.3
		rz	11.3	15.8	18.6	14.7
		x	7.4	8.0	15.6	6.6
		y	7.9	9.3	15.8	16.6
		z	7.4	10.3	13.2	6.4
Twinrider	1	rx	4.6	4.7	5.9	6.1
		ry	7.6	4.9	5.2	12.6
		rz	5.2	4.8	5.9	5.0
		x	5.1	5.0	8.9	8.1
		y	6.2	6.2	6.0	7.3
		z	6.7	8.1	9.9	8.1
	2	rx	5.6	5.6		
		ry	8.1	8.1		
		rz	4.8	4.7		
		x	7.1	10.2		
		y	6.4	6.4		
		z	6.7	9.8		

Average Snowcruiser models: 15.7
Average Twinrider: 6.7

VIII. RESULTS – REACTIONS AFTER SUBJECTIVE TEST

Gina van der Werf (advanced sit-snowboarder)

Comfort

- The comfort of the Twinrider is not good. I used my legs to prevent experiencing hard shocks on my bottom and (weak) back.
- Going over bumps feels better. My trunk stays more calm; it is less thrown around like with the Twinrider.
- The seat is higher. This is scary because when I will fall, I will fall from high. Especially when I switch from heel-to toe side.

Control

- Twinrider: When going over a hill while leaning on the heel side, I fell with all 3 tries.
  Snowcruiser: When going over the hill with the Snowcruiser, I did not fall!
- The seat is placed more horizontal which makes it harder to lean to the toe-side.
- Quite a lot of nose-tail movement was possible. This is something that needs to be controlled with the arms. Some of this movement was due to the mechanism, but also some movement occurred due to loose connections of the prototype.
- I needed to get used to the nose-tail movement.
- The nose-tail movement should be a little bit more stiff and less far.
- I know less well where my center of mass is with respect to the board. It feels a bit insecure compared to the Twinrider.
- The beam beneath the seat was too wide, which makes it collide with the handlebars, making the steering harder.
- The handlebars were lower with respect to the seat and wider than I am used to. I was not bothered by the fact that they were lower, maybe I even prefer this. The fact that they were wider makes the nose-tail controlling harder.

Ease of use

- Getting seated and started was harder, which makes it less independent to use than the Twinrider. This was mainly because of the higher seat and the footrests which were in the way.

Lisanne Fioole (novice sit-snowboarder)

Comfort

- I did not experience any painful shocks with the Twinrider, but my body was shaken quite a lot after I passed a hill. With the Snowcruiser my hips were tilted and my trunk stayed still.
- The seat was horizontal, making the semi-sitting position a sitting position, which felt scary.

Control

- The Snowcruiser prototype was starting to show more and more moving parts during the testing day because of some slack in the connections. This made the Snowcruiser rattle and not rigid. Because of the allowed movement in nose-tail direction, the control was harder because the seat could move without the board following.
- The horizontal seat made me sit in a less active position.
- The flexion in the Snowcruiser board was clearly visible, and clearly lacking for the Twinrider.

Ease of use

- It was hard to get in because the seat was too high.
- The footrests could not handle the forces applied and the connection started loosen.